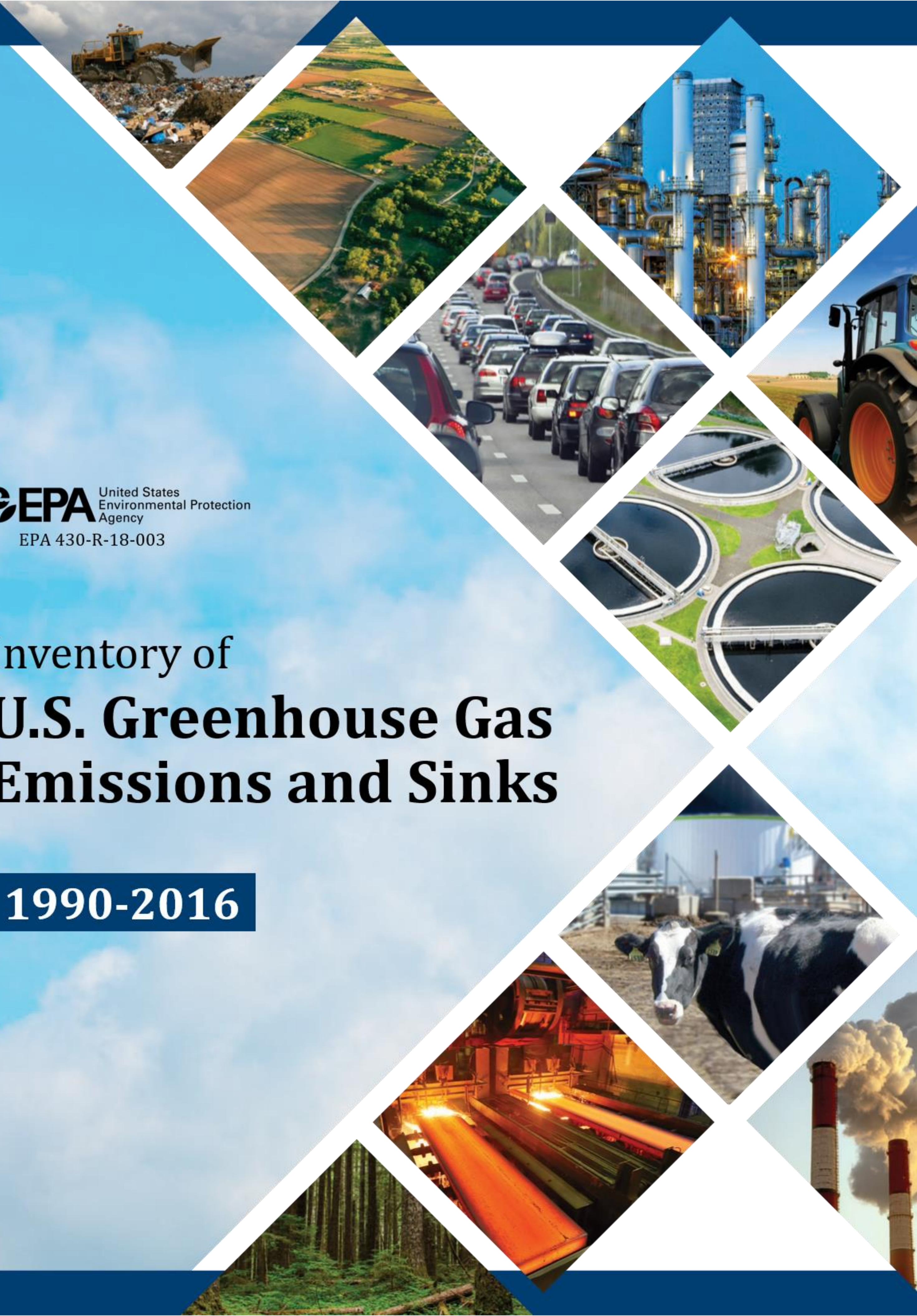

United States
Environmental Protection
Agency

EPA 430-R-18-003

Inventory of
U.S. Greenhouse Gas Emissions and Sinks

1990-2016

Front cover photo credit for cow and digester: Vanguard Renewables.

HOW TO OBTAIN COPIES

You can electronically download this document on the U.S. EPA's homepage at <https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks>.

All data tables of this document for the full time series 1990 through 2016, inclusive, will be made available for the final report published on April 12, 2018 at the internet site mentioned above.

FOR FURTHER INFORMATION

Contact Ms. Mausami Desai, Environmental Protection Agency, (202) 343-9381, desai.mausami@epa.gov,

or Mr. Vincent Camobreco, Environmental Protection Agency, (202) 564–9043, camobreco.vincent@epa.gov.

For more information regarding climate change and greenhouse gas emissions, see the EPA web site at <https://www.epa.gov/ghgemissions>.

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Preface

The United States Environmental Protection Agency (EPA) prepares the official U.S. Inventory of Greenhouse Gas Emissions and Sinks to comply with existing commitments under the United Nations Framework Convention on Climate Change (UNFCCC). Under decision 3/CP.5 of the UNFCCC Conference of the Parties, national inventories for UNFCCC Annex I parties should be provided to the UNFCCC Secretariat each year by April 15.

In an effort to engage the public and researchers across the country, the EPA has instituted an annual public review and comment process for this document. The availability of the draft document is announced via Federal Register Notice and is posted on the EPA web site. Copies are also emailed upon request. The public comment period is generally limited to 30 days; however, comments received after the closure of the public comment period are accepted and considered for the next edition of this annual report. Public review of this report occurred from February 7 to March 9, 2018, and comments received are posted to the EPA web site.

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Executive Summary

An emissions inventory that identifies and quantifies a country's anthropogenic[1] sources and sinks of greenhouse gases is essential for addressing climate change. This inventory adheres to both (1) a comprehensive and detailed set of methodologies for estimating sources and sinks of anthropogenic greenhouse gases, and (2) a common and consistent format that enables Parties to the United Nations Framework Convention on Climate Change (UNFCCC) to compare the relative contribution of different emission sources and greenhouse gases to climate change.

In 1992, the United States signed and ratified the UNFCCC. As stated in Article 2 of the UNFCCC, "The ultimate objective of this Convention and any related legal instruments that the Conference of the Parties may adopt is to achieve, in accordance with the relevant provisions of the Convention, stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner."[2]

Parties to the Convention, by ratifying, "shall develop, periodically update, publish and make available…national inventories of anthropogenic emissions by sources and removals by sinks of all greenhouse gases not controlled by the Montreal Protocol, using comparable methodologies…"[3] The United States views this report as an opportunity to fulfill these commitments.

This chapter summarizes the latest information on U.S. anthropogenic greenhouse gas emission trends from 1990 through 2016. To ensure that the U.S. emissions inventory is comparable to those of other UNFCCC Parties, the estimates presented here were calculated using methodologies consistent with those recommended in the *2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories* (IPCC 2006). The structure of this report is consistent with the UNFCCC guidelines for inventory reporting, as discussed in Box ES-1.[4]

Box ES-1: Methodological Approach for Estimating and Reporting U.S. Emissions and Removals

In following the UNFCCC requirement under Article 4.1 to develop and submit national greenhouse gas emission inventories, the emissions and removals presented in this report and this chapter, are organized by source and sink categories and calculated using internationally-accepted methods provided by the IPCC in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories (2006 IPCC Guidelines)*. Additionally, the calculated emissions and removals in a given year for the United States are presented in a common manner in line with the

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[1] The term "anthropogenic," in this context, refers to greenhouse gas emissions and removals that are a direct result of human activities or are the result of natural processes that have been affected by human activities (IPCC 2006).

[2] Article 2 of the Framework Convention on Climate Change published by the UNEP/WMO Information Unit on Climate Change. See <http://unfccc.int>.

[3] Article 4(1)(a) of the United Nations Framework Convention on Climate Change (also identified in Article 12). Subsequent decisions by the Conference of the Parties elaborated the role of Annex I Parties in preparing national inventories. See <http://unfccc.int>.

[4] See <http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf>.

UNFCCC reporting guidelines for the reporting of inventories under this international agreement. The use of consistent methods to calculate emissions and removals by all nations providing their inventories to the UNFCCC ensures that these reports are comparable. The presentation of emissions and removals provided in this Inventory does not preclude alternative examinations, but rather this Inventory presents emissions and removals in a common format consistent with how countries are to report Inventories under the UNFCCC. The report itself, and this chapter, follows this standardized format, and provides an explanation of the application of methods used to calculate emissions and removals.

Box ES-2: EPA's Greenhouse Gas Reporting Program

On October 30, 2009, the U.S. Environmental Protection Agency (EPA) promulgated a rule requiring annual reporting of greenhouse gas data from large greenhouse gas emissions sources in the United States. Implementation of the rule, codified at 40 CFR Part 98, is referred to as EPA's Greenhouse Gas Reporting Program (GHGRP). The rule applies to direct greenhouse gas emitters, fossil fuel suppliers, industrial gas suppliers, and facilities that inject carbon dioxide (CO_2) underground for sequestration or other reasons.[5] Annual reporting is at the facility level, except for certain suppliers of fossil fuels and industrial greenhouse gases.

EPA's GHGRP dataset and the data presented in this Inventory report are complementary. The GHGRP dataset continues to be an important resource for the Inventory, providing not only annual emissions information, but also other annual information, such as activity data and emission factors that can improve and refine national emission estimates and trends over time. GHGRP data also allow EPA to disaggregate national inventory estimates in new ways that can highlight differences across regions and sub-categories of emissions, along with enhancing application of QA/QC procedures and assessment of uncertainties.

EPA uses annual GHGRP data in a number of categories to improve the national estimates presented in this Inventory consistent with IPCC guidance.[6]

ES.1 Background Information

Greenhouse gases absorb infrared radiation, thereby trapping heat and making the planet warmer. The most important greenhouse gases directly emitted by humans include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and several other fluorine-containing halogenated substances. Although CO_2, CH_4, and N_2O occur naturally in the atmosphere, human activities have changed their atmospheric concentrations. From the pre-industrial era (i.e., ending about 1750) to 2016, concentrations of these greenhouse gases have increased globally by 44, 163, and 22 percent, respectively (IPCC 2013; NOAA/ESRL 2017a, 2017b, 2017c). This annual report estimates the total national greenhouse gas emissions and removals associated with human activities across the United States.

Global Warming Potentials

Gases in the atmosphere can contribute to climate change both directly and indirectly. Direct effects occur when the gas itself absorbs radiation. Indirect radiative forcing occurs when chemical transformations of the substance produce other greenhouse gases, when a gas influences the atmospheric lifetimes of other gases, and/or when a gas affects atmospheric processes that alter the radiative balance of the earth (e.g., affect cloud formation or albedo).[7]

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[5] See <http://www.epa.gov/ghgreporting> and <http://ghgdata.epa.gov/ghgp/main.do>.

[6] See <http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf>.

[7] Albedo is a measure of the Earth's reflectivity, and is defined as the fraction of the total solar radiation incident on a body that is reflected by it.

The IPCC developed the Global Warming Potential (GWP) concept to compare the ability of each greenhouse gas to trap heat in the atmosphere relative to another gas.

The GWP of a greenhouse gas is defined as the ratio of the accumulated radiative forcing within a specific time horizon caused by emitting 1 kilogram of the gas, relative to that of the reference gas CO_2 (IPCC 2014). The reference gas used is CO_2, and therefore GWP-weighted emissions can be provided in million metric tons of CO_2 equivalent (MMT CO_2 Eq.).[8,9] All gases in this Executive Summary are presented in units of MMT CO_2 Eq. Emissions by gas in unweighted mass kilotons are provided in the Trends chapter of this report.

UNFCCC reporting guidelines for national inventories require the use of GWP values from the *IPCC Fourth Assessment Report* (AR4) (IPCC 2007).[10] All estimates are provided throughout the report in both CO_2 equivalents and unweighted units. A comparison of emission values using the AR4 GWP values versus the SAR (IPCC 1996), and the *IPCC Fifth Assessment Report* (AR5) (IPCC 2013) GWP values can be found in Chapter 1 and, in more detail, in Annex 6.1 of this report. The GWP values used in this report are listed below in Table ES-1.

Table ES-1: Global Warming Potentials (100-Year Time Horizon) Used in this Report

Gas	GWP
CO_2	1
CH_4[a]	25
N_2O	298
HFC-23	14,800
HFC-32	675
HFC-125	3,500
HFC-134a	1,430
HFC-143a	4,470
HFC-152a	124
HFC-227ea	3,220
HFC-236fa	9,810
HFC-4310mee	1,640
CF_4	7,390
C_2F_6	12,200
C_4F_{10}	8,860
C_6F_{14}	9,300
SF_6	22,800
NF_3	17,200

[a] The CH_4 GWP includes the direct effects and those indirect effects due to the production of tropospheric ozone and stratospheric water vapor. The indirect effect due to production of CO_2 is not included.
Source: IPCC (2007)

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[8] Carbon comprises 12/44 of carbon dioxide by weight.

[9] One million metric ton is equal to 10^{12} grams or one teragram.

[10] See <http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf>.

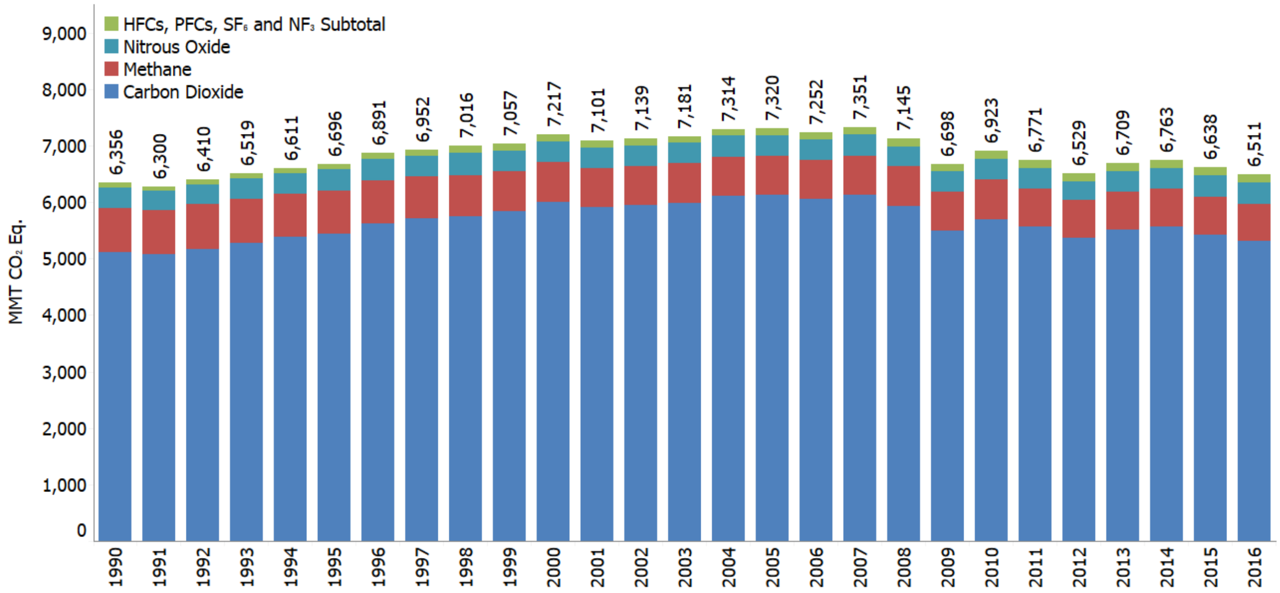
ES.2 Recent Trends in U.S. Greenhouse Gas Emissions and Sinks

In 2016, total gross U.S. greenhouse gas emissions were 6,511.3 million metric tons (MMT) of CO_2 Eq.[11] Total U.S. emissions have increased by 2.4 percent from 1990 to 2016, and emissions decreased from 2015 to 2016 by 1.9 percent (126.8 MMT CO_2 Eq.). The decrease in total greenhouse gas emissions between 2015 and 2016 was driven in large part by a decrease in CO_2 emissions from fossil fuel combustion. The decrease in CO_2 emissions from fossil fuel combustion was a result of multiple factors, including:

(1) substitution from coal to natural gas and other non-fossil energy sources in the electric power sector; and
(2) warmer winter conditions in 2016 resulting in a decreased demand for heating fuel in the residential and commercial sectors.

Relative to 1990, the baseline for this Inventory, gross emissions in 2016 are higher by 2.4 percent, down from a high of 15.7 percent above 1990 levels in 2007. Overall, net emissions in 2016 were 11.1 percent below 2005 levels as shown in Table ES-2. Figure ES-1 through Figure ES-3 illustrate the overall trends in total U.S. emissions by gas, annual changes, and absolute change since 1990, and Table ES-2 provides a detailed summary of gross U.S. greenhouse gas emissions and sinks for 1990 through 2016. Note, unless otherwise stated, all tables and figures provide total gross emissions, and exclude the greenhouse gas fluxes from the Land Use, Land-Use Change, and Forestry (LULUCF) sector (see Section ES.3 Overview of Sector Emissions and Trends).

Figure ES-1: Gross U.S. Greenhouse Gas Emissions by Gas (MMT CO_2 Eq.)



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[11] The gross emissions total presented in this report for the United States excludes emissions and removals from Land Use, Land-Use Change, and Forestry (LULUCF). The net emissions total presented in this report for the United States includes emissions and removals from LULUCF.

Figure ES-2: Annual Percent Change in Gross U.S. Greenhouse Gas Emissions Relative to the Previous Year

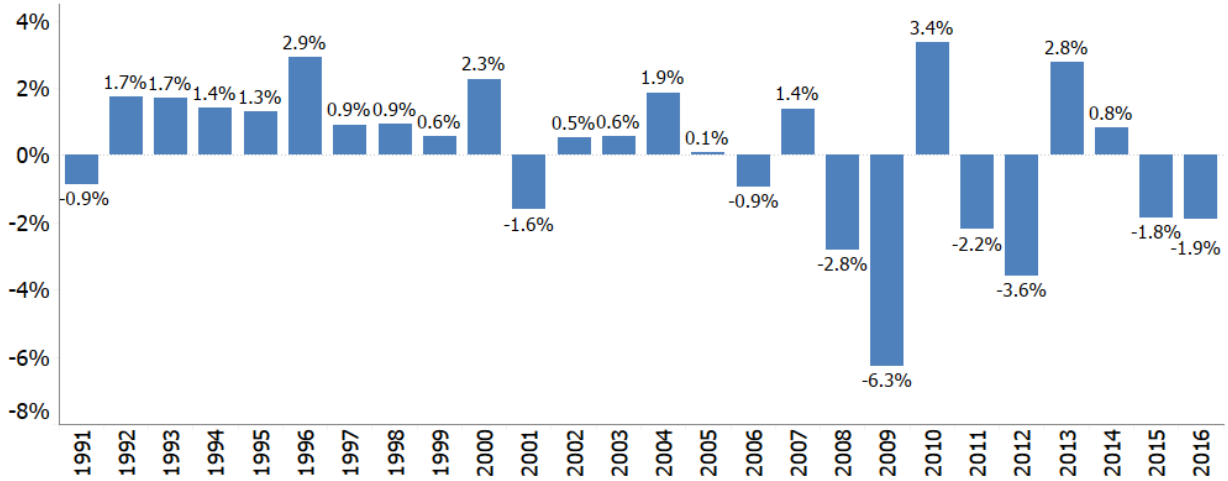
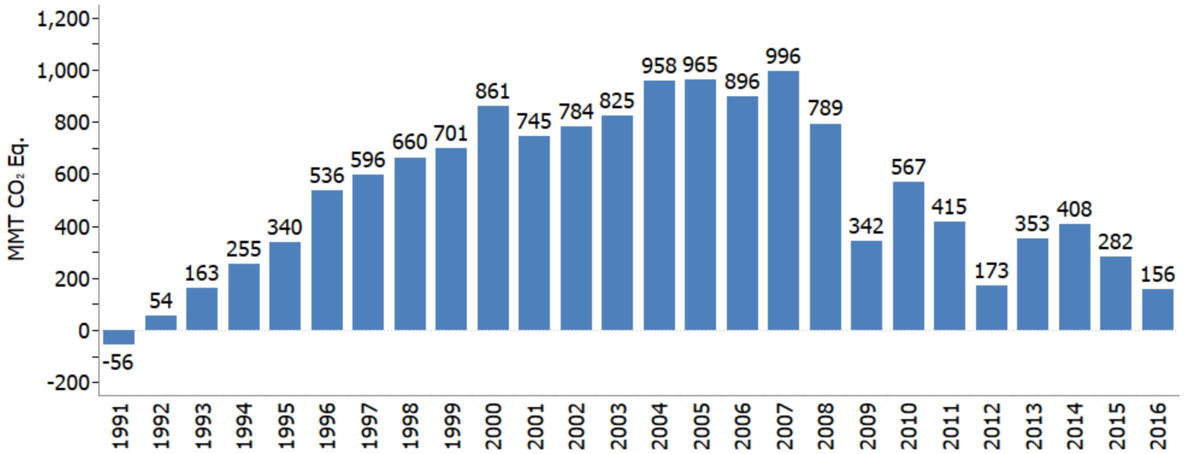


Figure ES-3: Cumulative Change in Annual Gross U.S. Greenhouse Gas Emissions Relative to 1990 (1990=0, MMT CO_2 Eq.)



Box ES-3: Improvements and Recalculations Relative to the Previous Inventory

Each year, some emission and sink estimates in the Inventory are recalculated and revised with improved methods and/or data. In general, recalculations are made to the U.S. greenhouse gas emission estimates either to incorporate new methodologies or, most commonly, to update recent historical data. These improvements are implemented consistently across the previous Inventory's time series (i.e., 1990 to 2015) to ensure that the trend is accurate.

Below are categories with recalculations resulting in an average change over the time series of greater than 10 MMT CO_2 Eq. For more information on specific methodological updates, please see the Energy chapter (Chapter 3) and the Recalculations and Improvements chapter (Chapter 9).

- *Fossil Fuel Combustion-Transportation (CO_2).* Changes were made to the historic allocation of gasoline to on-road and non-road applications. These changes resulted in a decrease of gasoline use and emissions in the transportation sector and an increase in the commercial and industrial sectors. These changes resulted in an average annual shift in CO_2 emissions of 27.3 MMT CO_2 Eq. (1.6 percent) relative to the previous Inventory.

- *Petroleum Systems (CH_4).* Average decrease of 13.4 MMT CO_2 Eq. (28 percent) for a given year relative to the estimate provided in the previous Inventory, resulting primarily from recalculation of associated gas venting and flaring emissions using a basin-level approach. In addition, recalculations of CO_2 emissions for petroleum systems resulted in an increase of 9.1 MMT CO_2 (240 percent) for a given year relative to the estimate provided in the previous Inventory, resulting primarily from reallocation of CO_2 from flaring to petroleum systems from natural gas systems. Further details on the methodological improvements can be found in Section 3.6 of the Energy chapter (Chapter 3).
- *Natural Gas Systems (CO_2).* Average decrease of 10.5 MMT CO_2 Eq. (29 percent) for a given year relative to the estimate provided in the previous Inventory, resulting primarily from reallocation of CO_2 from flaring to petroleum systems from natural gas systems. Further details on the methodological improvements can be found in Section 3.7 of the Energy chapter (Chapter 3).
- Other improvements of note include recalculations of CH_4 estimates from Municipal Solid Waste (MSW) Landfills (See Section 7.1 of the Waste chapter).

In implementing improvements, the United States follows the *2006 IPCC Guidelines* (IPCC 2006), which states, "Both methodological changes and refinements over time are an essential part of improving inventory quality. It is good practice to change or refine methods when: available data have changed; the previously used method is not consistent with the IPCC guidelines for that category; a category has become key; the previously used method is insufficient to reflect mitigation activities in a transparent manner; the capacity for inventory preparation has increased; new inventory methods become available; and for correction of errors."

In each Inventory, the results of all methodological changes and historical data updates are presented in the Recalculations and Improvements chapter of this report; and detailed descriptions of each recalculation including references for data, are provided within each source or sink's description in the report, if applicable. Changes in historical data are generally the result of changes in statistical data supplied by other agencies.

Table ES-2: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks (MMT CO_2 Eq.)

Gas/Source	1990	2005	2012	2013	2014	2015	2016
CO_2	**5,121.3**	**6,132.0**	**5,366.7**	**5,519.6**	**5,568.8**	**5,420.8**	**5,310.9**
Fossil Fuel Combustion	4,740.3	5,746.9	5,024.4	5,156.9	5,200.3	5,049.3	4,966.0
Electric Power Sector	*1,820.8*	*2,400.9*	*2,022.2*	*2,038.1*	*2,038.0*	*1,900.7*	*1,809.3*
Transportation	*1,467.6*	*1,855.8*	*1,661.9*	*1,677.6*	*1,717.1*	*1,735.5*	*1,782.6*
Industrial	*858.8*	*855.7*	*812.9*	*843.3*	*824.9*	*809.5*	*809.1*
Residential	*338.3*	*357.8*	*282.5*	*329.7*	*345.3*	*316.8*	*292.5*
Commercial	*227.2*	*227.0*	*201.3*	*225.7*	*233.6*	*245.4*	*231.3*
U.S. Territories	*27.6*	*49.7*	*43.5*	*42.5*	*41.4*	*41.4*	*41.4*
Non-Energy Use of Fuels	119.5	138.9	108.0	123.5	118.9	125.6	112.2
Iron and Steel Production & Metallurgical Coke Production	101.6	68.2	55.6	53.5	58.4	47.8	42.3
Cement Production	33.5	46.2	35.3	36.4	39.4	39.9	39.4
Petrochemical Production	21.2	26.8	26.5	26.4	26.5	28.1	28.1
Natural Gas Systems	29.8	22.5	23.3	24.8	25.3	24.9	25.5
Petroleum Systems	7.7	11.7	19.3	22.6	26.3	28.8	22.8
Lime Production	11.7	14.6	13.8	14.0	14.2	13.3	12.9
Ammonia Production	13.0	9.2	9.4	10.0	9.6	10.9	12.2
Other Process Uses of Carbonates	6.3	7.6	9.1	11.5	13.0	12.3	11.0
Incineration of Waste	8.0	12.5	10.4	10.4	10.6	10.7	10.7
Urea Fertilization	2.4	3.5	4.3	4.4	4.5	4.9	5.1
Carbon Dioxide Consumption	1.5	1.4	4.0	4.2	4.5	4.5	4.5
Urea Consumption for Non-Agricultural Purposes	3.8	3.7	4.4	4.1	1.5	4.2	4.0
Liming	4.7	4.3	6.0	3.9	3.6	3.8	3.9
Ferroalloy Production	2.2	1.4	1.9	1.8	1.9	2.0	1.8

Soda Ash Production	1.4	1.7	1.7	1.7	1.7	1.7	1.7
Titanium Dioxide Production	1.2	1.8	1.5	1.7	1.7	1.6	1.6
Aluminum Production	6.8	4.1	3.4	3.3	2.8	2.8	1.3
Glass Production	1.5	1.9	1.2	1.3	1.3	1.3	1.2
Phosphoric Acid Production	1.5	1.3	1.1	1.1	1.0	1.0	1.0
Zinc Production	0.6	1.0	1.5	1.4	1.0	0.9	0.9
Lead Production	0.5	0.6	0.5	0.5	0.5	0.5	0.5
Silicon Carbide Production and Consumption	0.4	0.2	0.2	0.2	0.2	0.2	0.2
Abandoned Oil and Gas Wells	+	+	+	+	+	+	+
Magnesium Production and Processing	+	+	+	+	+	+	+
Wood Biomass, Ethanol, and Biodiesel Consumption[a]	*219.4*	*230.7*	*287.7*	*316.4*	*324.3*	*310.4*	*309.3*
International Bunker Fuels[b]	*103.5*	*113.1*	*105.8*	*99.8*	*103.4*	*110.9*	*116.6*
CH$_4$[c]	**779.9**	**688.6**	**662.5**	**662.6**	**664.0**	**665.4**	**657.4**
Enteric Fermentation	164.2	168.9	166.7	165.5	164.2	166.5	170.1
Natural Gas Systems	195.2	169.1	159.6	163.8	164.3	166.3	163.5
Landfills	179.6	132.7	117.0	113.3	112.7	111.7	107.7
Manure Management	37.2	56.3	65.6	63.3	62.9	66.3	67.7
Coal Mining	96.5	64.1	66.5	64.6	64.6	61.2	53.8
Petroleum Systems	39.8	32.1	32.7	36.6	38.6	38.1	38.6
Wastewater Treatment	15.7	15.8	15.1	14.9	15.0	15.1	14.8
Rice Cultivation	16.0	16.7	11.3	11.5	12.7	12.3	13.7
Stationary Combustion	8.6	7.8	7.4	8.8	8.9	7.9	7.3
Abandoned Oil and Gas Wells	6.5	6.9	7.0	7.0	7.1	7.2	7.1
Abandoned Underground Coal Mines	7.2	6.6	6.2	6.2	6.3	6.4	6.7
Mobile Combustion	12.7	9.4	5.1	4.7	4.2	3.8	3.6
Composting	0.4	1.9	1.9	2.0	2.1	2.1	2.1
Field Burning of Agricultural Residues	0.2	0.2	0.3	0.3	0.3	0.3	0.3
Petrochemical Production	0.2	0.1	0.1	0.1	0.1	0.2	0.2
Ferroalloy Production	+	+	+	+	+	+	+
Silicon Carbide Production and Consumption	+	+	+	+	+	+	+
Iron and Steel Production & Metallurgical Coke Production	+	+	+	+	+	+	+
Incineration of Waste	+	+	+	+	+	+	+
International Bunker Fuels[b]	*0.2*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*
N$_2$O[c]	**354.8**	**357.8**	**335.8**	**363.2**	**361.2**	**379.6**	**369.5**
Agricultural Soil Management	250.5	253.5	247.9	276.6	274.0	295.0	283.6
Stationary Combustion	11.1	17.5	16.9	18.7	19.0	18.1	18.6
Mobile Combustion	41.7	38.8	24.3	22.5	20.6	19.3	18.4
Manure Management	14.0	16.5	17.5	17.5	17.5	17.7	18.1
Nitric Acid Production	12.1	11.3	10.5	10.7	10.9	11.6	10.2
Adipic Acid Production	15.2	7.1	5.5	3.9	5.4	4.3	7.0
Wastewater Treatment	3.4	4.4	4.6	4.7	4.8	4.8	5.0
N$_2$O from Product Uses	4.2	4.2	4.2	4.2	4.2	4.2	4.2
Caprolactam, Glyoxal, and Glyoxylic Acid Production	1.7	2.1	2.0	2.0	2.0	2.0	2.0
Composting	0.3	1.7	1.7	1.8	1.9	1.9	1.9
Incineration of Waste	0.5	0.4	0.3	0.3	0.3	0.3	0.3
Semiconductor Manufacture	+	0.1	0.2	0.2	0.2	0.2	0.2
Field Burning of Agricultural Residues	0.1	0.1	0.1	0.1	0.1	0.1	0.1
International Bunker Fuels[b]	*0.9*	*1.0*	*0.9*	*0.9*	*0.9*	*0.9*	*1.0*
HFCs	**46.6**	**123.0**	**150.5**	**151.1**	**156.7**	**160.8**	**162.3**

Substitution of Ozone Depleting Substances[d]	0.3	102.7	144.8	146.8	151.3	156.1	159.1
HCFC-22 Production	46.1	20.0	5.5	4.1	5.0	4.3	2.8
Semiconductor Manufacture	0.2	0.2	0.2	0.2	0.3	0.3	0.3
Magnesium Production and Processing	0.0	0.0	+	0.1	0.1	0.1	0.1
PFCs	**24.3**	**6.7**	**5.9**	**5.8**	**5.6**	**5.1**	**4.3**
Semiconductor Manufacture	2.8	3.3	3.0	2.8	3.1	3.1	3.0
Aluminum Production	21.5	3.4	2.9	3.0	2.5	2.0	1.4
Substitution of Ozone Depleting Substances	0.0	+	+	+	+	+	+
SF_6	**28.8**	**11.8**	**6.7**	**6.3**	**6.4**	**5.9**	**6.2**
Electrical Transmission and Distribution	23.1	8.3	4.7	4.5	4.7	4.3	4.3
Magnesium Production and Processing	5.2	2.7	1.6	1.5	1.0	0.9	1.0
Semiconductor Manufacture	0.5	0.7	0.3	0.4	0.7	0.7	0.8
NF_3	**+**	**0.5**	**0.6**	**0.6**	**0.5**	**0.6**	**0.6**
Semiconductor Manufacture	+	0.5	0.6	0.6	0.5	0.6	0.6
Total Emissions	**6,355.6**	**7,320.3**	**6,528.8**	**6,709.1**	**6,763.1**	**6,638.1**	**6,511.3**
LULUCF Emissions[c]	**10.6**	**23.0**	**26.1**	**19.2**	**19.6**	**38.2**	**38.1**
LULUCF CH_4 Emissions	6.7	13.3	15.0	10.9	11.2	22.4	22.4
LULUCF N_2O Emissions	3.9	9.7	11.1	8.3	8.4	15.8	15.7
LULUCF Carbon Stock Change[e]	**(830.2)**	**(754.2)**	**(779.5)**	**(755.0)**	**(760.0)**	**(733.4)**	**(754.9)**
LULUCF Sector Net Total[f]	**(819.6)**	**(731.1)**	**(753.5)**	**(735.8)**	**(740.4)**	**(695.2)**	**(716.8)**
Net Emissions (Sources and Sinks)	**5,536.0**	**6,589.1**	**5,775.3**	**5,973.3**	**6,022.8**	**5,942.9**	**5,794.5**

Notes: Total emissions presented without LULUCF. Net emissions presented with LULUCF.

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Emissions from Wood Biomass and Biofuel Consumption are not included specifically in summing Energy sector totals. Net carbon fluxes from changes in biogenic carbon reservoirs are accounted for in the estimates for Land Use, Land-Use Change, and Forestry.

[b] Emissions from International Bunker Fuels are not included in totals.

[c] LULUCF emissions of CH_4 and N_2O are reported separately from gross emissions totals. LULUCF emissions include the CH_4 and N_2O emissions reported for *Peatlands Remaining Peatlands*, Forest Fires, Drained Organic Soils, Grassland Fires, and *Coastal Wetlands Remaining Coastal Wetlands*; CH_4 emissions from *Land Converted to Coastal Wetlands*; and N_2O emissions from Forest Soils and Settlement Soils. Refer to Table ES-5 for a breakout of emissions and removals for Land Use, Land-Use Change, and Forestry by gas and source category.

[d] Small amounts of PFC emissions also result from this source.

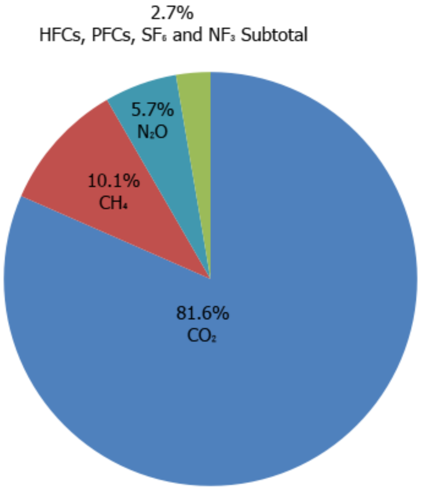
[e] LULUCF Carbon Stock Change is the net C stock change from the following categories: *Forest Land Remaining Forest Land, Land Converted to Forest Land, Cropland Remaining Cropland, Land Converted to Cropland, Grassland Remaining Grassland, Land Converted to Grassland, Wetlands Remaining Wetlands, Land Converted to Wetlands, Settlements Remaining Settlements*, and *Land Converted to Settlements*. Refer to Table ES-5 for a breakout of emissions and removals for Land Use, Land-Use Change, and Forestry by gas and source category.

[f] The LULUCF Sector Net Total is the net sum of all CH_4 and N_2O emissions to the atmosphere plus net carbon stock changes.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or sequestration.

Figure ES-4 illustrates the relative contribution of the direct greenhouse gases to total U.S. emissions in 2016, weighted by global warming potential. The primary greenhouse gas emitted by human activities in the United States was CO_2, representing approximately 81.6 percent of total greenhouse gas emissions. The largest source of CO_2, and of overall greenhouse gas emissions, was fossil fuel combustion. Methane emissions, which have decreased by 15.7 percent since 1990, resulted primarily from enteric fermentation associated with domestic livestock, natural gas systems, and decomposition of wastes in landfills. Agricultural soil management, stationary fuel combustion, manure management, and mobile source fuel combustion were the major sources of N_2O emissions. Ozone depleting substance substitute emissions and emissions of HFC-23 during the production of HCFC-22 were the primary contributors to aggregate hydrofluorocarbon (HFC) emissions. Perfluorocarbon (PFC) emissions resulted from semiconductor manufacturing and as a byproduct of primary aluminum production, electrical transmission and distribution systems accounted for most sulfur hexafluoride (SF_6) emissions, and semiconductor manufacturing is the only source of nitrogen trifluoride (NF_3) emissions.

Figure ES-4: 2016 U.S. Greenhouse Gas Emissions by Gas (Percentages based on MMT CO_2 Eq.)



Overall, from 1990 to 2016, total emissions of CO_2 increased by 189.6 MMT CO_2 Eq. (3.7 percent), while total emissions of CH_4 decreased by 122.5 MMT CO_2 Eq. (15.7 percent), and N_2O emissions increased by 14.8 MMT CO_2 Eq. (4.2 percent). During the same period, aggregate weighted emissions of HFCs, PFCs, SF_6 and NF_3 rose by 73.8 MMT CO_2 Eq. (74.0 percent). From 1990 to 2016, HFCs increased by 115.8 MMT CO_2 Eq. (248.5 percent), PFCs decreased by 19.9 MMT CO_2 Eq. (82.1 percent), SF_6 decreased by 22.6 MMT CO_2 Eq. (78.5 percent), and NF_3 increased by 0.5 MMT CO_2 Eq. (1,110.2 percent). Despite being emitted in smaller quantities relative to the other principal greenhouse gases, emissions of HFCs, PFCs, SF_6 and NF_3 are significant because many of these gases have extremely high global warming potentials and, in the cases of PFCs and SF_6, long atmospheric lifetimes. Conversely, U.S. greenhouse gas emissions were partly offset by carbon (C) sequestration in forests, trees in urban areas, agricultural soils, landfilled yard trimmings and food scraps, and coastal wetlands, which, in aggregate, offset 11.5 percent of total emissions in 2016. The following sections describe each gas's contribution to total U.S. greenhouse gas emissions in more detail.

Carbon Dioxide Emissions

The global carbon cycle is made up of large carbon flows and reservoirs. Billions of tons of carbon in the form of CO_2 are absorbed by oceans and living biomass (i.e., sinks) and are emitted to the atmosphere annually through natural processes (i.e., sources). When in equilibrium, carbon fluxes among these various reservoirs are roughly balanced.[12]

Since the Industrial Revolution (i.e., about 1750), global atmospheric concentrations of CO_2 have risen approximately 44 percent (IPCC 2013; NOAA/ESRL 2017a), principally due to the combustion of fossil fuels for

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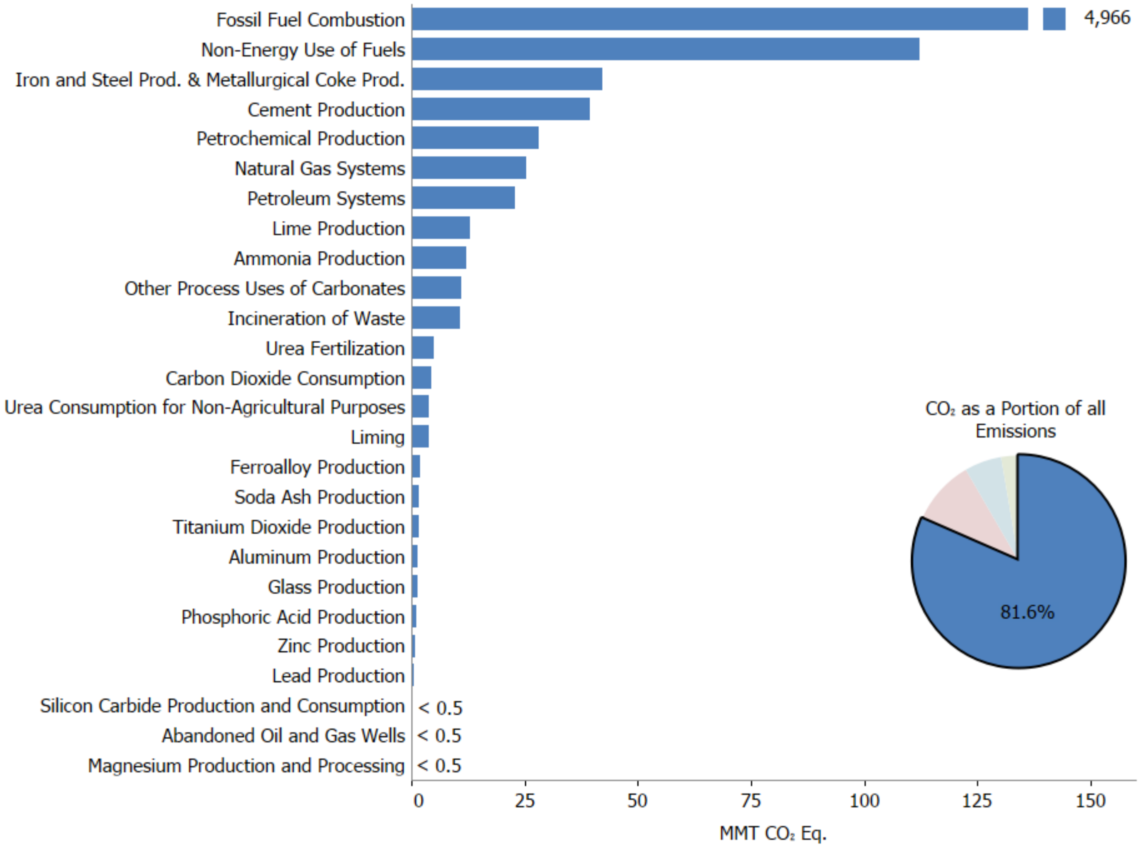
[12] The term "flux" is used to describe the net emissions of greenhouse gases accounting for both the emissions of CO_2 to and the removals of CO_2 from the atmosphere. Removal of CO_2 from the atmosphere is also referred to as "carbon sequestration."

energy. Globally, approximately 32,294 MMT of CO_2 were added to the atmosphere through the combustion of fossil fuels in 2015, of which the United States accounted for approximately 15 percent.[13]

Within the United States, fossil fuel combustion accounted for 93.5 percent of CO_2 emissions in 2016. There are 25 additional sources of CO_2 emissions included in the Inventory (see Figure ES-5). Although not illustrated in the Figure ES-5, changes in land use and forestry practices can also lead to net CO_2 emissions (e.g., through conversion of forest land to agricultural or urban use) or to a net sink for CO_2 (e.g., through net additions to forest biomass).

Figure ES-5: 2016 Sources of CO_2 Emissions (MMT CO_2 Eq.)



As the largest source of U.S. greenhouse gas emissions, CO_2 from fossil fuel combustion has accounted for approximately 77 percent of GWP-weighted emissions since 1990. Important drivers influencing emissions levels include: (1) changes in demand for energy; and (2) a general decline in the carbon intensity of fuels combusted for energy in recent years by non-transport sectors of the economy.

Between 1990 and 2016, CO_2 emissions from fossil fuel combustion increased from 4,740.3 MMT CO_2 Eq. to 4,966.0 MMT CO_2 Eq., a 4.8 percent total increase over the twenty-seven-year period. Conversely, CO_2 emissions from fossil fuel combustion decreased by 780.9 MMT CO_2 Eq. from 2005 levels, a decrease of approximately 13.6 percent between 2005 and 2016. From 2015 to 2016, these emissions decreased by 83.2 MMT CO_2 Eq. (1.6 percent).

Historically, changes in emissions from fossil fuel combustion have been the dominant factor affecting U.S. emission trends. Changes in CO_2 emissions from fossil fuel combustion are influenced by many long-term and short-term factors. Long-term factors include population and economic trends, technological changes, shifting

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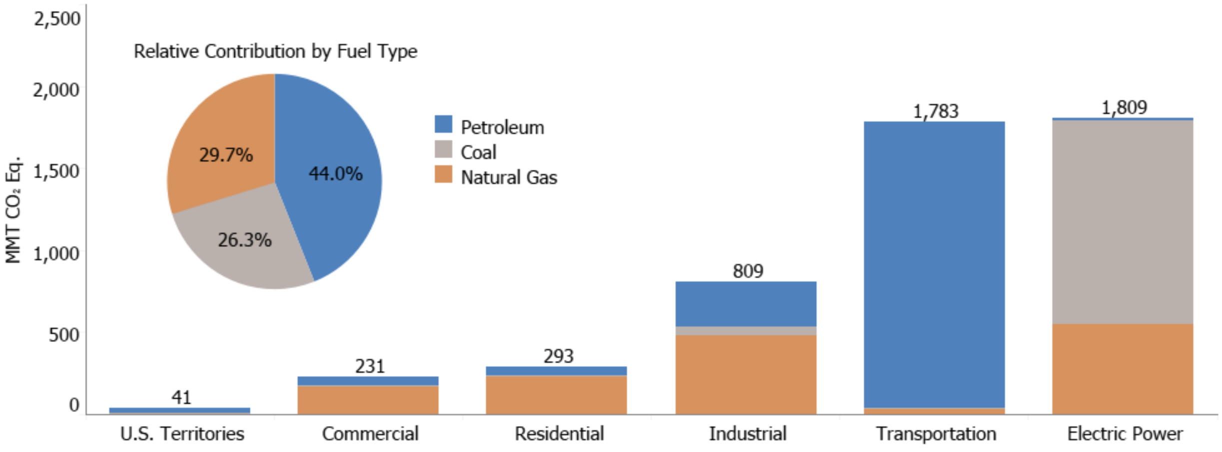
[13] Global CO_2 emissions from fossil fuel combustion were taken from International Energy Agency *CO_2 Emissions from Fossil Fuels Combustion – Highlights*. IEA (2017). See <https://www.iea.org/publications/freepublications/publication/co2-emissions-from-fuel-combustion-highlights-2017.html>. The publication has not yet been updated to include 2016 data.

energy fuel choices, and various policies at the national, state, and local level. In the short term, the overall consumption and mix of fossil fuels in the United States fluctuates primarily in response to changes in general economic conditions, overall energy prices, the relative price of different fuels, weather, and the availability of non-fossil alternatives.

The five major fuel consuming economic sectors contributing to CO_2 emissions from fossil fuel combustion are electric power, transportation, industrial, residential, and commercial. Carbon dioxide emissions are produced by the electric power sector as fossil fuel is consumed to provide electricity to one of the other four sectors, or "end-use" sectors. For the discussion below, electric power emissions have been distributed to each end-use sector on the basis of each sector's share of aggregate electricity use. This method of distributing emissions assumes that each end-use sector uses electricity that is generated from the national average mix of fuels according to their carbon intensity. Emissions from electric power are also addressed separately after the end-use sectors have been discussed. Note that emissions from U.S. Territories are calculated separately due to a lack of specific consumption data for the individual end-use sectors. Figure ES-6, Figure ES-7, and Table ES-3 summarize CO_2 emissions from fossil fuel combustion by end-use sector.

Figure ES-6: 2016 CO_2 Emissions from Fossil Fuel Combustion by Sector and Fuel Type (MMT CO_2 Eq.)



Note on Figure ES-6: Fossil Fuel Combustion for electric power also includes emissions of less than 0.5 MMT CO_2 Eq. from geothermal-based generation.

Figure ES-7: 2016 End-Use Sector Emissions of CO_2 from Fossil Fuel Combustion (MMT CO_2 Eq.)

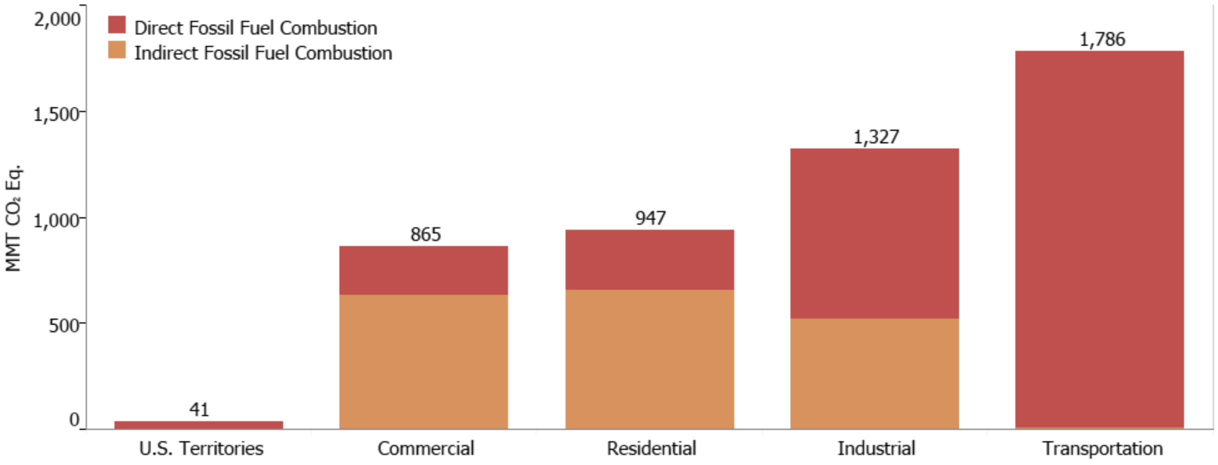


Table ES-3: CO_2 Emissions from Fossil Fuel Combustion by End-Use Sector (MMT CO_2 Eq.)

End-Use Sector	1990	2005	2012	2013	2014	2015	2016
Transportation	**1,470.6**	**1,860.5**	**1,665.8**	**1,681.6**	**1,721.2**	**1,739.2**	**1,786.1**
Combustion	1,467.6	1,855.8	1,661.9	1,677.6	1,717.1	1,735.5	1,782.6
Electricity	3.0	4.7	3.9	4.0	4.1	3.7	3.5
Industrial	**1,545.6**	**1,592.3**	**1,405.7**	**1,438.0**	**1,418.1**	**1,359.0**	**1,326.7**
Combustion	858.8	855.7	812.9	843.3	824.9	809.5	809.1
Electricity	686.7	736.6	592.8	594.7	593.2	549.6	517.7
Residential	**931.4**	**1,214.1**	**1,007.8**	**1,064.6**	**1,080.0**	**1,001.1**	**946.7**
Combustion	338.3	357.8	282.5	329.7	345.3	316.8	292.5
Electricity	593.0	856.3	725.3	734.9	734.7	684.3	654.2
Commercial	**765.2**	**1,030.3**	**901.6**	**930.2**	**939.6**	**908.6**	**865.2**
Combustion	227.2	227.0	201.3	225.7	233.6	245.4	231.3
Electricity	538.0	803.3	700.3	704.5	706.0	663.1	633.9
U.S. Territories[a]	**27.6**	**49.7**	**43.5**	**42.5**	**41.4**	**41.4**	**41.4**
Total	**4,740.3**	**5,746.9**	**5,024.4**	**5,156.9**	**5,200.3**	**5,049.3**	**4,966.0**
Electric Power	**1,820.8**	**2,400.9**	**2,022.2**	**2,038.1**	**2,038.0**	**1,900.7**	**1,809.3**

[a] Fuel consumption by U.S. Territories (i.e., American Samoa, Guam, Puerto Rico, U.S. Virgin Islands, Wake Island, and other U.S. Pacific Islands) is included in this report.

Notes: Combustion-related emissions from electric power are allocated based on aggregate national electricity use by each end-use sector. Totals may not sum due to independent rounding.

Transportation End-Use Sector. When electricity-related emissions are distributed to economic end-use sectors, transportation activities accounted for 36.0 percent of U.S. CO_2 emissions from fossil fuel combustion in 2016. The largest sources of transportation CO_2 emissions in 2016 were passenger cars (42.0 percent), medium- and heavy-duty trucks (23.4 percent), light-duty trucks, which include sport utility vehicles, pickup trucks, and minivans (17.3 percent), commercial aircraft (6.7 percent), other aircraft (2.6 percent), rail (2.3 percent), pipelines (2.2 percent), and ships and boats (2.2 percent). Annex 3.2 presents the total emissions from all transportation and mobile sources, including CO_2, CH_4, N_2O, and HFCs.

In terms of the overall trend, from 1990 to 2016, total transportation CO_2 emissions increased due, in large part, to increased demand for travel. The number of vehicle miles traveled (VMT) by light-duty motor vehicles (i.e., passenger cars and light-duty trucks) increased 44 percent from 1990 to 2016,[14] as a result of a confluence of factors including population growth, economic growth, urban sprawl, and low fuel prices during the beginning of this period. Almost all of the energy consumed for transportation was supplied by petroleum-based products, with more than half being related to gasoline consumption in automobiles and other highway vehicles. Other fuel uses, especially diesel fuel for freight trucks and jet fuel for aircraft, accounted for the remainder.

Industrial End-Use Sector. Industrial CO_2 emissions, resulting both directly from the combustion of fossil fuels and indirectly from the generation of electricity that is used by industry, accounted for 27 percent of CO_2 from fossil fuel combustion in 2016. Approximately 61 percent of these emissions resulted from direct fossil fuel combustion to produce steam and/or heat for industrial processes. The remaining emissions resulted from the use of electricity for motors, electric furnaces, ovens, lighting, and other applications. In contrast to the other end-use sectors, emissions from industry have declined since 1990. This decline is due to structural changes in the U.S. economy (i.e., shifts from a manufacturing-based to a service-based economy), fuel switching, and efficiency improvements.

Residential and Commercial End-Use Sectors. The residential and commercial end-use sectors accounted for 19 and 17 percent, respectively, of CO_2 emissions from fossil fuel combustion in 2016. Both sectors relied heavily on electricity for meeting energy demands, with 69 and 73 percent, respectively, of their emissions attributable to electricity use for lighting, heating, cooling, and operating appliances. The remaining emissions were due to the consumption of natural gas and petroleum for heating and cooking. Emissions from the residential and commercial end-use sectors have increased by 2 percent and 13 percent since 1990, respectively.

Electric Power. The United States relies on electricity to meet a significant portion of its energy demands. Electricity generators used 33 percent of U.S. energy from fossil fuels and emitted 36 percent of the CO_2 from fossil fuel combustion in 2016. The type of energy source used to generate electricity is the main factor influencing emissions.[15] For example, some electricity is generated through non-fossil fuel options such as nuclear, hydroelectric, wind, solar, or geothermal energy. See Figure ES-8 for trends in energy sources used to generate electricity and impact on CO_2 emissions.

Including all electricity generation modes, electric power sector generators relied on coal for approximately 30 percent of their total energy requirements in 2016. In addition, the coal used by electricity generators accounted for 93 percent of all coal consumed for energy in the United States in 2016.[16] Recently, a decrease in the carbon intensity of the mix of fuels consumed to generate electricity has occurred due to a decrease in coal consumption, increased natural gas consumption, and increased reliance on non-fossil generation sources. Including all electricity generation modes, electric power sector generators used natural gas for approximately 34 percent of their total energy requirements in 2016.

Across the time series, changes in electricity demand and the carbon intensity of fuels used for electric power have a significant impact on CO_2 emissions. While emissions from the electric power sector have decreased by approximately 0.1 percent since 1990, the carbon intensity of the electric power sector, in terms of CO_2 Eq. per QBtu, input has significantly decreased—by 12 percent—during that same time-frame. This trend away from a direct relationship between electric power and the resulting emissions is shown in Figure ES-8.

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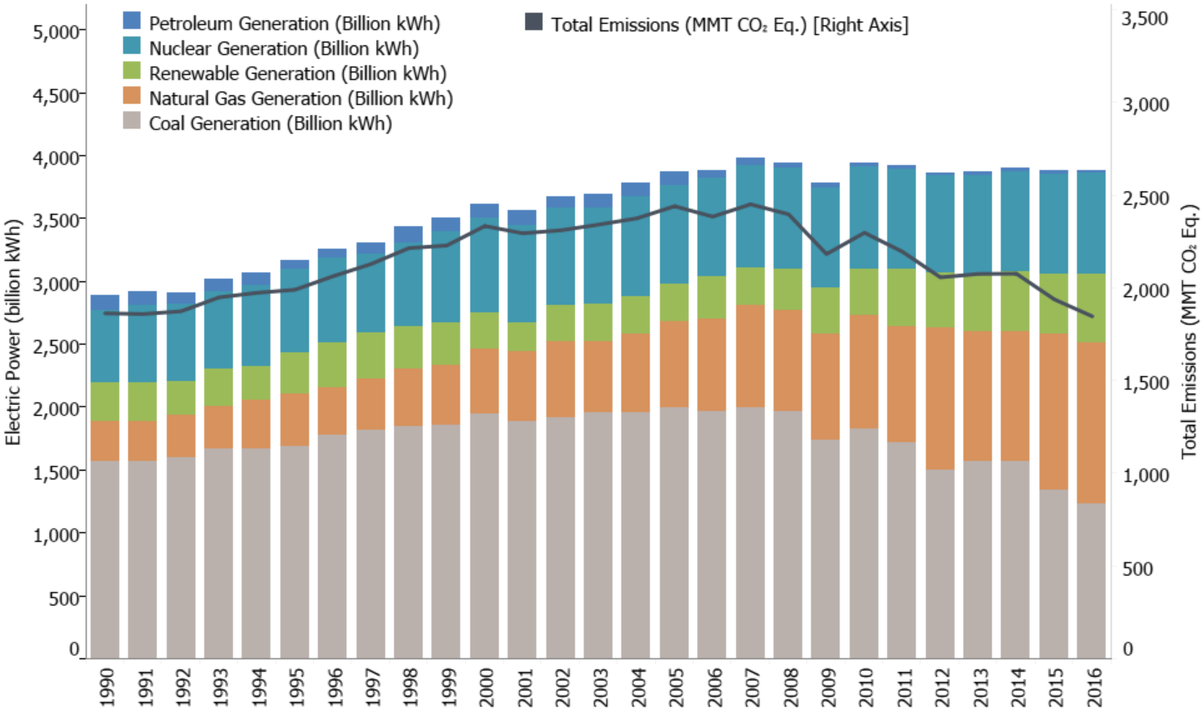
[14] VMT estimates are based on data from FHWA Highway Statistics Table VM-1 (FHWA 1996 through 2017). In 2011, FHWA changed its methods for estimating VMT by vehicle class, which led to a shift in VMT and emissions among on-road vehicle classes in the 2007 to 2016 time period. In absence of these method changes, light-duty VMT growth between 1990 and 2016 would likely have been even higher.

[15] In line with the reporting requirements for inventories submitted under the UNFCCC, CO_2 emissions from biomass combustion have been estimated separately from fossil fuel CO_2 emissions and are not included in the electricity sector totals and trends discussed in this section. Net carbon fluxes from changes in biogenic carbon reservoirs are accounted for in the estimates for Land Use, Land-Use Change, and Forestry.

[16] See Table 6.2 Coal Consumption by Sector of EIA 2018.

Figure ES-8: Electric Power Generation (Billion kWh) and Emissions (MMT CO_2 Eq.)



Other significant CO_2 trends included the following:

- Carbon dioxide emissions from non-energy use of fossil fuels decreased by 7.3 MMT CO_2 Eq. (6.1 percent) from 1990 through 2016. Emissions from non-energy uses of fossil fuels were 112.2 MMT CO_2 Eq. in 2016, which constituted 2.1 percent of total national CO_2 emissions, approximately the same proportion as in 1990.
- Carbon dioxide emissions from iron and steel production and metallurgical coke production have decreased by 59.3 MMT CO_2 Eq. (58.4 percent) from 1990 through 2016, due to restructuring of the industry, technological improvements, and increased scrap steel utilization.
- Total C stock change (i.e., net CO_2 removals) in the LULUCF sector decreased by approximately 9.1 percent between 1990 and 2016. This decrease was primarily due to a decrease in the rate of net C accumulation in forest C stocks and *Cropland Remaining Cropland*, as well as an increase in emissions from *Land Converted to Settlements*.

Box ES-4: Use of Ambient Measurements Systems for Validation of Emission Inventories

In following the UNFCCC requirement under Article 4.1 to develop and submit national greenhouse gas emission inventories, the emissions and sinks presented in this report are organized by source and sink categories and calculated using internationally-accepted methods provided by the IPCC.[17] Several recent studies have measured emissions at the national or regional level with results that sometimes differ from EPA's estimate of emissions. EPA has engaged with researchers on how remote sensing, ambient measurement, and inverse modeling techniques for greenhouse gas emissions could assist in improving the understanding of inventory estimates. In working with the research community on ambient measurement and remote sensing techniques to improve national greenhouse gas inventories, EPA follows guidance from the IPCC on the use of measurements and modeling to validate emission inventories.[18]An area of particular interest in EPA's outreach efforts is how ambient measurement data can be used

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[17] See <http://www.ipcc-nggip.iges.or.jp/public/index.html>.

[18] See <http://www.ipcc-nggip.iges.or.jp/meeting/pdfiles/1003_Uncertainty%20meeting_report.pdf>.

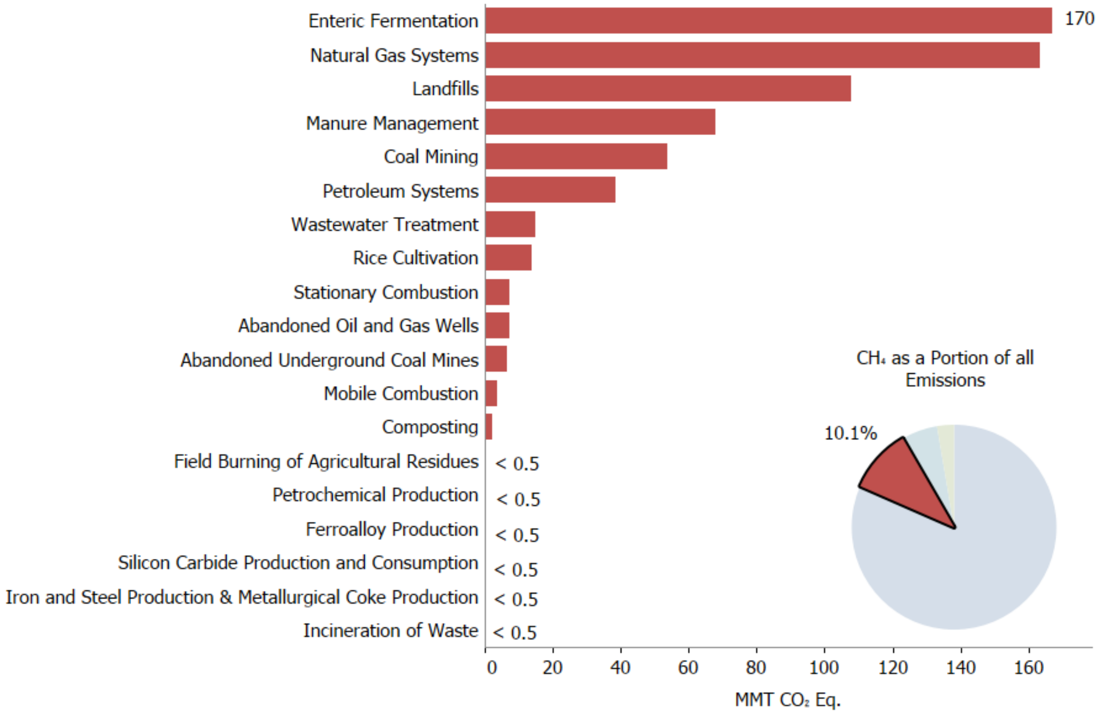
in a manner consistent with this Inventory report's transparency on its calculation methodologies, and the ability of these techniques to attribute emissions and removals from remote sensing to anthropogenic sources, as defined by the IPCC for this report, versus natural sources and sinks.

In an effort to improve the ability to compare the national-level greenhouse gas inventory with measurement results that may be at other scales, a team at Harvard University along with EPA and other coauthors developed a gridded inventory of U.S. anthropogenic methane emissions with 0.1° x 0.1° spatial resolution, monthly temporal resolution, and detailed scale-dependent error characterization. The Inventory is designed to be consistent with the 1990 to 2014 U.S. EPA *Inventory of U.S. Greenhouse Gas Emissions and Sinks* estimates for the year 2012, which presents national totals for different source types.[19]

Methane Emissions

Methane (CH_4) is 25 times as effective as CO_2 at trapping heat in the atmosphere (IPCC 2007). Over the last two hundred and fifty years, the concentration of CH_4 in the atmosphere increased by 163 percent (IPCC 2013; NOAA/ESRL 2017b). Anthropogenic sources of CH_4 include natural gas and petroleum systems, agricultural activities, LULUCF, landfills, coal mining, wastewater treatment, stationary and mobile combustion, and certain industrial processes (see Figure ES-9).

Figure ES-9: 2016 Sources of CH_4 Emissions (MMT CO_2 Eq.)



Note: LULUCF emissions are reported separately from gross emissions totals and are not included in Figure ES-9. Refer to Table ES-5 for a breakout of LULUCF emissions by gas.

Significant trends for the largest sources of U.S. CH_4 emissions include the following:

- Enteric fermentation is the largest anthropogenic source of CH_4 emissions in the United States. In 2016, enteric fermentation CH_4 emissions were 170.1 MMT CO_2 Eq. (25.9 percent of total CH_4 emissions),

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[19] See <https://www.epa.gov/ghgemissions/gridded-2012-methane-emissions>.

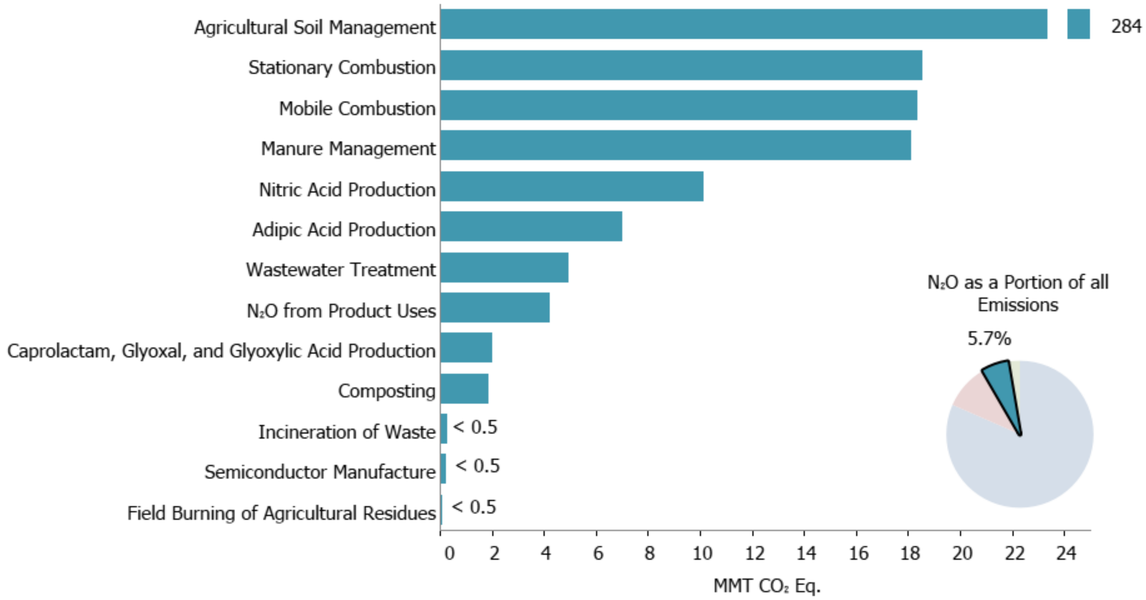
which represents an increase of 6.0 MMT CO_2 Eq. (3.6 percent) since 1990. This increase in emissions from 1990 to 2016 generally follows the increasing trends in cattle populations.

- Natural gas systems were the second largest anthropogenic source category of CH_4 emissions in the United States in 2016 with 163.5 MMT CO_2 Eq. of CH_4 emitted into the atmosphere. Those emissions have decreased by 31.6 MMT CO_2 Eq. (16.2 percent) since 1990. The decrease in CH_4 emissions is largely due to the decrease in emissions from transmission, storage, and distribution. The decrease in transmission and storage emissions is largely due to reduced compressor station emissions (including emissions from compressors and fugitives). The decrease in distribution emissions is largely attributed to increased use of plastic piping, which has lower emissions than other pipe materials, and station upgrades at metering and regulating (M&R) stations.
- Landfills are the third largest anthropogenic source of CH_4 emissions in the United States (107.7 MMT CO_2 Eq.), accounting for 16.4 percent of total CH_4 emissions in 2016. From 1990 to 2016, CH_4 emissions from landfills decreased by 71.9 MMT CO_2 Eq. (40.0 percent), with small increases occurring in some interim years. This downward trend in emissions coincided with increased landfill gas collection and control systems, and a reduction of decomposable materials (i.e., paper and paperboard, food scraps, and yard trimmings) discarded in MSW landfills over the time series,[20] which has more than offset the additional CH_4 emissions that would have resulted from an increase in the amount of municipal solid waste landfilled.

Nitrous Oxide Emissions

Nitrous oxide (N_2O) is produced by biological processes that occur in soil and water and by a variety of anthropogenic activities in the agricultural, energy, industrial, and waste management fields. While total N_2O emissions are much lower than CO_2 emissions, N_2O is nearly 300 times more powerful than CO_2 at trapping heat in the atmosphere (IPCC 2007). Since 1750, the global atmospheric concentration of N_2O has risen by approximately 22 percent (IPCC 2013; NOAA/ESRL 2017c). The main anthropogenic activities producing N_2O in the United States are agricultural soil management, stationary fuel combustion, fuel combustion in motor vehicles, manure management, and nitric acid production (see Figure ES-10).

Figure ES-10: 2016 Sources of N_2O Emissions (MMT CO_2 Eq.)



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[20] Carbon dioxide emissions from landfills are not included specifically in summing waste sector totals. Net carbon fluxes from changes in biogenic carbon reservoirs and decay of disposed wood products are accounted for in the estimates for LULUCF.

Note: LULUCF emissions are reported separately from gross emissions totals and are not included in Figure ES-10. Refer to Table ES-5 for a breakout of LULUCF emissions by gas.

Significant trends for the largest sources of U.S. emissions of N_2O include the following:

- Agricultural soils accounted for approximately 76.7 percent of N_2O emissions and 4.4 percent of total emissions in the United States in 2016. Estimated emissions from this source in 2016 were 283.6 MMT CO_2 Eq. Annual N_2O emissions from agricultural soils fluctuated between 1990 and 2016, although overall emissions were 13.2 percent higher in 2016 than in 1990. Year-to-year fluctuations are largely a reflection of annual variation in weather patterns, synthetic fertilizer use, and crop production.
- Nitrous oxide emissions from stationary combustion increased 7.5 MMT CO_2 Eq. (67.5 percent) from 1990 through 2016. Nitrous oxide emissions from this source increased primarily as a result of an increase in the number of coal fluidized bed boilers in the electric power sector.
- Nitrous oxide emissions from mobile combustion decreased by 23.3 MMT CO_2 Eq. (55.9 percent) from 1990 through 2016, primarily as a result of N_2O national emission control standards and emission control technologies for on-road vehicles.

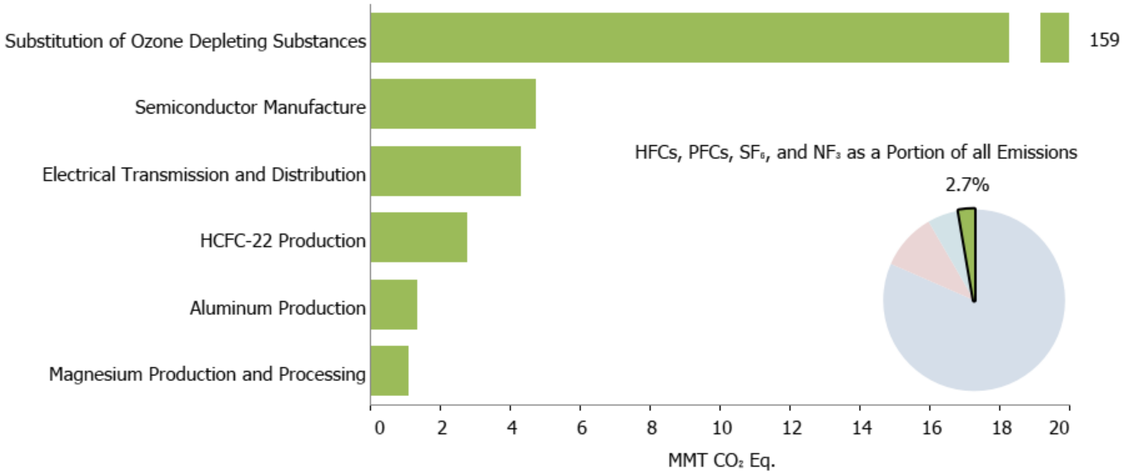
HFC, PFC, SF_6, and NF_3 Emissions

Hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs) are families of synthetic chemicals that are used as alternatives to ozone depleting substances (ODS), which are being phased out under the Montreal Protocol and Clean Air Act Amendments of 1990. Hydrofluorocarbons and PFCs do not deplete the stratospheric ozone layer, and are therefore acceptable alternatives under the Montreal Protocol on Substances that Deplete the Ozone Layer.

These compounds, however, along with SF_6 and NF_3, are potent greenhouse gases. In addition to having high global warming potentials, SF_6 and PFCs have extremely long atmospheric lifetimes, resulting in their essentially irreversible accumulation in the atmosphere once emitted. Sulfur hexafluoride is the most potent greenhouse gas the IPCC has evaluated (IPCC 2013).

Other emissive sources of these gases include HCFC-22 production, electrical transmission and distribution systems, semiconductor manufacturing, aluminum production, and magnesium production and processing (see Figure ES-11).

Figure ES-11: 2016 Sources of HFCs, PFCs, SF_6, and NF_3 Emissions (MMT CO_2 Eq.)



Some significant trends for the largest sources of U.S. HFC, PFC, SF_6, and NF_3 emissions include the following:

- Hydrofluorocarbon and perfluorocarbon emissions resulting from the substitution of ODS (e.g., chlorofluorocarbons [CFCs]) have been consistently increasing, from small amounts in 1990 to 159.1 MMT CO_2 Eq. in 2016. This increase was in large part the result of efforts to phase out CFCs and other

ODS in the United States. In the short term, this trend is expected to continue, and will likely continue over the next decade as hydrochlorofluorocarbons (HCFCs), which are interim substitutes in many applications, are themselves phased out under the provisions of the Copenhagen Amendments to the Montreal Protocol.

- GWP-weighted PFC, HFC, SF_6, and NF_3 emissions from semiconductor manufacturing have increased by 32.8 percent from 1990 to 2016, due to competing factors of industrial growth and the adoption of emission reduction technologies. Within that time span, emissions peaked at 9.0 MMT CO_2 Eq. in 1999, the initial year of EPA's PFC Reduction/Climate Partnership for the Semiconductor Industry, but have since declined to 4.7 MMT CO_2 Eq. in 2016 (a 47.6 percent decrease relative to 1999).
- Sulfur hexafluoride emissions from electric power transmission and distribution systems decreased by 81.2 percent (18.8 MMT CO_2 Eq.) from 1990 to 2016. There are two potential causes for this decrease: (1) a sharp increase in the price of SF_6 during the 1990s and (2) a growing awareness of the environmental impact of SF_6 emissions through programs such as EPA's SF_6 Emission Reduction Partnership for Electric Power Systems.

ES.3 Overview of Sector Emissions and Trends

In accordance with the UNFCCC decision to set the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006) as the standard for Annex I countries at the Nineteenth Conference of the Parties (UNFCCC 2014), Figure ES-12 and Table ES-4 aggregate emissions and sinks by the sectors defined by those guidelines. Over the twenty-seven-year period of 1990 to 2016, total emissions from the Energy, Industrial Processes and Product Use, and Agriculture sectors grew by 130.1 MMT CO_2 Eq. (2.4 percent), 20.0 MMT CO_2 Eq. (5.9 percent), and 73.4 MMT CO_2 Eq. (15.0 percent), respectively. Emissions from the Waste sector decreased by 67.9 MMT CO_2 Eq. (34.1 percent). Over the same period, total C sequestration in the LULUCF sector decreased by 75.4 MMT CO_2 (9.1 percent decrease in total C sequestration), and emissions from the LULUCF sector increased by 27.4 MMT CO_2 Eq. (258 percent).

Figure ES-12: U.S. Greenhouse Gas Emissions and Sinks by Chapter/IPCC Sector (MMT CO_2 Eq.)

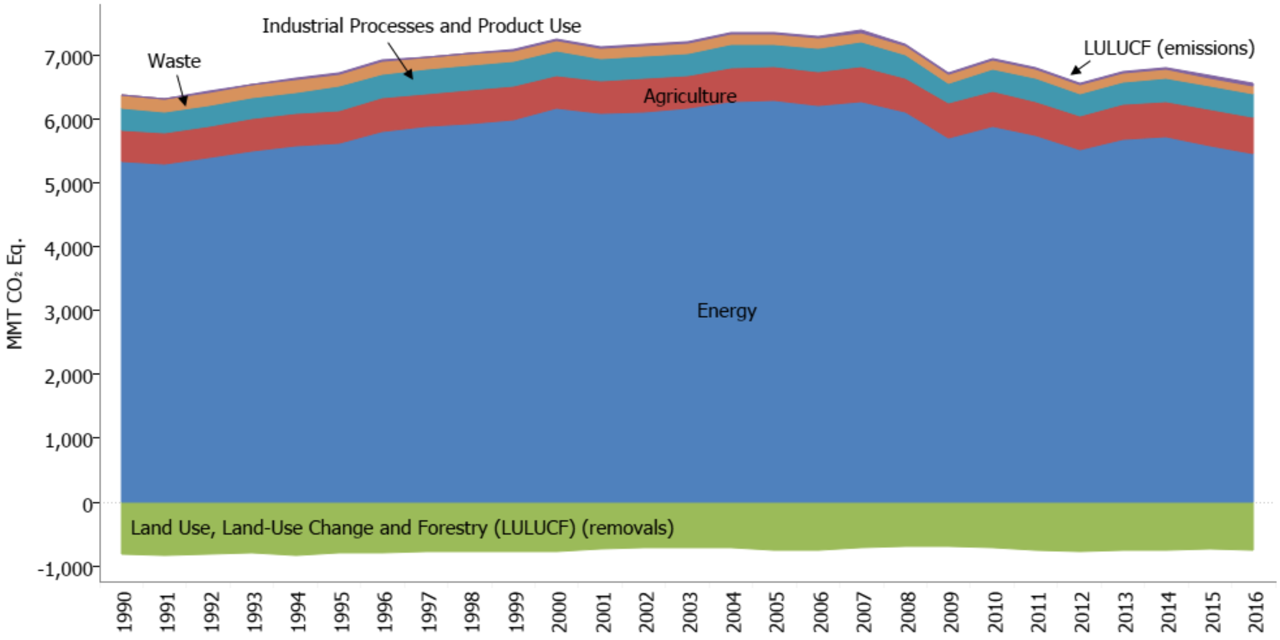


Table ES-4: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks by Chapter/IPCC Sector (MMT CO_2 Eq.)

Chapter/IPCC Sector	1990	2005	2012	2013	2014	2015	2016
Energy	**5,325.1**	**6,285.2**	**5,511.2**	**5,671.4**	**5,715.4**	**5,567.8**	**5,455.2**
Fossil Fuel Combustion	4,740.3	5,746.9	5,024.4	5,156.9	5,200.3	5,049.3	4,966.0
Natural Gas Systems	225.0	191.6	182.9	188.6	189.6	191.2	189.0
Non-Energy Use of Fuels	119.5	138.9	108.0	123.5	118.9	125.6	112.2
Petroleum Systems	47.5	43.8	52.0	59.2	64.9	66.8	61.4
Coal Mining	96.5	64.1	66.5	64.6	64.6	61.2	53.8
Stationary Combustion	19.7	25.3	24.3	27.5	28.0	26.1	25.9
Mobile Combustion	54.4	48.2	29.4	27.2	24.9	23.1	22.0
Incineration of Waste	8.4	12.9	10.7	10.7	10.9	11.0	11.0
Abandoned Oil and Gas Wells	6.5	6.9	7.0	7.0	7.1	7.2	7.1
Abandoned Underground Coal Mines	7.2	6.6	6.2	6.2	6.3	6.4	6.7
Industrial Processes and Product Use	**342.0**	**358.6**	**357.4**	**357.9**	**371.4**	**367.8**	**362.1**
Substitution of Ozone Depleting Substances	0.3	102.7	144.9	146.8	151.3	156.1	159.1
Iron and Steel Production & Metallurgical Coke Production	101.7	68.2	55.6	53.5	58.4	47.8	42.3
Cement Production	33.5	46.2	35.3	36.4	39.4	39.9	39.4
Petrochemical Production	21.4	26.9	26.6	26.5	26.6	28.2	28.4
Lime Production	11.7	14.6	13.8	14.0	14.2	13.3	12.9
Ammonia Production	13.0	9.2	9.4	10.0	9.6	10.9	12.2
Other Process Uses of Carbonates	6.3	7.6	9.1	11.5	13.0	12.3	11.0
Nitric Acid Production	12.1	11.3	10.5	10.7	10.9	11.6	10.2
Adipic Acid Production	15.2	7.1	5.5	3.9	5.4	4.3	7.0
Semiconductor Manufacture	3.6	4.7	4.4	4.0	4.9	5.0	5.0
Carbon Dioxide Consumption	1.5	1.4	4.0	4.2	4.5	4.5	4.5
Electrical Transmission and Distribution	23.1	8.3	4.7	4.5	4.7	4.3	4.3
N_2O from Product Uses	4.2	4.2	4.2	4.2	4.2	4.2	4.2
Urea Consumption for Non-Agricultural Purposes	3.8	3.7	4.4	4.1	1.5	4.2	4.0
HCFC-22 Production	46.1	20.0	5.5	4.1	5.0	4.3	2.8
Aluminum Production	28.3	7.6	6.4	6.2	5.4	4.8	2.7
Caprolactam, Glyoxal, and Glyoxylic Acid Production	1.7	2.1	2.0	2.0	2.0	2.0	2.0
Ferroalloy Production	2.2	1.4	1.9	1.8	1.9	2.0	1.8
Soda Ash Production	1.4	1.7	1.7	1.7	1.7	1.7	1.7
Titanium Dioxide Production	1.2	1.8	1.5	1.7	1.7	1.6	1.6
Glass Production	1.5	1.9	1.2	1.3	1.3	1.3	1.2
Magnesium Production and Processing	5.2	2.7	1.7	1.5	1.1	1.0	1.1
Phosphoric Acid Production	1.5	1.3	1.1	1.1	1.0	1.0	1.0
Zinc Production	0.6	1.0	1.5	1.4	1.0	0.9	0.9
Lead Production	0.5	0.6	0.5	0.5	0.5	0.5	0.5
Silicon Carbide Production and Consumption	0.4	0.2	0.2	0.2	0.2	0.2	0.2
Agriculture	**489.2**	**520.0**	**519.8**	**543.1**	**539.8**	**566.9**	**562.6**
Agricultural Soil Management	250.5	253.5	247.9	276.6	274.0	295.0	283.6
Enteric Fermentation	164.2	168.9	166.7	165.5	164.2	166.5	170.1
Manure Management	51.1	72.9	83.2	80.8	80.4	84.0	85.9
Rice Cultivation	16.0	16.7	11.3	11.5	12.7	12.3	13.7
Urea Fertilization	2.4	3.5	4.3	4.4	4.5	4.9	5.1
Liming	4.7	4.3	6.0	3.9	3.6	3.8	3.9
Field Burning of Agricultural Residues	0.3	0.3	0.4	0.4	0.4	0.4	0.4
Waste	**199.3**	**156.4**	**140.4**	**136.7**	**136.5**	**135.6**	**131.5**
Landfills	179.6	132.7	117.0	113.3	112.7	111.7	107.7
Wastewater Treatment	19.1	20.2	19.7	19.6	19.8	20.0	19.8
Composting	0.7	3.5	3.7	3.9	4.0	4.0	4.0
Total Emissions[a]	**6,355.6**	**7,320.3**	**6,528.8**	**6,709.1**	**6,763.1**	**6,638.1**	**6,511.3**

Land Use, Land-Use Change, and Forestry	**(819.6)**	**(731.1)**	**(753.5)**	**(735.8)**	**(740.4)**	**(695.2)**	**(716.8)**
Forest land	(784.3)	(730.0)	(723.3)	(733.3)	(731.7)	(709.9)	(714.2)
Cropland	2.4	(0.7)	1.3	11.9	11.2	16.8	13.8
Grassland	13.8	25.3	0.8	18.5	14.7	33.6	21.0
Wetlands	(4.0)	(5.3)	(4.1)	(4.1)	(4.1)	(4.1)	(4.2)
Settlements	(47.6)	(20.5)	(28.3)	(28.8)	(30.5)	(31.5)	(33.2)
Net Emission (Sources and Sinks)[b]	**5,536.0**	**6,589.1**	**5,775.3**	**5,973.3**	**6,022.8**	**5,942.9**	**5,794.5**

Notes: Total emissions presented without LULUCF. Net emissions presented with LULUCF.

[a] Total emissions without LULUCF.

[b] Total emissions with LULUCF.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or sequestration.

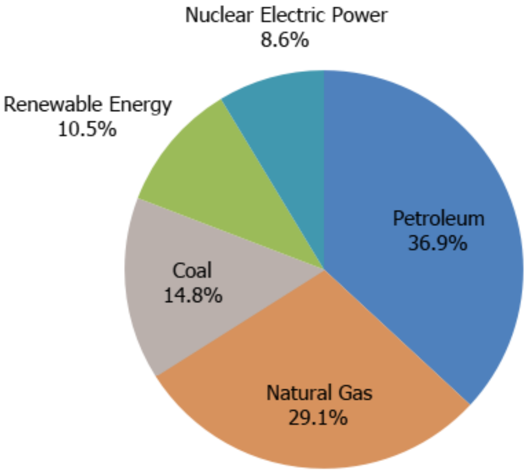
Energy

The Energy chapter contains emissions of all greenhouse gases resulting from stationary and mobile energy activities including fuel combustion and fugitive fuel emissions, and the use of fossil fuels for non-energy purposes. Energy-related activities, primarily fossil fuel combustion, accounted for the vast majority of U.S. CO_2 emissions for the period of 1990 through 2016.

In 2016, approximately 81 percent of the energy used in the United States (on a Btu basis) was produced through the combustion of fossil fuels. The remaining 19 percent came from other energy sources such as hydropower, biomass, nuclear, wind, and solar energy (see Figure ES-13).

Energy-related activities are also responsible for CH_4 and N_2O emissions (43 percent and 10 percent of total U.S. emissions of each gas, respectively). Overall, emission sources in the Energy chapter account for a combined 83.8 percent of total U.S. greenhouse gas emissions in 2016.

Figure ES-13: 2016 U.S. Energy Consumption by Energy Source (Percent)



Industrial Processes and Product Use

The Industrial Processes and Product Use (IPPU) chapter includes greenhouse gas emissions occurring from industrial processes and from the use of greenhouse gases in products.

In many cases, greenhouse gas emissions are produced as the byproducts of many non-energy-related industrial activities. For example, industrial processes can chemically transform raw materials, which often release waste gases such as CO_2, CH_4, N_2O, and fluorinated gases (e.g., HFC-23). These processes include iron and steel production and metallurgical coke production, cement production, lime production, other process uses of carbonates (e.g., flux stone, flue gas desulfurization, and glass manufacturing), ammonia production and urea consumption, petrochemical production, aluminum production, HCFC-22 production, soda ash production and use, titanium dioxide production, ferroalloy production, glass production, zinc production, phosphoric acid production, lead production, silicon carbide production and consumption, nitric acid production, adipic acid production, and caprolactam production.

Industrial manufacturing processes and use by end-consumers also release HFCs, PFCs, SF_6, and NF_3 and other fluorinated compounds. In addition to the use of HFCs and some PFCs as ODS substitutes, HFCs, PFCs, SF_6, NF_3, and other fluorinated compounds are employed and emitted by a number of other industrial sources in the United States. These industries include semiconductor manufacture, electric power transmission and distribution, and magnesium metal production and processing. In addition, N_2O is used in and emitted by semiconductor manufacturing and anesthetic and aerosol applications, and CO_2 is consumed and emitted through various end-use applications. Overall, emission sources in the Industrial Process and Product Use chapter account for 5.6 percent of U.S. greenhouse gas emissions in 2016.

Agriculture

The Agriculture chapter contains information on anthropogenic emissions from agricultural activities (except fuel combustion, which is addressed in the Energy chapter, and some agricultural CO_2, CH_4 and N_2O fluxes, which are addressed in the Land Use, Land-Use Change, and Forestry chapter). Agricultural activities contribute directly to emissions of greenhouse gases through a variety of processes, including the following source categories: enteric fermentation in domestic livestock, livestock manure management, rice cultivation, agricultural soil management, liming, urea fertilization, and field burning of agricultural residues.

In 2016, agricultural activities were responsible for emissions of 562.6 MMT CO_2 Eq., or 8.6 percent of total U.S. greenhouse gas emissions. Methane, N_2O, and CO_2 were the primary greenhouse gases emitted by agricultural activities. Methane emissions from enteric fermentation and manure management represented approximately 25.9 percent and 10.3 percent of total CH_4 emissions from anthropogenic activities, respectively, in 2016. Agricultural soil management activities, such as application of synthetic and organic fertilizers, deposition of livestock manure, and growing N-fixing plants, were the largest source of U.S. N_2O emissions in 2016, accounting for 76.7 percent. Carbon dioxide emissions from the application of crushed limestone and dolomite (i.e., soil liming) and urea fertilization represented 0.2 percent of total CO_2 emissions from anthropogenic activities. Figure 2-11 and Table 2-7 illustrate agricultural greenhouse gas emissions by source.

Land Use, Land-Use Change, and Forestry

The LULUCF chapter contains emissions of CH_4 and N_2O, and emissions and removals of CO_2 from managed lands in the United States. Consistent with the *2006 IPCC Guidelines*, emissions and removals from managed lands are considered to be anthropogenic, while emissions and removals for unmanaged lands are considered to be natural.[21] More information on the definition of managed land used in the Inventory is provided in Chapter 6.

Overall, managed land is a net sink for CO_2 (C sequestration) in the United States. The primary drivers of fluxes on managed lands include, for example, forest management practices, tree planting in urban areas, the management of agricultural soils, landfilling of yard trimmings and food scraps, and activities that cause changes in C stocks in coastal wetlands. The main drivers for forest C sequestration include forest growth and increasing forest area, as well as a net accumulation of C stocks in harvested wood pools. The net sequestration in *Settlements Remaining Settlements*, which occurs predominantly from urban forests and landfilled yard trimmings and food scraps, is a result of net tree growth and increased urban forest size, as well as long-term accumulation of yard trimmings and food scraps carbon in landfills.

The LULUCF sector in 2016 resulted in a net increase in C stocks (i.e., net CO_2 removals) of 754.9 MMT CO_2 Eq. (Table ES-5).[22] This represents an offset of 11.6 percent of total (i.e., gross) greenhouse gas emissions in 2016.

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[21] See <http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_01_Ch1_Introduction.pdf>.

[22] LULUCF Carbon Stock Change is the net C stock change from the following categories: *Forest Land Remaining Forest Land, Land Converted to Forest Land, Cropland Remaining Cropland, Land Converted to Cropland, Grassland Remaining*

Emissions of CH_4 and N_2O from LULUCF activities in 2016 were 38.1 MMT CO_2 Eq. and represent 0.6 percent of total greenhouse gas emissions.[23] Between 1990 and 2016, total C sequestration in the LULUCF sector decreased by 9.1 percent, primarily due to a decrease in the rate of net C accumulation in forests and *Cropland Remaining Cropland*, as well as an increase in CO_2 emissions from *Land Converted to Settlements*.

Forest fires were the largest source of CH_4 emissions from LULUCF in 2016, totaling 18.5 MMT CO_2 Eq. (740 kt of CH_4). *Coastal Wetlands Remaining Coastal Wetlands* resulted in CH_4 emissions of 3.6 MMT CO_2 Eq. (143 kt of CH_4). Grassland fires resulted in CH_4 emissions of 0.3 MMT CO_2 Eq. (11 kt of CH_4). *Peatlands Remaining Peatlands*, *Land Converted to Wetlands*, and *Drained Organic Soils* resulted in CH_4 emissions of less than 0.05 MMT CO_2 Eq. each.

Forest fires were also the largest source of N_2O emissions from LULUCF in 2016, totaling 12.2 MMT CO_2 Eq. (41 kt of N_2O). Nitrous oxide emissions from fertilizer application to settlement soils in 2016 totaled to 2.5 MMT CO_2 Eq. (8 kt of N_2O). Additionally, the application of synthetic fertilizers to forest soils in 2016 resulted in N_2O emissions of 0.5 MMT CO_2 Eq. (2 kt of N_2O). Grassland fires resulted in N_2O emissions of 0.3 MMT CO_2 Eq. (1 kt of N_2O). *Coastal Wetlands Remaining Coastal Wetlands* and *Drained Organic Soils* resulted in N_2O emissions of 0.1 MMT CO_2 Eq. each (less than 0.5 kt of N_2O). *Peatlands Remaining Peatlands* resulted in N_2O emissions of less than 0.05 MMT CO_2 Eq.

Carbon dioxide removals from C stock changes are presented in Table ES-5 along with CH_4 and N_2O emissions for LULUCF source categories.

Table ES-5: U.S. Greenhouse Gas Emissions and Removals (Net Flux) from Land Use, Land-Use Change, and Forestry (MMT CO_2 Eq.)

Gas/Land-Use Category	1990	2005	2012	2013	2014	2015	2016
Carbon Stock Change[a]	**(830.2)**	**(754.2)**	**(779.5)**	**(755.0)**	**(760.0)**	**(733.4)**	**(754.9)**
Forest Land Remaining Forest Land	(697.7)	(664.6)	(666.9)	(670.9)	(669.3)	(666.2)	(670.5)
Land Converted to Forest Land	(92.0)	(81.6)	(74.9)	(74.9)	(75.0)	(75.0)	(75.0)
Cropland Remaining Cropland	(40.9)	(26.5)	(21.4)	(11.4)	(12.0)	(6.3)	(9.9)
Land Converted to Cropland	43.3	25.9	22.7	23.3	23.2	23.2	23.8
Grassland Remaining Grassland	(4.2)	5.5	(20.8)	(3.7)	(7.5)	9.6	(1.6)
Land Converted to Grassland	17.9	19.2	20.4	21.9	21.5	23.3	22.0
Wetlands Remaining Wetlands	(7.6)	(8.9)	(7.7)	(7.8)	(7.8)	(7.8)	(7.9)
Land Converted to Wetlands	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Settlements Remaining Settlements	(86.2)	(91.4)	(99.2)	(99.8)	(101.2)	(102.2)	(103.7)
Land Converted to Settlements	37.2	68.4	68.3	68.3	68.2	68.1	68.0
CH_4	**6.7**	**13.3**	**15.0**	**10.9**	**11.2**	**22.4**	**22.4**
Forest Land Remaining Forest Land: Forest Fires	3.2	9.4	10.8	7.2	7.2	18.5	18.5
Wetlands Remaining Wetlands: Coastal Wetlands Remaining Coastal Wetlands	3.4	3.5	3.5	3.6	3.6	3.6	3.6
Grassland Remaining Grassland: Grassland Fires	0.1	0.3	0.6	0.2	0.4	0.3	0.3
Forest Land Remaining Forest Land: Drained Organic Soils	+	+	+	+	+	+	+
Land Converted to Wetlands: Land Converted to Coastal Wetlands	+	+	+	+	+	+	+
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	+	+	+	+	+	+	+
N_2O	**3.9**	**9.7**	**11.1**	**8.3**	**8.4**	**15.8**	**15.7**
Forest Land Remaining Forest Land: Forest Fires	2.1	6.2	7.1	4.8	4.7	12.2	12.2
Settlements Remaining Settlements:	1.4	2.5	2.7	2.6	2.6	2.5	2.5

Grassland, Land Converted to Grassland, Wetlands Remaining Wetlands, Land Converted to Wetlands, Settlements Remaining Settlements, and *Land Converted to Settlements.*

[23] LULUCF emissions include the CH_4 and N_2O emissions reported for *Peatlands Remaining Peatlands*, Forest Fires, Drained Organic Soils, Grassland Fires, and *Coastal Wetlands Remaining Coastal Wetlands*; CH_4 emissions from *Land Converted to Coastal Wetlands*; and N_2O emissions from Forest Soils and Settlement Soils.

Settlement Soils[b]							
Forest Land Remaining Forest Land: Forest Soils[c]	0.1	0.5	0.5	0.5	0.5	0.5	0.5
Grassland Remaining Grassland: Grassland Fires	0.1	0.3	0.6	0.2	0.4	0.3	0.3
Wetlands Remaining Wetlands: Coastal Wetlands Remaining Coastal Wetlands	0.1	0.2	0.1	0.1	0.1	0.1	0.1
Forest Land Remaining Forest Land: Drained Organic Soils	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	+	+	+	+	+	+	+
LULUCF Emissions[d]	**10.6**	**23.0**	**26.1**	**19.2**	**19.6**	**38.2**	**38.1**
LULUCF Carbon Stock Change[a]	**(830.2)**	**(754.2)**	**(779.5)**	**(755.0)**	**(760.0)**	**(733.4)**	**(754.9)**
LULUCF Sector Net Total[e]	**(819.6)**	**(731.1)**	**(753.5)**	**(735.8)**	**(740.4)**	**(695.2)**	**(716.8)**

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

[a] LULUCF Carbon Stock Change is the net C stock change from the following categories: *Forest Land Remaining Forest Land, Land Converted to Forest Land, Cropland Remaining Cropland, Land Converted to Cropland, Grassland Remaining Grassland, Land Converted to Grassland, Wetlands Remaining Wetlands, Land Converted to Wetlands, Settlements Remaining Settlements,* and *Land Converted to Settlements.*

[b] Estimates include emissions from N fertilizer additions on both *Settlements Remaining Settlements* and *Land Converted to Settlements.*

[c] Estimates include emissions from N fertilizer additions on both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.

[d] LULUCF emissions include the CH_4 and N_2O emissions reported for *Peatlands Remaining Peatlands*, Forest Fires, Drained Organic Soils, Grassland Fires, and *Coastal Wetlands Remaining Coastal Wetlands*; CH_4 emissions from *Land Converted to Coastal Wetlands*; and N_2O emissions from Forest Soils and Settlement Soils.

[e] The LULUCF Sector Net Total is the net sum of all CH_4 and N_2O emissions to the atmosphere plus net carbon stock changes.

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Waste

The Waste chapter contains emissions from waste management activities (except incineration of waste, which is addressed in the Energy chapter). Landfills were the largest source of anthropogenic greenhouse gas emissions in the Waste chapter, accounting for 81.9 percent of this chapter's emissions, and 16.4 percent of total U.S. CH_4 emissions.[24] Additionally, wastewater treatment accounts for 15.1 percent of Waste emissions, 2.3 percent of U.S. CH_4 emissions, and 1.3 percent of U.S. N_2O emissions. Emissions of CH_4 and N_2O from composting are also accounted for in this chapter, generating emissions of 2.1 MMT CO_2 Eq. and 1.9 MMT CO_2 Eq., respectively. Overall, emission sources accounted for in the Waste chapter generated 2.0 percent of total U.S. greenhouse gas emissions in 2016.

ES.4 Other Information

Emissions by Economic Sector

Throughout the Inventory of U.S. Greenhouse Gas Emissions and Sinks report, emission estimates are grouped into five sectors (i.e., chapters) defined by the IPCC: Energy; IPPU; Agriculture; LULUCF; and Waste. While it is important to use this characterization for consistency with UNFCCC reporting guidelines and to promote comparability across countries, it is also useful to characterize emissions according to commonly used economic sector categories: residential, commercial, industry, transportation, electric power, agriculture, and U.S. Territories.

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[24] Landfills also store carbon, due to incomplete degradation of organic materials such as harvest wood products, yard trimmings, and food scraps, as described in the Land-Use, Land-Use Change, and Forestry chapter of the Inventory report.

Figure ES-14 shows the trend in emissions by economic sector from 1990 to 2016, and Table ES-6 summarizes emissions from each of these economic sectors.

Figure ES-14: U.S. Greenhouse Gas Emissions Allocated to Economic Sectors (MMT CO_2 Eq.)

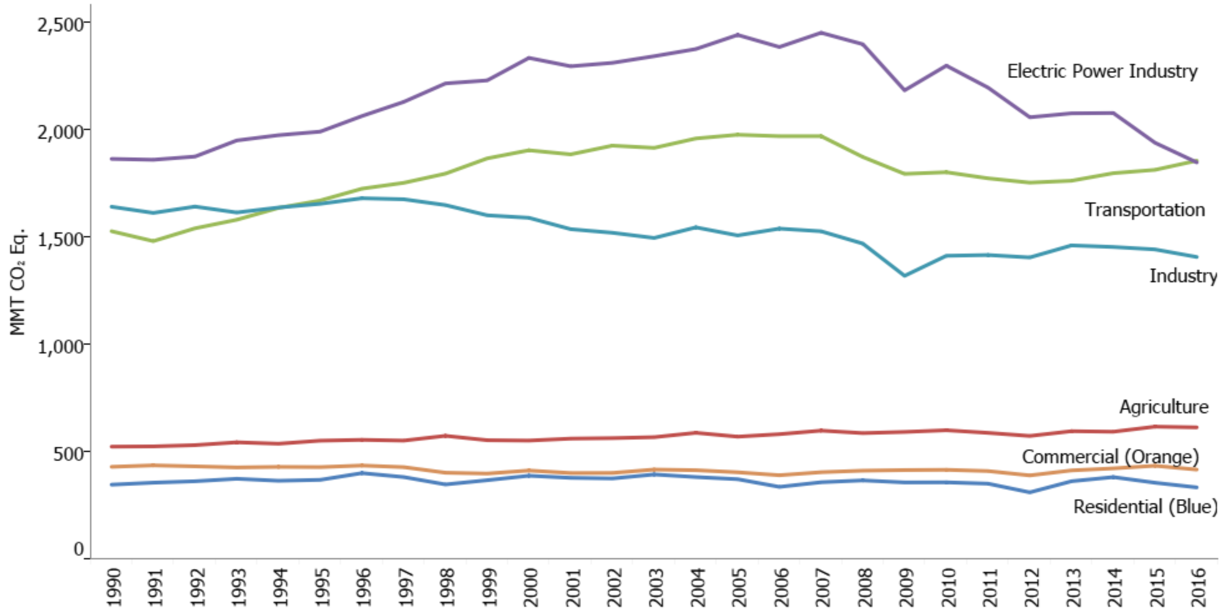

Table ES-6: U.S. Greenhouse Gas Emissions Allocated to Economic Sectors (MMT CO_2 Eq.)

Economic Sectors	**1990**	**2005**	**2012**	**2013**	**2014**	**2015**	**2016**
Transportation	1,525.5	1,974.9	1,751.9	1,760.6	1,795.9	1,811.4	1,854.0
Electric Power Industry	1,862.4	2,439.9	2,056.3	2,074.7	2,076.1	1,937.5	1,846.1
Industry	1,639.5	1,505.8	1,403.4	1,459.5	1,452.1	1,440.7	1,405.5
Agriculture	522.0	568.5	571.8	594.1	591.5	615.1	611.8
Commercial	428.0	402.6	388.0	411.3	420.8	432.9	415.2
Residential	344.9	370.4	309.0	360.9	380.1	353.9	332.1
U.S. Territories	33.3	58.1	48.5	48.1	46.6	46.6	46.6
Total Emissions	**6,355.6**	**7,320.3**	**6,528.8**	**6,709.1**	**6,763.1**	**6,638.1**	**6,511.3**
LULUCF Sector Net Total[a]	**(819.6)**	**(731.1)**	**(753.5)**	**(735.8)**	**(740.4)**	**(695.2)**	**(716.8)**
Net Emissions (Sources and Sinks)	**5,536.0**	**6,589.1**	**5,775.3**	**5,973.3**	**6,022.8**	**5,942.9**	**5,794.5**

Notes: Total emissions presented without LULUCF. Total net emissions presented with LULUCF.

[a] The LULUCF Sector Net Total is the net sum of all CH_4 and N_2O emissions to the atmosphere plus net carbon stock changes.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or sequestration.

Using this categorization, emissions from transportation activities, in aggregate, accounted for the largest portion (28.5 percent) of total U.S. greenhouse gas emissions in 2016. Electric power accounted for the second largest portion (28.4 percent), while emissions from industry accounted for the third largest portion (21.6 percent) of total U.S. greenhouse gas emissions in 2016. Emissions from industry have in general declined over the past decade, due to a number of factors, including structural changes in the U.S. economy (i.e., shifts from a manufacturing-based to a service-based economy), fuel switching, and energy efficiency improvements.

The remaining 21.6 percent of U.S. greenhouse gas emissions were contributed by, in order of magnitude, the agriculture, commercial, and residential sectors, plus emissions from U.S. Territories.[25] Activities related to agriculture accounted for 9.4 percent of U.S. emissions; unlike other economic sectors, agricultural sector emissions were dominated by N_2O emissions from agricultural soil management and CH_4 emissions from enteric fermentation. The commercial and residential sectors accounted for 6.4 percent and 5.1 percent of emissions, respectively, and U.S. Territories accounted for 0.7 percent of emissions; emissions from these sectors primarily consisted of CO_2 emissions from fossil fuel combustion. CO_2 was also emitted and sequestered by a variety of activities related to forest management practices, tree planting in urban areas, the management of agricultural soils, landfilling of yard trimmings, and changes in C stocks in coastal wetlands.

Electricity is ultimately used in the economic sectors described above. Table ES-7 presents greenhouse gas emissions from economic sectors with emissions related to electric power distributed into end-use categories (i.e., emissions from electric power are allocated to the economic sectors in which the electricity is used). To distribute electricity emissions among end-use sectors, emissions from the source categories assigned to electric power were allocated to the residential, commercial, industry, transportation, and agriculture economic sectors according to retail sales of electricity (EIA 2018 and Duffield 2006). These source categories include CO_2 from fossil fuel combustion and the use of limestone and dolomite for flue gas desulfurization, CO_2 and N_2O from incineration of waste, CH_4 and N_2O from stationary sources, and SF_6 from electrical transmission and distribution systems.

When emissions from electricity use are distributed among these sectors, industrial activities and transportation account for the largest shares of U.S. greenhouse gas emissions (29.1 percent and 28.5 percent, respectively) in 2016. The residential and commercial sectors contributed the next largest shares of total U.S. greenhouse gas emissions in 2016. Emissions from these sectors increase substantially when emissions from electricity are included, due to their relatively large share of electricity use (e.g., lighting, appliances). In all sectors except agriculture, CO_2 accounts for at least 81 percent of greenhouse gas emissions, primarily from the combustion of fossil fuels.

Figure ES-15 shows the trend in these emissions by sector from 1990 to 2016.

Table ES-7: U.S. Greenhouse Gas Emissions by Economic Sector with Electricity-Related Emissions Distributed (MMT CO_2 Eq.)

Implied Sectors	1990	2005	2012	2013	2014	2015	2016
Industry	2,307.1	2,216.3	1,963.1	2,022.8	2,012.4	1,959.9	1,894.8
Transportation	1,528.6	1,979.7	1,755.8	1,764.7	1,800.0	1,815.1	1,857.6
Commercial	978.3	1,218.9	1,100.1	1,128.4	1,140.0	1,108.9	1,061.9
Residential	951.5	1,240.7	1,046.5	1,109.0	1,128.6	1,051.4	999.6
Agriculture	556.9	606.6	614.8	636.1	635.5	656.1	650.7
U.S. Territories	33.3	58.1	48.5	48.1	46.6	46.6	46.6
Total Emissions	**6,355.6**	**7,320.3**	**6,528.8**	**6,709.1**	**6,763.1**	**6,638.1**	**6,511.3**
LULUCF Sector Net Total[a]	**(819.6)**	**(731.1)**	**(753.5)**	**(735.8)**	**(740.4)**	**(695.2)**	**(716.8)**
Net Emissions (Sources and Sinks)	**5,536.0**	**6,589.1**	**5,775.3**	**5,973.3**	**6,022.8**	**5,942.9**	**5,794.5**

[a] The LULUCF Sector Net Total is the net sum of all CH_4 and N_2O emissions to the atmosphere plus net carbon stock changes.

Notes: Emissions from electric power are allocated based on aggregate electricity use in each end-use sector. Totals may not sum due to independent rounding. Parentheses indicate negative values or sequestration.

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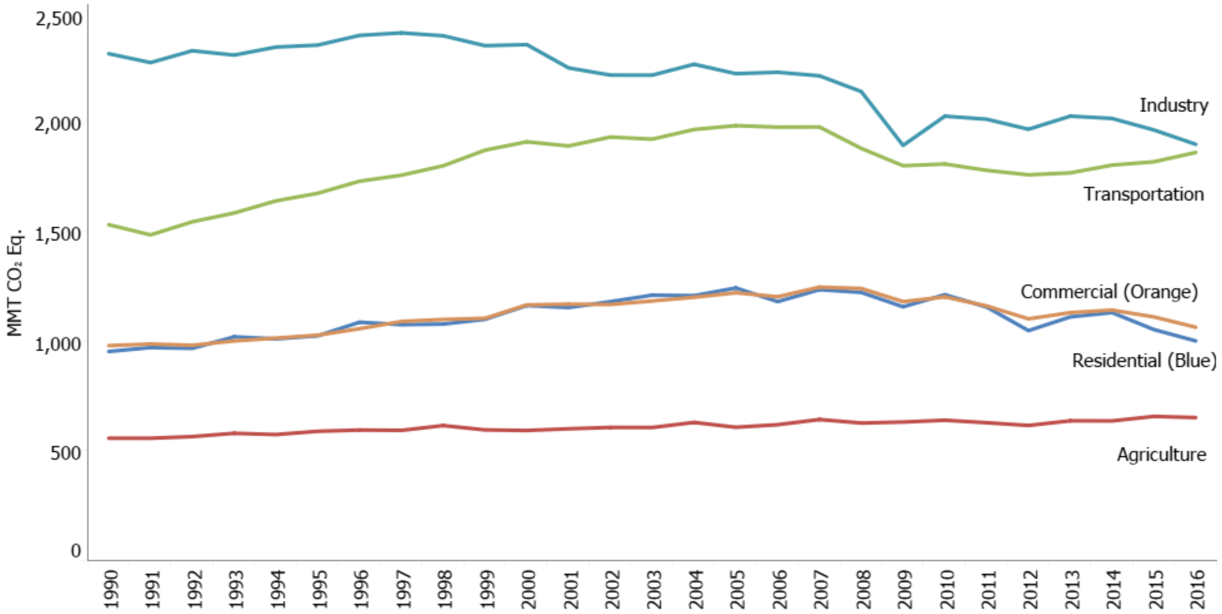
[25] Emissions were not distributed to U.S. Territories, since the electric power sector only includes emissions related to the generation of electricity in the 50 states and the District of Columbia.

Figure ES-15: U.S. Greenhouse Gas Emissions with Electricity-Related Emissions Distributed to Economic Sectors (MMT CO₂ Eq.)



Box ES-5: Recent Trends in Various U.S. Greenhouse Gas Emissions-Related Data

Total emissions can be compared to other economic and social indices to highlight changes over time. These comparisons include: (1) emissions per unit of aggregate energy use, because energy-related activities are the largest sources of emissions; (2) emissions per unit of fossil fuel consumption, because almost all energy-related emissions involve the combustion of fossil fuels; (3) emissions per unit of electricity use, because the electric power industry—utilities and non-utilities combined—was the second largest source of U.S. greenhouse gas emissions in 2016; (4) emissions per unit of total gross domestic product as a measure of national economic activity; and (5) emissions per capita.

Table ES-8 provides data on various statistics related to U.S. greenhouse gas emissions normalized to 1990 as a baseline year. These values represent the relative change in each statistic since 1990. Greenhouse gas emissions in the United States have grown at an average annual rate of 0.1 percent since 1990, although changes from year to year have been significantly larger. This rate is slightly slower than that for total energy use and fossil fuel consumption, and much slower than that for electricity use, overall gross domestic product (GDP), and national population (see Figure ES-16). The direction of these trends started to change relative to 2005, when greenhouse gas emissions, total energy use and fossil fuel consumption began to peak. Greenhouse gas emissions in the United States have decreased at an average annual rate of 1.0 percent since 2005. Total energy use and fossil fuel consumption have also decreased at slower rates than emissions since 2005, while electricity use, GDP, and national population continued to increase.

Table ES-8: Recent Trends in Various U.S. Data (Index 1990 = 100)

Variable	1990	2005	2012	2013	2014	2015	2016	Avg. Annual Change since 1990	Avg. Annual Change since 2005[a]
Greenhouse Gas Emissions[b]	100	115	103	106	106	104	102	0.1%	-1.0%
Energy Use[c]	100	118	112	116	117	116	116	0.6%	-0.2%
Fossil Fuel Consumption[c]	100	119	107	110	111	110	109	0.4%	-0.7%
Electricity Use[c]	100	134	135	136	138	137	138	1.2%	0.1%
GDP[d]	100	159	171	174	179	184	187	2.4%	1.5%
Population[e]	100	118	125	126	127	128	129	1.0%	0.8%

[a] Average annual growth rate

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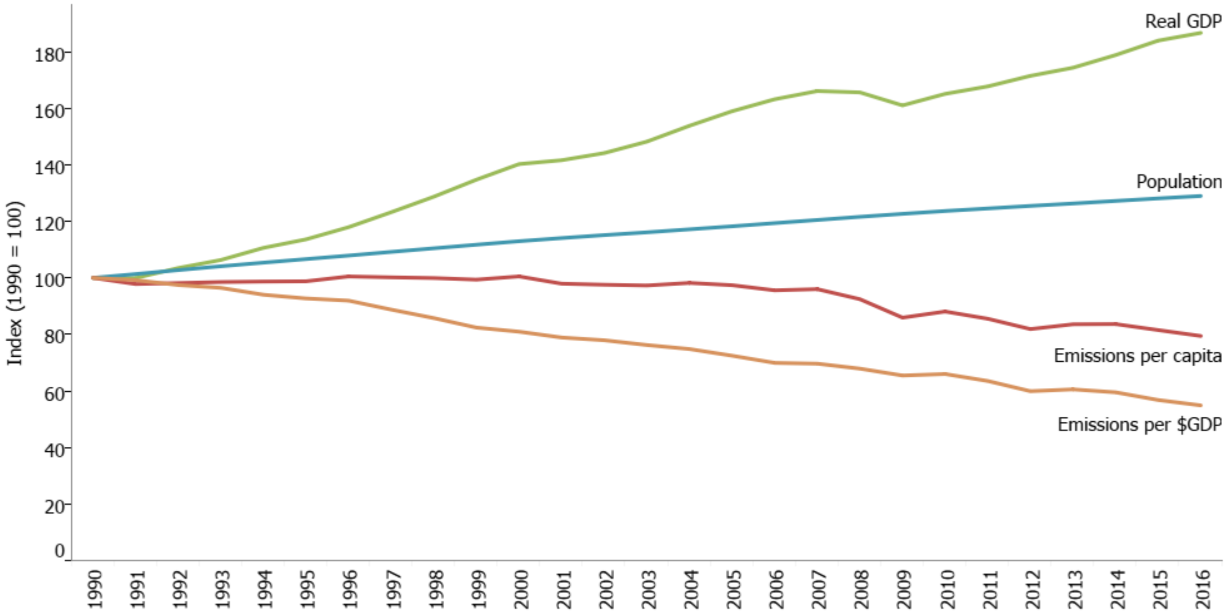
[b] GWP-weighted values

[c] Energy content-weighted values (EIA 2018)

[d] GDP in chained 2009 dollars (BEA 2018)

[e] U.S. Census Bureau (2017)

Figure ES-16: U.S. Greenhouse Gas Emissions Per Capita and Per Dollar of Gross Domestic Product (GDP)



Source: BEA (2018), U.S. Census Bureau (2017), and emission estimates in this report.

Key Categories

The *2006 IPCC Guidelines* (IPCC 2006) defines a key category as a "[category] that is prioritized within the national inventory system because its estimate has a significant influence on a country's total inventory of greenhouse gases in terms of the absolute level, the trend, or the uncertainty in emissions and removals."[26] By definition, key categories are sources or sinks that have the greatest contribution to the absolute overall level of national emissions in any of the years covered by the time series. In addition, when an entire time series of emission estimates is prepared, a thorough investigation of key categories must also account for the influence of trends of individual source and sink categories. Finally, a qualitative evaluation of key categories should be performed, in order to capture any key categories that were not identified in either of the quantitative analyses.

Figure ES-17 presents 2016 emission estimates for the key categories as defined by a level analysis including the LULUCF sector (i.e., the absolute value of the contribution of each source or sink category to the total inventory level). The UNFCCC reporting guidelines request that key category analyses be reported at an appropriate level of disaggregation, which may lead to source and sink category names which differ from those used elsewhere in the Inventory report. For more information regarding key categories, including a complete list of categories accounting for the influence of trends of individual source and sink categories, see Section 1.5 – Key Categories and Annex 1.

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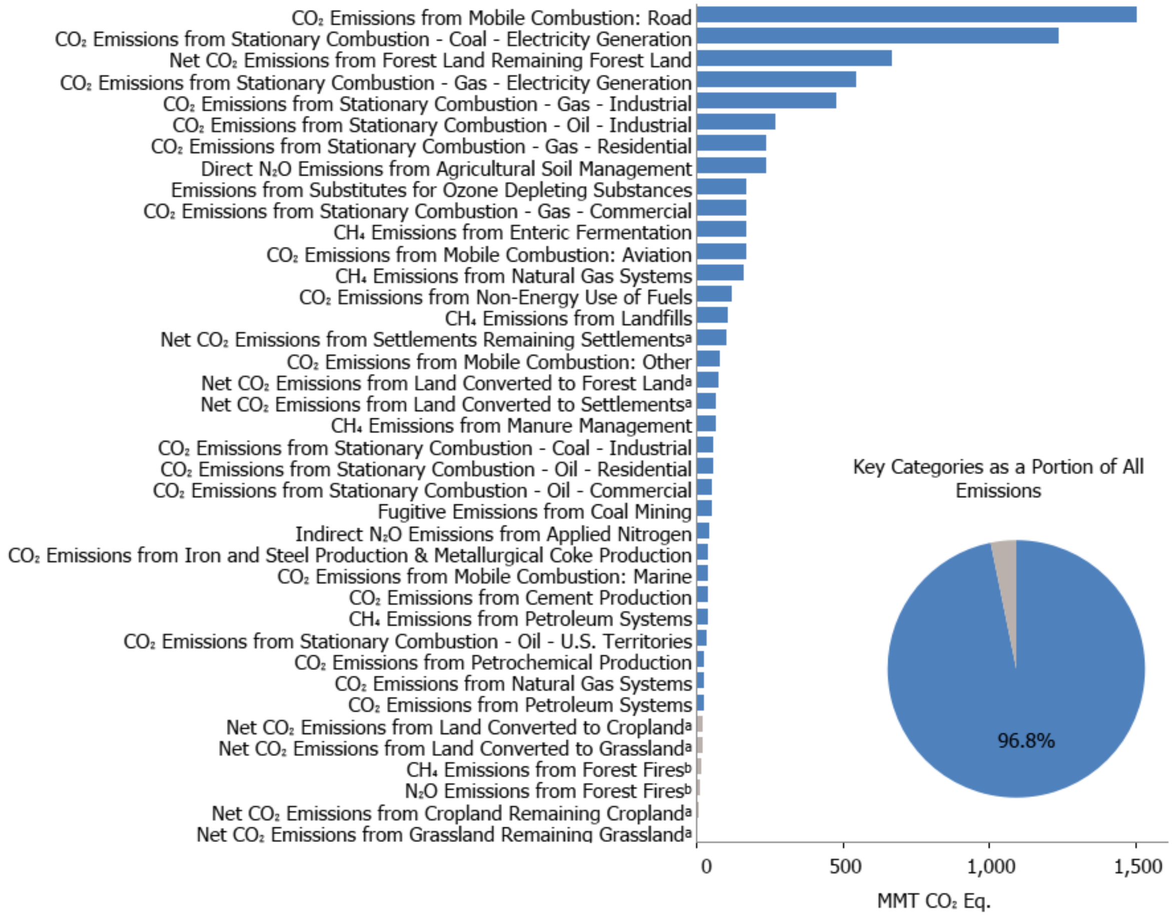
[26] See Chapter 4 "Methodological Choice and Identification of Key Categories" in IPCC (2006). See <http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol1.html>.

Figure ES-17: 2016 Key Categories (MMT CO_2 Eq.)



[a] The absolute values of net CO_2 emissions from LULUCF are presented in this figure but reported separately from gross emissions totals. Refer to Table ES-5 for a breakout of emissions and removals for LULUCF by gas and source category.

[b] Non-CO_2 emissions from Forest Fires are presented in this figure but reported separately from gross emissions totals. Refer to Table ES-5 for a breakout of emissions and removals for LULUCF by gas and source category.

Note: For a complete discussion of the key category analysis, see Annex 1. Blue bars indicate either an Approach 1, or Approach 1 *and* Approach 2 level assessment key category. Gray bars indicate solely an Approach 2 level assessment key category.

Quality Assurance and Quality Control (QA/QC)

The United States seeks to continually improve the quality, transparency, and credibility of the *Inventory of U.S. Greenhouse Gas Emissions and Sinks*. To assist in these efforts, the United States implemented a systematic approach to QA/QC. The procedures followed for the Inventory have been formalized in accordance with the *Quality Assurance/Quality Control and Uncertainty Management Plan* (QA/QC Management Plan) for the Inventory, and the UNFCCC reporting guidelines. The QA process includes expert and public reviews for both the Inventory estimates and the Inventory report.

Uncertainty Analysis of Emission Estimates

Uncertainty estimates are an essential element of a complete inventory of greenhouse gas emissions and removals, because they help to prioritize future work and improve overall quality. Some of the current estimates, such as those for CO_2 emissions from energy-related activities, are considered to have low uncertainties. This is because the amount of CO_2 emitted from energy-related activities is directly related to the amount of fuel consumed, the fraction of the fuel that is oxidized, and the carbon content of the fuel and, for the United States, the uncertainties associated with estimating those factors is believed to be relatively small. For some other categories of emissions, however, a lack of data or an incomplete understanding of how emissions are generated increases the uncertainty or systematic error associated with the estimates presented. Recognizing the benefit of conducting an uncertainty analysis, the UNFCCC reporting guidelines follow the recommendations of the *2006 IPCC Guidelines* (IPCC 2006), Volume 1, Chapter 3 and require that countries provide single estimates of uncertainty for source and sink categories.

In addition to quantitative uncertainty assessments provided in accordance with UNFCCC reporting guidelines, a qualitative discussion of uncertainty is presented for all source and sink categories. Within the discussion of each emission source, specific factors affecting the uncertainty surrounding the estimates are discussed.

1. Introduction

This report presents estimates by the United States government of U.S. anthropogenic greenhouse gas emissions and sinks for the years 1990 through 2016. A summary of these estimates is provided in Table 2-1 and Table 2-2 by gas and source category in the Trends in Greenhouse Gas Emissions chapter. The emission estimates in these tables are presented on both a full molecular mass basis and on a Global Warming Potential (GWP) weighted basis[27] in order to show the relative contribution of each gas to global average radiative forcing. This report also discusses the methods and data used to calculate these emission estimates.

In 1992, the United States signed and ratified the United Nations Framework Convention on Climate Change (UNFCCC). As stated in Article 2 of the UNFCCC, "The ultimate objective of this Convention and any related legal instruments that the Conference of the Parties may adopt is to achieve, in accordance with the relevant provisions of the Convention, stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner."[28,29]

Parties to the Convention, by ratifying, "shall develop, periodically update, publish and make available…national inventories of anthropogenic emissions by sources and removals by sinks of all greenhouse gases not controlled by the Montreal Protocol, using comparable methodologies…"[30] The United States views this report as an opportunity to fulfill these commitments under the UNFCCC.

In 1988, preceding the creation of the UNFCCC, the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) jointly established the Intergovernmental Panel on Climate Change (IPCC). The role of the IPCC is to assess on a comprehensive, objective, open and transparent basis the scientific, technical and socio-economic information relevant to understanding the scientific basis of risk of human-induced climate change, its potential impacts and options for adaptation and mitigation (IPCC 2014). Under Working Group 1 of the IPCC, nearly 140 scientists and national experts from more than thirty countries collaborated in the creation of the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC/UNEP/OECD/IEA 1997) to ensure that the emission inventories submitted to the UNFCCC are consistent and comparable between nations. The *IPCC Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* and the *IPCC Good Practice Guidance for Land Use, Land-Use Change, and Forestry* further expanded upon the methodologies in the *Revised 1996 IPCC Guidelines*. In 2006, the IPCC accepted the *2006 Guidelines for National Greenhouse Gas Inventories* at its Twenty-Fifth Session (Mauritius, April 2006). The *2006 IPCC Guidelines* built

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[27] More information provided in "Global Warming Potentials" section of this chapter on the use of *IPCC Fourth Assessment Report* (AR4) GWP values.

[28] The term "anthropogenic," in this context, refers to greenhouse gas emissions and removals that are a direct result of human activities or are the result of natural processes that have been affected by human activities (IPCC 2006).

[29] Article 2 of the Framework Convention on Climate Change published by the UNEP/WMO Information Unit on Climate Change (UNEP/WMO 2000). See <http://unfccc.int>.

[30] Article 4(1)(a) of the United Nations Framework Convention on Climate Change (also identified in Article 12). Subsequent decisions by the Conference of the Parties elaborated the role of Annex I Parties in preparing national inventories. See <http://unfccc.int>.

upon the previous bodies of work and include new sources and gases "…as well as updates to the previously published methods whenever scientific and technical knowledge have improved since the previous guidelines were issued." The UNFCCC adopted the *2006 IPCC Guidelines* as the standard methodological approach for Annex I countries at the Nineteenth Conference of the Parties (Warsaw, November 11-23, 2013). This report presents information in accordance with these guidelines.

Overall, this Inventory of anthropogenic greenhouse gas emissions and sinks provides a common and consistent mechanism through which Parties to the UNFCCC can estimate emissions and compare the relative contribution of individual sources, gases, and nations to climate change. The Inventory provides a national estimate of sources and sinks for the United States, including all states and U.S. Territories.[31] The structure of this report is consistent with the current UNFCCC Guidelines on Annual Inventories (UNFCCC 2014) for Parties included in Annex I of the Convention.

Box 1-1: Methodological Approach for Estimating and Reporting U.S. Emissions and Removals

In following the UNFCCC requirement under Article 4.1 to develop and submit national greenhouse gas emissions inventories, the gross emissions total presented in this report for the United States excludes emissions and removals from Land Use, Land-Use Change, and Forestry (LULUCF). The net emissions total presented in this report for the United States includes emissions and removals from LULUCF. All emissions and removals are calculated using internationally-accepted methods consistent with the IPCC Guidelines.[32] Additionally, the calculated emissions and removals in a given year for the United States are presented in a common manner in line with the UNFCCC reporting guidelines for the reporting of inventories under this international agreement.[33] The use of consistent methods to calculate emissions and removals by all nations providing their inventories to the UNFCCC ensures that these reports are comparable. The report itself follows this standardized format, and provides an explanation of the IPCC methods used to calculate emissions and removals.

On October 30, 2009, the U.S. Environmental Protection Agency (EPA) published a rule for the mandatory reporting of greenhouse gases from large greenhouse gas emissions sources in the United States. Implementation of 40 CFR Part 98 is referred to as the EPA's Greenhouse Gas Reporting Program (GHGRP). 40 CFR Part 98 applies to direct greenhouse gas emitters, fossil fuel suppliers, industrial gas suppliers, and facilities that inject CO_2 underground for sequestration or other reasons.[34] Reporting is at the facility level, except for certain suppliers of fossil fuels and industrial greenhouse gases. The GHGRP dataset and the data presented in this Inventory are complementary.

EPA's GHGRP dataset continues to be an important resource for the Inventory, providing not only annual emissions information, but also other annual information, such as activity data and emission factors that can improve and refine national emission estimates and trends over time. GHGRP data also allow EPA to disaggregate national Inventory estimates in new ways that can highlight differences across regions and sub-categories of emissions. The GHGRP will continue to enhance QA/QC procedures and assessment of uncertainties.

EPA continues to analyze the data on an annual basis to improve the national estimates presented in this Inventory and uses that data for a number of categories consistent with IPCC guidance.[35] EPA has integrated GHGRP information for several categories[36] this year and also identifies other categories[37] where EPA plans to integrate

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[31] U.S. Territories include American Samoa, Guam, Puerto Rico, U.S. Virgin Islands, Wake Island, and other U.S. Pacific Islands.

[32] See <http://www.ipcc-nggip.iges.or.jp/public/index.html>.

[33] See <http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf>.

[34] See <https://www.epa.gov/ghgreporting>.

[35] See <http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf>.

[36] Energy Sector (Coal Mining, Stationary Combustion [Industrial Combustion Disaggregation], and Oil and Gas Systems); Industrial Processes and Product Use (Adipic Acid Production, Aluminum Production, Carbon Dioxide Consumption, Electrical Transmission and Distribution, HCFC-22 Production, Lime Production, Magnesium Production and Processing, ODS Substitutes, Nitric Acid Production, Petrochemical Production, Semiconductor Manufacture); and Waste (Landfills).

[37] Industrial Process and Product Use (Ammonia Production, Cement Production, and Other Fluorinated Gas Production)

additional GHGRP data in the next edition of this report (see those categories' Planned Improvement sections for details).

1.1 Background Information

Science

For over the past 200 years, the burning of fossil fuels such as coal and oil, deforestation, land-use changes, and other activities have caused the concentrations of heat-trapping "greenhouse gases" to increase significantly in our atmosphere (NOAA 2017). These gases in the atmosphere absorb some of the energy being radiated from the surface of the Earth that would otherwise be lost to space, essentially acting like a blanket that makes the Earth's surface warmer than it would be otherwise.

Greenhouse gases are necessary to life as we know it. Without greenhouse gases to create the natural heat-trapping properties of the atmosphere, the planet's surface would be about 60 degrees Fahrenheit cooler than present (USGCRP 2017). Carbon dioxide is also necessary for plant growth. With emissions from biological and geological sources, there is a natural level of greenhouse gases that is maintained in the atmosphere. Human emissions of greenhouse gases and subsequent changes in atmospheric concentrations alter the balance of energy transfers between space and the earth system (IPCC 2013). A gauge of these changes is called radiative forcing, which is a measure of a substance's total net effect on the global energy balance for which a positive number represents a warming effect and a negative number represents a cooling effect (IPCC 2013). IPCC concluded in its most recent scientific assessment report that it is extremely likely that human influences have been the dominant cause of warming since the mid-20th century (IPCC 2013).

As concentrations of greenhouse gases continue to increase in from man-made sources, the Earth's temperature is climbing above past levels. The Earth's average land and ocean surface temperature has increased by about 1.2 to 1.9 degrees Fahrenheit since 1880. The last three decades have each been the warmest decade successively at the Earth's surface since 1850 (IPCC 2013). Other aspects of the climate are also changing, such as rainfall patterns, snow and ice cover, and sea level. If greenhouse gas concentrations continue to increase, climate models predict that the average temperature at the Earth's surface is likely to increase from 0.5 to 8.6 degrees Fahrenheit above 1986 through 2005 levels by the end of this century, depending on future emissions and the responsiveness of the climate system (IPCC 2013).

For further information on greenhouse gases, radiative forcing, and implications for climate change, see the recent scientific assessment reports from the IPCC,[38] the U.S. Global Change Research Program (USGCRP),[39] and the National Academies of Sciences, Engineering, and Medicine (NAS).[40]

Greenhouse Gases

Although the Earth's atmosphere consists mainly of oxygen and nitrogen, neither plays a significant role in enhancing the greenhouse effect because both are essentially transparent to terrestrial radiation. The greenhouse effect is primarily a function of the concentration of water vapor, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and other trace gases in the atmosphere that absorb the terrestrial radiation leaving the surface of the Earth (IPCC 2013).

Naturally occurring greenhouse gases include water vapor, CO_2, CH_4, N_2O, and ozone (O_3). Several classes of halogenated substances that contain fluorine, chlorine, or bromine are also greenhouse gases, but they are, for the

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[38] See <http://www.ipcc.ch/report/ar5>.

[39] See < https://science2017.globalchange.gov/>.

[40] See <http://nas-sites.org/americasclimatechoices/>.

most part, solely a product of industrial activities. Chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) are halocarbons that contain chlorine, while halocarbons that contain bromine are referred to as bromofluorocarbons (i.e., halons). As stratospheric ozone depleting substances, CFCs, HCFCs, and halons are covered under the Montreal Protocol on Substances that Deplete the Ozone Layer. The UNFCCC defers to this earlier international treaty. Consequently, Parties to the UNFCCC are not required to include these gases in national greenhouse gas inventories.[41] Some other fluorine-containing halogenated substances—hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6), and nitrogen trifluoride (NF_3)—do not deplete stratospheric ozone but are potent greenhouse gases. These latter substances are addressed by the UNFCCC and accounted for in national greenhouse gas inventories.

There are also several other substances that influence the global radiation budget but are short-lived and therefore not well-mixed, leading to spatially variable radiative forcing effects. These substances include carbon monoxide (CO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and tropospheric (ground level) ozone (O_3). Tropospheric ozone is formed from chemical reactions in the atmosphere of precursor pollutants, which include volatile organic compounds (VOCs, including CH_4) and nitrogen oxides (NO_x), in the presence of ultraviolet light (sunlight).

Aerosols are extremely small particles or liquid droplets suspended in the Earth's atmosphere that are often composed of sulfur compounds, carbonaceous combustion products (e.g., black carbon), crustal materials (e.g., dust) and other human-induced pollutants. They can affect the absorptive characteristics of the atmosphere (e.g., scattering incoming sunlight away from the Earth's surface, or, in the case of black carbon, absorb sunlight) and can play a role in affecting cloud formation and lifetime, as well as the radiative forcing of clouds and precipitation patterns. Comparatively, however, while the understanding of aerosols has increased in recent years, they still account for the largest contribution to uncertainty estimates in global energy budgets (IPCC 2013).

Carbon dioxide, CH_4, and N_2O are continuously emitted to and removed from the atmosphere by natural processes on Earth. Anthropogenic activities (such as fossil fuel combustion, cement production, land-use, land-use change, and forestry, agriculture, or waste management), however, can cause additional quantities of these and other greenhouse gases to be emitted or sequestered, thereby changing their global average atmospheric concentrations. Natural activities such as respiration by plants or animals and seasonal cycles of plant growth and decay are examples of processes that only cycle carbon or nitrogen between the atmosphere and organic biomass. Such processes, except when directly or indirectly perturbed out of equilibrium by anthropogenic activities, generally do not alter average atmospheric greenhouse gas concentrations over decadal timeframes. Climatic changes resulting from anthropogenic activities, however, could have positive or negative feedback effects on these natural systems. Atmospheric concentrations of these gases, along with their rates of growth and atmospheric lifetimes, are presented in Table 1-1.

Table 1-1: Global Atmospheric Concentration, Rate of Concentration Change, and Atmospheric Lifetime of Selected Greenhouse Gases

Atmospheric Variable	CO_2	CH_4	N_2O	SF_6	CF_4
Pre-industrial atmospheric concentration	280 ppm	0.700 ppm	0.270 ppm	0 ppt	40 ppt
Atmospheric concentration	404 ppm[a]	1.843 ppm[b]	0.329 ppm[c]	8.9 ppt[d]	79 ppt[e]
Rate of concentration change	2.3 ppm/yr[g]	7 ppb/yr[f,g]	0.8 ppb/yr[g]	0.27 ppt/yr[g]	0.7 ppt/yr[g]
Atmospheric lifetime (years)	See footnote[h]	12.4[i]	121[i]	3,200	50,000

[a] The atmospheric CO_2 concentration is the 2016 annual average at the Mauna Loa, HI station (NOAA/ESRL 2017a). The concentration in 2017 at Mauna Loa was 407 ppm. The global atmospheric CO_2 concentration, computed using an average of sampling sites across the world, was 403 ppm in 2016.

[b] The values presented are global 2016 annual average mole fractions (NOAA/ESRL 2017b).

[c] The values presented are global 2016 annual average mole fractions (NOAA/ESRL 2017c).

[d] The values presented are global 2016 annual average mole fractions (NOAA/ESRL 2017d).

[e] The 2011 CF_4 global mean atmospheric concentration is from the Advanced Global Atmospheric Gases Experiment (IPCC 2013).

[f] The growth rate for atmospheric CH_4 decreased from over 10 ppb/year in the 1980s to nearly zero in the early 2000s; recently, the growth rate has been about 7 ppb/year.

[g] The rate of concentration change for CO_2 and CH_4 is the average rate of change between 2007 and 2016 (NOAA/ESRL 2017a).

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[41] Emissions estimates of CFCs, HCFCs, halons and other ozone-depleting substances are included in this document for informational purposes.

The rate of concentration change for N_2O, SF_6, and CF_4 is the average rate of change between 2005 and 2011 (IPCC 2013).

[h] For a given amount of CO_2 emitted, some fraction of the atmospheric increase in concentration is quickly absorbed by the oceans and terrestrial vegetation, some fraction of the atmospheric increase will only slowly decrease over a number of years, and a small portion of the increase will remain for many centuries or more.

[i] This lifetime has been defined as an "adjustment time" that takes into account the indirect effect of the gas on its own residence time.

Source: Pre-industrial atmospheric concentrations, atmospheric lifetime, and rate of concentration changes for CH_4, N_2O, SF_6, and CF_4 are from IPCC (2013). The rate of concentration change for CO_2 is an average of the rates from 2007 through 2016 and has fluctuated between 1.9 to 3.0 ppm per year over this period (NOAA/ESRL 2017a).

A brief description of each greenhouse gas, its sources, and its role in the atmosphere is given below. The following section then explains the concept of GWPs, which are assigned to individual gases as a measure of their relative average global radiative forcing effect.

Water Vapor (H_2O). Water vapor is the largest contributor to the natural greenhouse effect. Water vapor is fundamentally different from other greenhouse gases in that it can condense and rain out when it reaches high concentrations, and the total amount of water vapor in the atmosphere is in part a function of the Earth's temperature. While some human activities such as evaporation from irrigated crops or power plant cooling release water vapor into the air, these activities have been determined to have a negligible effect on climate (IPCC 2013). The lifetime of water vapor in the troposphere is on the order of 10 days. Water vapor can also contribute to cloud formation, and clouds can have both warming and cooling effects by either trapping or reflecting heat. Because of the relationship between water vapor levels and temperature, water vapor and clouds serve as a feedback to climate change, such that for any given increase in other greenhouse gases, the total warming is greater than would happen in the absence of water vapor. Aircraft emissions of water vapor can create contrails, which may also develop into contrail-induced cirrus clouds, with complex regional and temporal net radiative forcing effects that currently have a low level of scientific certainty (IPCC 2013).

Carbon Dioxide (CO_2). In nature, carbon is cycled between various atmospheric, oceanic, land biotic, marine biotic, and mineral reservoirs. The largest fluxes occur between the atmosphere and terrestrial biota, and between the atmosphere and surface water of the oceans. In the atmosphere, carbon predominantly exists in its oxidized form as CO_2. Atmospheric CO_2 is part of this global carbon cycle, and therefore its fate is a complex function of geochemical and biological processes. Carbon dioxide concentrations in the atmosphere increased from approximately 280 parts per million by volume (ppmv) in pre-industrial times to 404 ppmv in 2016, a 44 percent increase (IPCC 2013; NOAA/ESRL 2017a).[42,43] The IPCC definitively states that "the increase of CO_2 … is caused by anthropogenic emissions from the use of fossil fuel as a source of energy and from land use and land use changes, in particular agriculture" (IPCC 2013). The predominant source of anthropogenic CO_2 emissions is the combustion of fossil fuels. Forest clearing, other biomass burning, and some non-energy production processes (e.g., cement production) also emit notable quantities of CO_2. In its *Fifth Assessment Report*, the IPCC stated "it is extremely likely that more than half of the observed increase in global average surface temperature from 1951 to 2010 was caused by the anthropogenic increase in greenhouse gas concentrations and other anthropogenic forcings together," of which CO_2 is the most important (IPCC 2013).

Methane (CH_4). Methane is primarily produced through anaerobic decomposition of organic matter in biological systems. Agricultural processes such as wetland rice cultivation, enteric fermentation in animals, and the decomposition of animal wastes emit CH_4, as does the decomposition of municipal solid wastes. Methane is also emitted during the production and distribution of natural gas and petroleum, and is released as a byproduct of coal mining and incomplete fossil fuel combustion. Atmospheric concentrations of CH_4 have increased by about 163 percent since 1750, from a pre-industrial value of about 700 ppb to 1,843 ppb in 2016[44] although the rate of increase decreased to near zero in the early 2000s, and has recently increased again to about 7 ppb/year. The IPCC has estimated that slightly more than half of the current CH_4 flux to the atmosphere is anthropogenic, from human activities such as agriculture, fossil fuel use, and waste disposal (IPCC 2007).

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[42] The pre-industrial period is considered as the time preceding the year 1750 (IPCC 2013).

[43] Carbon dioxide concentrations during the last 1,000 years of the pre-industrial period (i.e., 750 to 1750), a time of relative climate stability, fluctuated by about ±10 ppmv around 280 ppmv (IPCC 2013).

[44] This value is the global 2016 annual average mole fraction (NOAA/ESRL 2017b).

Methane is primarily removed from the atmosphere through a reaction with the hydroxyl radical (OH) and is ultimately converted to CO_2. Minor removal processes also include reaction with chlorine in the marine boundary layer, a soil sink, and stratospheric reactions. Increasing emissions of CH_4 reduce the concentration of OH, a feedback that increases the atmospheric lifetime of CH_4 (IPCC 2013). Methane's reactions in the atmosphere also lead to production of tropospheric ozone and stratospheric water vapor, both of which also contribute to climate change.

Nitrous Oxide (N_2O). Anthropogenic sources of N_2O emissions include agricultural soils, especially production of nitrogen-fixing crops and forages, the use of synthetic and manure fertilizers, and manure deposition by livestock; fossil fuel combustion, especially from mobile combustion; adipic (nylon) and nitric acid production; wastewater treatment and waste incineration; and biomass burning. The atmospheric concentration of N_2O has increased by 22 percent since 1750, from a pre-industrial value of about 270 ppb to 329 ppb in 2016,[45] a concentration that has not been exceeded during the last 800 thousand years. Nitrous oxide is primarily removed from the atmosphere by the photolytic action of sunlight in the stratosphere (IPCC 2013).

Ozone (O_3). Ozone is present in both the upper stratosphere,[46] where it shields the Earth from harmful levels of ultraviolet radiation, and at lower concentrations in the troposphere,[47] where it is the main component of anthropogenic photochemical "smog." During the last two decades, emissions of anthropogenic chlorine and bromine-containing halocarbons, such as CFCs, have depleted stratospheric ozone concentrations. This loss of ozone in the stratosphere has resulted in negative radiative forcing, representing an indirect effect of anthropogenic emissions of chlorine and bromine compounds (IPCC 2013). The depletion of stratospheric ozone and its radiative forcing remains relatively unchanged since 2000 and recovery is expected to start occurring in the middle of the twenty-first century (WMO/UNEP 2014, WMO 2015).

The past increase in tropospheric ozone, which is also a greenhouse gas, is estimated to provide the fourth largest increase in direct radiative forcing since the pre-industrial era, behind CO_2, black carbon, and CH_4. Tropospheric ozone is produced from complex chemical reactions of volatile organic compounds (including CH_4) mixing with NO_x in the presence of sunlight. The tropospheric concentrations of ozone and these other pollutants are short-lived and, therefore, spatially variable (IPCC 2013).

Halocarbons, Sulfur Hexafluoride, and Nitrogen Trifluoride. Halocarbons are, for the most part, man-made chemicals that have direct radiative forcing effects and could also have an indirect effect. Halocarbons that contain chlorine (CFCs, HCFCs, methyl chloroform, and carbon tetrachloride) and bromine (halons, methyl bromide, and hydrobromofluorocarbons) result in stratospheric ozone depletion and are therefore controlled under the Montreal Protocol on Substances that Deplete the Ozone Layer. Although most CFCs and HCFCs are potent global warming gases, their net radiative forcing effect on the atmosphere is reduced because they cause stratospheric ozone depletion, which itself is a greenhouse gas but which also shields the Earth from harmful levels of ultraviolet radiation. Under the Montreal Protocol, the United States phased out the production and importation of halons by 1994 and of CFCs by 1996. Under the Copenhagen Amendments to the Protocol, a cap was placed on the production and importation of HCFCs by non-Article 5[48] countries, including the United States, beginning in 1996, and then followed by intermediate requirements and a complete phase-out by the year 2030. While ozone depleting gases covered under the Montreal Protocol and its Amendments are not covered by the UNFCCC, they are reported in this Inventory under Annex 6.2 for informational purposes.

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[45] This value is the global 2016 annual average (NOAA/ESRL 2017c).

[46] The stratosphere is the layer from the troposphere up to roughly 50 kilometers. In the lower regions the temperature is nearly constant but in the upper layer the temperature increases rapidly because of sunlight absorption by the ozone layer. The ozone-layer is the part of the stratosphere from 19 kilometers up to 48 kilometers where the concentration of ozone reaches up to 10 parts per million.

[47] The troposphere is the layer from the ground up to 11 kilometers near the poles and up to 16 kilometers in equatorial regions (i.e., the lowest layer of the atmosphere where people live). It contains roughly 80 percent of the mass of all gases in the atmosphere and is the site for most weather processes, including most of the water vapor and clouds.

[48] Article 5 of the Montreal Protocol covers several groups of countries, especially developing countries, with low consumption rates of ozone depleting substances. Developing countries with per capita consumption of less than 0.3 kg of certain ozone depleting substances (weighted by their ozone depleting potential) receive financial assistance and a grace period of ten additional years in the phase-out of ozone depleting substances.

Hydrofluorocarbons, PFCs, SF_6, and NF_3 are not ozone depleting substances. The most common HFCs are, however, powerful greenhouse gases. Hydrofluorocarbons are primarily used as replacements for ozone depleting substances but also emitted as a byproduct of the HCFC-22 (chlorodifluoromethane) manufacturing process. Currently, they have a small aggregate radiative forcing impact, but it is anticipated that without further controls their contribution to overall radiative forcing will increase (IPCC 2013). An amendment to the Montreal Protocol was adopted in 2016 which includes obligations for Parties to phase down the production and consumption of HFCs.

Perfluorocarbons, SF_6, and NF_3 are predominantly emitted from various industrial processes including aluminum smelting, semiconductor manufacturing, electric power transmission and distribution, and magnesium casting. Currently, the radiative forcing impact of PFCs, SF_6, and NF_3 is also small, but they have a significant growth rate, extremely long atmospheric lifetimes, and are strong absorbers of infrared radiation, and therefore have the potential to influence climate far into the future (IPCC 2013).

Carbon Monoxide (CO). Carbon monoxide has an indirect radiative forcing effect by elevating concentrations of CH_4 and tropospheric ozone through chemical reactions with other atmospheric constituents (e.g., the hydroxyl radical, OH) that would otherwise assist in destroying CH_4 and tropospheric ozone. Carbon monoxide is created when carbon-containing fuels are burned incompletely. Through natural processes in the atmosphere, it is eventually oxidized to CO_2. Carbon monoxide concentrations are both short-lived in the atmosphere and spatially variable.

Nitrogen Oxides (NO_x). The primary climate change effects of nitrogen oxides (i.e., NO and NO_2) are indirect. Warming effects can occur due to reactions leading to the formation of ozone in the troposphere, but cooling effects can occur due to the role of NO_x as a precursor to nitrate particles (i.e., aerosols) and due to destruction of stratospheric ozone when emitted from very high-altitude aircraft.[49] Additionally, NO_x emissions are also likely to decrease CH_4 concentrations, thus having a negative radiative forcing effect (IPCC 2013). Nitrogen oxides are created from lightning, soil microbial activity, biomass burning (both natural and anthropogenic fires) fuel combustion, and, in the stratosphere, from the photo-degradation of N_2O. Concentrations of NO_x are both relatively short-lived in the atmosphere and spatially variable.

Non-methane Volatile Organic Compounds (NMVOCs). Non-methane volatile organic compounds include substances such as propane, butane, and ethane. These compounds participate, along with NO_x, in the formation of tropospheric ozone and other photochemical oxidants. NMVOCs are emitted primarily from transportation and industrial processes, as well as biomass burning and non-industrial consumption of organic solvents. Concentrations of NMVOCs tend to be both short-lived in the atmosphere and spatially variable.

Aerosols. Aerosols are extremely small particles or liquid droplets found in the atmosphere that are either directly emitted into or are created through chemical reactions in the Earth's atmosphere. Aerosols or their chemical precursors can be emitted by natural events such as dust storms, biogenic or volcanic activity, or by anthropogenic processes such as transportation, coal combustion, cement manufacturing, waste incineration, or biomass burning. Various categories of aerosols exist from both natural and anthropogenic sources, such as soil dust, sea salt, biogenic aerosols, sulfates, nitrates, volcanic aerosols, industrial dust, and carbonaceous[50] aerosols (e.g., black carbon, organic carbon). Aerosols can be removed from the atmosphere relatively rapidly by precipitation or through more complex processes under dry conditions.

Aerosols affect radiative forcing differently than greenhouse gases. Their radiative effects occur through direct and indirect mechanisms: directly by scattering and absorbing solar radiation (and to a lesser extent scattering, absorption, and emission of terrestrial radiation); and indirectly by increasing cloud droplets and ice crystals that modify the formation, precipitation efficiency, and radiative properties of clouds (IPCC 2013). Despite advances in understanding of cloud-aerosol interactions, the contribution of aerosols to radiative forcing are difficult to quantify because aerosols generally have short atmospheric lifetimes, and have number concentrations, size distributions, and compositions that vary regionally, spatially, and temporally (IPCC 2013).

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[49] NO_x emissions injected higher in the stratosphere, primarily from fuel combustion emissions from high altitude supersonic aircraft, can lead to stratospheric ozone depletion.

[50] Carbonaceous aerosols are aerosols that are comprised mainly of organic substances and forms of black carbon (or soot) (IPCC 2013).

The net effect of aerosols on the Earth's radiative forcing is believed to be negative (i.e., net cooling effect on the climate). In fact, "despite the large uncertainty ranges on aerosol forcing, there is high confidence that aerosols have offset a substantial portion of GHG forcing" (IPCC 2013).[51] Although because they remain in the atmosphere for only days to weeks, their concentrations respond rapidly to changes in emissions.[52] Not all aerosols have a cooling effect. Current research suggests that another constituent of aerosols, black carbon, has a positive radiative forcing by heating the Earth's atmosphere and causing surface warming when deposited on ice and snow (IPCC 2013). Black carbon also influences cloud development, but the direction and magnitude of this forcing is an area of active research.

Global Warming Potentials

A global warming potential is a quantified measure of the globally averaged relative radiative forcing impacts of a particular greenhouse gas (see Table 1-2). It is defined as the accumulated radiative forcing within a specific time horizon caused by emitting 1 kilogram (kg) of the gas, relative to that of the reference gas CO_2 (IPCC 2014). Direct radiative effects occur when the gas itself absorbs radiation. Indirect radiative forcing occurs when chemical transformations involving the original gas produce a gas or gases that are greenhouse gases, or when a gas influences other radiatively important processes such as the atmospheric lifetimes of other gases. The reference gas used is CO_2, and therefore GWP-weighted emissions are measured in million metric tons of CO_2 equivalent (MMT CO_2 Eq.).[53] The relationship between kilotons (kt) of a gas and MMT CO_2 Eq. can be expressed as follows:

$$MMT\ CO_2\ Eq. = (kt\ of\ gas) \times (GWP) \times \left(\frac{MMT}{1{,}000\ kt}\right)$$

where,

MMT CO_2 Eq. = Million metric tons of CO_2 equivalent

kt = kilotons (equivalent to a thousand metric tons)

GWP = Global warming potential

MMT = Million metric tons

GWP values allow for a comparison of the impacts of emissions and reductions of different gases. According to the IPCC, GWPs typically have an uncertainty of ±35 percent. Parties to the UNFCCC have also agreed to use GWPs based upon a 100-year time horizon, although other time horizon values are available.

> *...the global warming potential values used by Parties included in Annex I to the Convention (Annex I Parties) to calculate the carbon dioxide equivalence of anthropogenic emissions by sources and removals by sinks of greenhouse gases shall be those listed in the column entitled "Global warming potential for given time horizon" in table 2.14 of the errata to the contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, based on the effects of greenhouse gases over a 100-year time horizon...*[54]

Greenhouse gases with relatively long atmospheric lifetimes (e.g., CO_2, CH_4, N_2O, HFCs, PFCs, SF_6, NF_3) tend to be evenly distributed throughout the atmosphere, and consequently global average concentrations can be determined. The short-lived gases such as water vapor, carbon monoxide, tropospheric ozone, ozone precursors

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[51] The IPCC (2013) defines high confidence as an indication of strong scientific evidence and agreement in this statement.

[52] Volcanic activity can inject significant quantities of aerosol producing sulfur dioxide and other sulfur compounds into the stratosphere, which can result in a longer negative forcing effect (i.e., a few years) (IPCC 2013).

[53] Carbon comprises 12/44$^{\text{ths}}$ of carbon dioxide by weight.

[54] Framework Convention on Climate Change; Available online at: <http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf>; 31 January 2014; Report of the Conference of the Parties at its nineteenth session; held in Warsaw from 11 to 23 November 2013; Addendum; Part two: Action taken by the Conference of the Parties at its nineteenth session; Decision 24/CP.19; Revision of the UNFCCC reporting guidelines on annual inventories for Parties included in Annex I to the Convention; p. 2. (UNFCCC 2014).

(e.g., NO_x, and NMVOCs), and tropospheric aerosols (e.g., SO_2 products and carbonaceous particles), however, vary regionally, and consequently it is difficult to quantify their global radiative forcing impacts. Parties to the UNFCCC have not agreed upon GWP values for these gases that are short-lived and spatially inhomogeneous in the atmosphere.

Table 1-2: Global Warming Potentials and Atmospheric Lifetimes (Years) Used in this Report

Gas	Atmospheric Lifetime	GWP[a]
CO_2	See footnote[b]	1
CH_4[c]	12	25
N_2O	114	298
HFC-23	270	14,800
HFC-32	4.9	675
HFC-125	29	3,500
HFC-134a	14	1,430
HFC-143a	52	4,470
HFC-152a	1.4	124
HFC-227ea	34.2	3,220
HFC-236fa	240	9,810
HFC-4310mee	15.9	1,640
CF_4	50,000	7,390
C_2F_6	10,000	12,200
C_4F_{10}	2,600	8,860
C_6F_{14}	3,200	9,300
SF_6	3,200	22,800
NF_3	740	17,200

[a] 100-year time horizon.

[b] For a given amount of carbon dioxide emitted, some fraction of the atmospheric increase in concentration is quickly absorbed by the oceans and terrestrial vegetation, some fraction of the atmospheric increase will only slowly decrease over a number of years, and a small portion of the increase will remain for many centuries or more.

[c] The GWP of CH_4 includes the direct effects and those indirect effects due to the production of tropospheric ozone and stratospheric water vapor. The indirect effect due to the production of CO_2 is not included.

Source: (IPCC 2007)

Box 1-2: The *IPCC Fifth Assessment Report* and Global Warming Potentials

In 2014, the IPCC published its *Fifth Assessment Report* (AR5), which updated its comprehensive scientific assessment of climate change. Within the AR5 report, the GWP values of gases were revised relative to previous IPCC reports, namely the *IPCC Second Assessment Report* (SAR) (IPCC 1996), the *IPCC Third Assessment Report* (TAR) (IPCC 2001), and the *IPCC Fourth Assessment Report* (AR4) (IPCC 2007). Although the AR4 GWP values are used throughout this report, consistent with UNFCCC reporting requirements, it is straight-forward to review the changes to the GWP values and their impact on estimates of the total GWP-weighted emissions of the United States. In the AR5, the IPCC applied an improved calculation of CO_2 radiative forcing and an improved CO_2 response function in presenting updated GWP values. Additionally, the atmospheric lifetimes of some gases have been recalculated, and updated background concentrations were used. In addition, the values for radiative forcing and lifetimes have been recalculated for a variety of halocarbons, and the indirect effects of methane on ozone have been adjusted to match more recent science. Table 1-3 presents the new GWP values, relative to those presented in the AR4 and using the 100-year time horizon common to UNFCCC reporting.

For consistency with international reporting standards under the UNFCCC, official emission estimates are reported by the United States using AR4 GWP values, as required by the 2013 revision to the UNFCCC reporting guidelines for national inventories.[55] All estimates provided throughout this report are also presented in unweighted units. For informational purposes, emission estimates that use GWPs from other IPCC Assessment Reports are presented in detail in Annex 6.1 of this report.

Table 1-3: Comparison of 100-Year GWP values

Gas	SAR	AR4	AR5[a]	AR5 with feedbacks[b]	Comparison to AR4		
					SAR	AR5	AR5 with feedbacks[b]
CO_2	1	1	1	1	NC	NC	NC
CH_4[c]	21	25	28	34	(4)	3	9
N_2O	310	298	265	298	12	(33)	0
HFC-23	11,700	14,800	12,400	13,856	(3,100)	(2,400)	(944)
HFC-32	650	675	677	817	(25)	2	142
HFC-125	2,800	3,500	3,170	3,691	(700)	(330)	191
HFC-134a	1,300	1,430	1,300	1,549	(130)	(130)	119
HFC-143a	3,800	4,470	4,800	5,508	(670)	330	1,038
HFC-152a	140	124	138	167	16	14	43
HFC-227ea	2,900	3,220	3,350	3,860	(320)	130	640
HFC-236fa	6,300	9,810	8,060	8,998	(3,510)	(1,750)	(812)
HFC-4310mee	1,300	1,640	1,650	1,952	(340)	10	312
CF_4	6,500	7,390	6,630	7,349	(890)	(760)	(41)
C_2F_6	9,200	12,200	11,100	12,340	(3,000)	(1,100)	140
C_4F_{10}	7,000	8,860	9,200	10,213	(1,860)	340	1,353
C_6F_{14}	7,400	9,300	7,910	8,780	(1,900)	(1,390)	(520)
SF_6	23,900	22,800	23,500	26,087	1,100	700	3,287
NF_3	NA	17,200	16,100	17,885	NA	(1,100)	685

NA (Not Applicable)
NC (No Change)
[a] The GWPs presented here are the ones most consistent with the methodology used in the AR4 report.
[b] The GWP values presented here from the AR5 report include climate-carbon feedbacks for the non-CO_2 gases in order to be consistent with the approach used in calculating the CO_2 lifetime. Additionally, the AR5 reported separate values for fossil versus biogenic methane in order to account for the CO_2 oxidation product.
[c] The GWP of CH_4 includes the direct effects and those indirect effects due to the production of tropospheric ozone and stratospheric water vapor. The indirect effect due to the production of CO_2 is only included in the value from AR5 that includes climate-carbon feedbacks.
Note: Parentheses indicate negative values.
Source: (IPCC 2013, IPCC 2007, IPCC 2001, IPCC 1996).

1.2 National Inventory Arrangements

The U.S. Environmental Protection Agency (EPA), in cooperation with other U.S. government agencies, prepares the *Inventory of U.S. Greenhouse Gas Emissions and Sinks*. A wide range of agencies and individuals are involved in supplying data to, planning methodological approaches and improvements, reviewing, or preparing portions of the U.S. Inventory—including federal and state government authorities, research and academic institutions, industry associations, and private consultants.

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[55] See <http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf>.

Within EPA, the Office of Atmospheric Programs (OAP) is the lead office responsible for the emission calculations provided in the Inventory, as well as the completion of the National Inventory Report and the Common Reporting Format (CRF) tables. EPA's Office of Transportation and Air Quality (OTAQ) is also involved in calculating emissions for the Inventory. The U.S. Department of State serves as the overall focal point to the UNFCCC, and EPA's OAP serves as the National Inventory Focal Point for this report, including responding to technical questions and comments on the U.S. Inventory. The staff of EPA coordinate the annual methodological choice, activity data collection, and emission calculations at the individual source category level. EPA, the inventory coordinator, compiles the entire Inventory into the proper reporting format for submission to the UNFCCC, and is responsible for the collection and consistency of cross-cutting issues in the Inventory.

Several other government agencies contribute to the collection and analysis of the underlying activity data used in the Inventory calculations, in addition to the calculation of estimates integrated in the report (e.g., U.S. Department of Agriculture's U.S. Forest Service and Agricultural Service, National Oceanic and Atmospheric Administration, Federal Aviation Administration, and Department of Defense). Formal and informal relationships exist between EPA and other U.S. agencies that provide official data for use in the Inventory. The U.S. Department of Energy's Energy Information Administration provides national fuel consumption data and the U.S. Department of Defense provides military fuel consumption and bunker fuels. Informal relationships also exist with other U.S. agencies to provide activity data for use in EPA's emission calculations. These include: the U.S. Department of Agriculture, National Oceanic and Atmospheric Administration, the U.S. Geological Survey, the Federal Highway Administration, the Department of Transportation, the Bureau of Transportation Statistics, the Department of Commerce, and the Federal Aviation Administration. Academic and research centers also provide activity data and calculations to EPA, as well as individual companies participating in voluntary outreach efforts with EPA. Finally, EPA as the National Inventory Focal Point, in coordination with the U.S. Department of State, officially submits the Inventory to the UNFCCC each April. Figure 1-1 diagrams the National Inventory Arrangements.

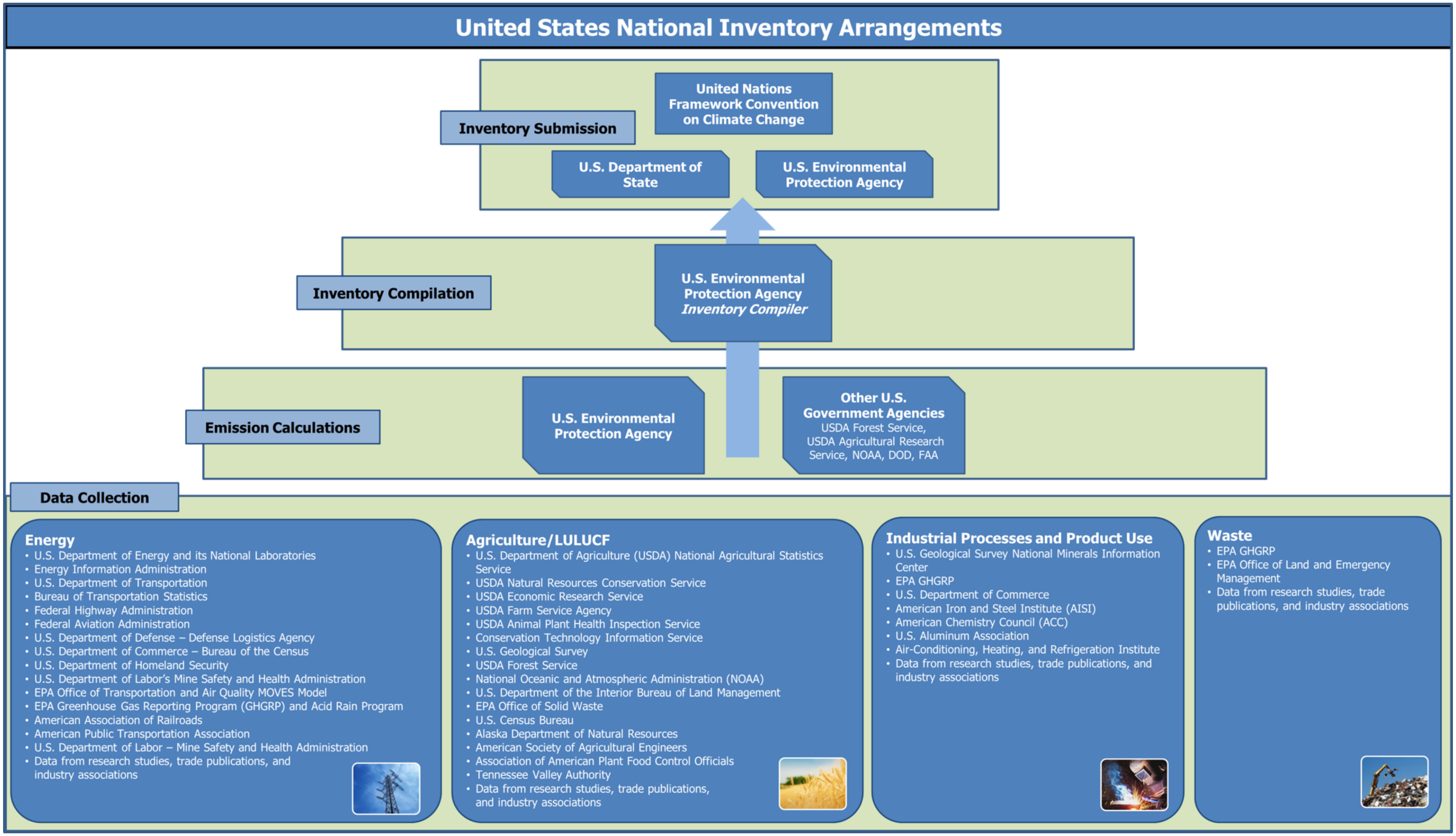

Figure 1-1: National Inventory Arrangements Diagram Inventory Process Inventory Process

United States National Inventory Arrangements

Inventory Submission

United Nations Framework Convention on Climate Change

U.S. Department of State

U.S. Environmental Protection Agency

Inventory Compilation

U.S. Environmental Protection Agency
Inventory Compiler

Emission Calculations

U.S. Environmental Protection Agency

Other U.S. Government Agencies
USDA Forest Service, USDA Agricultural Research Service, NOAA, DOD, FAA

Data Collection

Energy

- U.S. Department of Energy and its National Laboratories
- Energy Information Administration
- U.S. Department of Transportation
- Bureau of Transportation Statistics
- Federal Highway Administration
- Federal Aviation Administration
- U.S. Department of Defense – Defense Logistics Agency
- U.S. Department of Commerce – Bureau of the Census
- U.S. Department of Homeland Security
- U.S. Department of Labor's Mine Safety and Health Administration
- EPA Office of Transportation and Air Quality MOVES Model
- EPA Greenhouse Gas Reporting Program (GHGRP) and Acid Rain Program
- American Association of Railroads
- American Public Transportation Association
- U.S. Department of Labor – Mine Safety and Health Administration
- Data from research studies, trade publications, and industry associations

Agriculture/LULUCF

- U.S. Department of Agriculture (USDA) National Agricultural Statistics Service
- USDA Natural Resources Conservation Service
- USDA Economic Research Service
- USDA Farm Service Agency
- USDA Animal Plant Health Inspection Service
- Conservation Technology Information Service
- U.S. Geological Survey
- USDA Forest Service
- National Oceanic and Atmospheric Administration (NOAA)
- U.S. Department of the Interior Bureau of Land Management
- EPA Office of Solid Waste
- U.S. Census Bureau
- Alaska Department of Natural Resources
- American Society of Agricultural Engineers
- Association of American Plant Food Control Officials
- Tennessee Valley Authority
- Data from research studies, trade publications, and industry associations

Industrial Processes and Product Use

- U.S. Geological Survey National Minerals Information Center
- EPA GHGRP
- U.S. Department of Commerce
- American Iron and Steel Institute (AISI)
- American Chemistry Council (ACC)
- U.S. Aluminum Association
- Air-Conditioning, Heating, and Refrigeration Institute
- Data from research studies, trade publications, and industry associations

Waste

- EPA GHGRP
- EPA Office of Land and Emergency Management
- Data from research studies, trade publications, and industry associations

1.3 Inventory Process

This section describes EPA's approach to preparing the annual U.S. Inventory, which consists of a National Inventory Report (NIR) and Common Reporting Format (CRF) tables. The inventory coordinator at EPA, with support from the data/document manager is responsible for compiling all emission estimates and ensuring consistency and quality throughout the NIR and CRF tables. Emission calculations for individual sources are the responsibility of individual source leads, who are most familiar with each source category and the unique characteristics of its emissions profile. The individual source and sink category leads determine the most appropriate methodology and collect the best activity data to use in the emission calculations, based upon their expertise in the source or sink category, as well as coordinating with researchers and contractors familiar with the sources. A multi-stage process for collecting information from the individual source and and sink category leads and producing the Inventory is undertaken annually to compile all information and data.

Methodology Development, Data Collection, and Emissions and Sink Estimation

Source leads at EPA collect input data and, as necessary, evaluate or develop the estimation methodology for the individual source categories. Because EPA has been preparing the Inventory for many years, for most source and sink categories, the methodology for the previous year is applied to the new "current" year of the Inventory, and inventory analysts collect any new data or update data that have changed from the previous year. If estimates for a new source category are being developed for the first time, or if the methodology is changing for an existing source category (e.g., the United States is implementing a higher Tiered approach for that source category), then the source category lead will develop a new methodology, gather the most appropriate activity data and emission factors (or in some cases direct emission measurements) for the entire time series, and conduct a special source-specific review process involving relevant experts from industry, government, and universities (see Box ES-3: Improvements and Recalculations Relative to the Previous Inventory Box ES-3 on EPA's approach to recalculations).

Once the methodology is in place and the data are collected, the individual source and sink category leads calculate emission and removal estimates. The source leads then update or create the relevant text and accompanying annexes for the Inventory. Source and sink category leads are also responsible for completing the relevant sectoral background tables of the CRF, conducting quality assurance and quality control (QA/QC) checks, and uncertainty analyses.

The treatment of confidential business information (CBI) in the Inventory is based on EPA internal guidelines, as well as regulations[1] applicable to the data used. EPA has specific procedures in place to safeguard CBI during the inventory compilation process. When information derived from CBI data is used for development of inventory calculations, EPA procedures ensure that these confidential data are sufficiently aggregated to protect confidentiality while still providing useful information for analysis. For example, within the Energy and Industrial Processes and Product Use (IPPU) sectors, EPA has used aggregated facility-level data from the Greenhouse Gas Reporting Program (GHGRP) to develop, inform, and/or quality-assure U.S. emission estimates. In 2014, EPA's GHGRP, with industry engagement, compiled criteria that would be used for aggregating its confidential data to shield the underlying CBI from public disclosure.[2] In the Inventory, EPA is publishing only data values that meet the GHGRP aggregation criteria.[3] Specific uses of aggregated facility-level data are described in the respective methodological sections within those chapters. In addition, EPA uses historical data reported voluntarily to EPA via various

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[1] 40 CFR part 2, Subpart B titled "Confidentiality of Business Information" which is the regulation establishing rules governing handling of data entitled to confidentiality treatment. See <https://www.ecfr.gov/cgi-bin/text-idx?SID=a764235c9eadf9afe05fe04c07a28939&mc=true&node=sp40.1.2.b&rgn=div6>.

[2] Federal Register Notice on "Greenhouse Gas Reporting Program: Publication of Aggregated Greenhouse Gas Data." See pp, 79 and 110 of notice at <https://www.gpo.gov/fdsys/pkg/FR-2014-06-09/pdf/2014-13425.pdf>.

[3] U.S. EPA Greenhouse Gas Reporting Program. Developments on Publication of Aggregated Greenhouse Gas Data, November 25, 2014. See <http://www.epa.gov/ghgreporting/confidential-business-information-ghg-reporting>.

voluntary initiatives with U.S. industry (e.g., EPA Voluntary Aluminum Industrial Partnership (VAIP)) and follows guidelines established under the voluntary programs for managing CBI.

Summary Data Compilation and Storage

The inventory coordinator at EPA with support from the data/document manager collects the source and sink categories' descriptive text and Annexes, and also aggregates the emission estimates into a summary spreadsheet that links the individual source and sink category spreadsheets together. This summary sheet contains all of the essential data in one central location, in formats commonly used in the Inventory document. In addition to the data from each source and sink category, national trend and related data are also gathered in the summary sheet for use in the Executive Summary, Introduction, and Trends sections of the Inventory report. Electronic copies of each year's summary spreadsheet, which contains all the emission and sink estimates for the United States, are kept on a central server at EPA under the jurisdiction of the inventory coordinator.

National Inventory Report Preparation

The NIR is compiled from the sections developed by each individual source or sink category lead. In addition, the inventory coordinator prepares a brief overview of each chapter that summarizes the emissions from all sources discussed in the chapters. The inventory coordinator then carries out a key category analysis for the Inventory, consistent with the *2006 IPCC Guidelines for National Greenhouse Gas Inventories*, and in accordance with the reporting requirements of the UNFCCC. Also at this time, the Introduction, Executive Summary, and Trends in Greenhouse Gas Emissions chapters are drafted, to reflect the trends for the most recent year of the current Inventory. The analysis of trends necessitates gathering supplemental data, including weather and temperature conditions, economic activity and gross domestic product, population, atmospheric conditions, and the annual consumption of electricity, energy, and fossil fuels. Changes in these data are used to explain the trends observed in greenhouse gas emissions in the United States. Furthermore, specific factors that affect individual sectors are researched and discussed. Many of the factors that affect emissions are included in the Inventory document as separate analyses or side discussions in boxes within the text. Text boxes are also created to examine the data aggregated in different ways than in the remainder of the document, such as a focus on transportation activities or emissions from electricity generation. The document is prepared to match the specification of the UNFCCC reporting guidelines for National Inventory Reports.

Common Reporting Format Table Compilation

The CRF tables are compiled from individual tables completed by each individual source or sink category lead, which contain emissions and/or removals and activity data. The inventory coordinator integrates the category data into the UNFCCC's "CRF Reporter" for the United States, assuring consistency across all sectoral tables. The summary reports for emissions, methods, and emission factors used, the overview tables for completeness and quality of estimates, the recalculation tables, the notation key completion tables, and the emission trends tables are then completed by the inventory coordinator. Internal automated quality checks on the CRF Reporter, as well as reviews by the category leads, are completed for the entire time series of CRF tables before submission.

QA/QC and Uncertainty

QA/QC and uncertainty analyses are supervised by the QA/QC and uncertainty coordinators, who have general oversight over the implementation of the QA/QC plan and the overall uncertainty analysis for the Inventory in coordination with the Inventory coordinator (see sections on QA/QC and Uncertainty, below). These coordinators work closely with the Inventory coordinator and source and sink category leads to ensure that a consistent QA/QC plan and uncertainty analysis is implemented across all inventory sources. The inventory QA/QC plan, detailed in a following section, is consistent with the quality assurance procedures outlined by EPA and IPCC. The QA/QC and uncertainty findings also inform overall improvement planning, and specific improvements are noted in the Planned Improvements sections of respective categories. QA processes are outlined below.

Expert, Public, and UNFCCC Review Periods

During the 30-day Expert Review period, a first draft of sectoral chapters of the document are sent to a select list of technical experts outside of EPA who are not directly involved in preparing estimates. The purpose of the Expert Review is to provide an objective review, encourage feedback on the methodological and data sources used in the current Inventory, especially for sources which have experienced any changes since the previous Inventory.

Once comments are received and addressed, a second draft of the document is released for public review by publishing a notice in the U.S. Federal Register and posting the entire draft Inventory document on the EPA website. The Public Review period allows for a 30-day comment period and is open to the entire U.S. public. Comments may require further discussion with experts and/or additional research, and specific Inventory improvements requiring further analysis as a result of comments are noted in categories Planned Improvement sections. See those sections for specific details. EPA publishes comments received during both reviews with the publication of the final report on its website.

Following completion and submission of the report to the UNFCCC, the report also undergoes review by an independent international team of experts for adherence to UNFCCC reporting guidelines and IPCC Guidance.[4] Feedback from these review processes all contribute to improving inventory quality over time.

Final Submittal to UNFCCC and Document Printing

After the final revisions to incorporate any comments from the Expert Review and Public Review periods, EPA prepares the final National Inventory Report and the accompanying Common Reporting Format Reporter database. EPA as the National Inventory focal point and sends the official submission of the U.S. Inventory to the UNFCCC, coordinating with the U.S. Department of State. The document is then formatted and posted online, available for the public.[5]

1.4 Methodology and Data Sources

Emissions of greenhouse gases from various source and sink categories have been estimated using methodologies that are consistent with the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006). To a great extent, this report makes use of published official economic and physical statistics for activity data and emission factors. Depending on the emission source category, activity data can include fuel consumption or deliveries, vehicle-miles traveled, raw material processed, etc. Emission factors are factors that relate quantities of emissions to an activity. For more information on data sources see Section 1.2 above, Box 1-1 on use of GHGRP data, and categories' methodology sections for more information on data sources. In addition to official statistics, the report utilizes findings from academic studies, trade association surveys and statistical reports, along with expert judgment, consistent with the *2006 IPCC Guidelines*.

The methodologies provided in the *2006 IPCC Guidelines* represent foundational methodologies for a variety of source categories, and many of these methodologies continue to be improved and refined as new research and data become available. This report uses the IPCC methodologies when applicable, and supplements them with other available country-specific methodologies and data where possible. Choices made regarding the methodologies and data sources used are provided in conjunction with the discussion of each source category in the main body of the report. Complete documentation is provided in the annexes on the detailed methodologies and data sources utilized in the calculation of each source category.

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[4] See <http://unfccc.int/national_reports/annex_i_ghg_inventories/review_process/items/2762.php>.

[5] See <http://epa.gov/climatechange/ghgemissions/usinventoryreport.html>.

Box 1-3: IPCC Reference Approach

The UNFCCC reporting guidelines require countries to complete a "top-down" reference approach for estimating CO_2 emissions from fossil fuel combustion in addition to their “bottom-up” sectoral methodology. This estimation method uses alternative methodologies and different data sources than those contained in that section of the Energy chapter. The reference approach estimates fossil fuel consumption by adjusting national aggregate fuel production data for imports, exports, and stock changes rather than relying on end-user consumption surveys (see Annex 4 of this report). The reference approach assumes that once carbon-based fuels are brought into a national economy, they are either saved in some way (e.g., stored in products, kept in fuel stocks, or left unoxidized in ash) or combusted, and therefore the carbon in them is oxidized and released into the atmosphere. Accounting for actual consumption of fuels at the sectoral or sub-national level is not required.

1.5 Key Categories

The *2006 IPCC Guidelines* (IPCC 2006) defines a key category as a “[category] that is prioritized within the national inventory system because its estimate has a significant influence on a country’s total inventory of greenhouse gases in terms of the absolute level, the trend, or the uncertainty in emissions and removals.”[6] By definition, key categories include those categories that have the greatest contribution to the absolute level of national emissions. In addition, when an entire time series of emission and removal estimates is prepared, a thorough investigation of key categories must also account for the influence of trends and uncertainties of individual source and sink categories. This analysis can identify source and sink categories that diverge from the overall trend in national emissions. Finally, a qualitative evaluation of key categories is performed to capture any categories that were not identified in any of the quantitative analyses.

Approach 1, as defined in the *2006 IPCC Guidelines* (IPCC 2006), was implemented to identify the key categories for the United States. This analysis was performed twice; one analysis included sources and sinks from the Land Use, Land-Use Change, and Forestry (LULUCF) sector, the other analysis did not include the LULUCF categories. Following Approach 1, Approach 2, as defined in the *2006 IPCC Guidelines* (IPCC 2006), was then implemented to identify any additional key categories not already identified in Approach 1 assessment. This analysis, which includes each source category’s uncertainty assessments (or proxies) in its calculations, was also performed twice to include or exclude LULUCF categories.

In addition to conducting Approach 1 and 2 level and trend assessments, a qualitative assessment of the source categories, as described in the *2006 IPCC Guidelines* (IPCC 2006), was conducted to capture any key categories that were not identified by either quantitative method. For this inventory, no additional categories were identified using criteria recommend by IPCC, but EPA continues to update its qualitative assessment on an annual basis.

Table 1-4: Key Categories for the United States (1990-2016)

		Approach 1				Approach 2					
CRF Source Category	**Gas**	**Level Without LULUCF**	**Trend Without LULUCF**	**Level With LULUCF**	**Trend With LULUCF**	**Level Without LULUCF**	**Trend Without LULUCF**	**Level With LULUCF**	**Trend With LULUCF**	**Qual[a]**	2016 Emissions (MMT CO_2 Eq.)
Energy											
CO_2 Emissions from Mobile Combustion: Road	CO_2	•	•	•	•	•	•	•	•		1,496.0
CO_2 Emissions from Stationary Combustion - Coal -	CO_2	•	•	•	•	•	•	•	•		1,241.4

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[6] See Chapter 4 Volume 1, “Methodological Choice and Identification of Key Categories” in IPCC (2006). See <http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html>.

Electricity Generation											
CO_2 Emissions from Stationary Combustion - Gas - Electricity Generation	CO_2	•	•	•	•	•	•	•	•		546.0
CO_2 Emissions from Stationary Combustion - Gas - Industrial	CO_2	•	•	•	•	•	•	•	•		477.9
CO_2 Emissions from Stationary Combustion - Oil - Industrial	CO_2	•	•	•	•	•	•	•	•		272.5
CO_2 Emissions from Stationary Combustion - Gas - Residential	CO_2	•		•		•		•			238.3
CO_2 Emissions from Stationary Combustion - Gas - Commercial	CO_2	•	•	•	•	•	•	•			170.3
CO_2 Emissions from Mobile Combustion: Aviation	CO_2	•	•	•	•	•		•			167.4
CO_2 Emissions from Non-Energy Use of Fuels	CO_2	•	•	•	•	•	•	•			112.2
CO_2 Emissions from Mobile Combustion: Other	CO_2	•		•							80.2
CO_2 Emissions from Stationary Combustion - Oil - Commercial	CO_2	•	•	•	•						58.7
CO_2 Emissions from Stationary Combustion - Coal - Industrial	CO_2	•	•	•	•	•	•	•	•		58.7
CO_2 Emissions from Stationary Combustion - Oil - Residential	CO_2	•	•	•	•	•	•				54.2
CO_2 Emissions from Mobile Combustion: Marine	CO_2	•	•	•	•						39.0
CO_2 Emissions from Stationary Combustion - Oil - U.S. Territories	CO_2	•	•	•	•						34.3
CO_2 Emissions from Natural Gas Systems	CO_2	•		•							25.5
CO_2 Emissions from Petroleum Systems	CO_2		•	•	•	•	•		•		22.8
CO_2 Emissions from Stationary Combustion - Oil - Electricity Generation	CO_2	•	•	•	•	•	•		•		21.4
CO_2 Emissions from Stationary	CO_2						•				3.0

Combustion - Gas - U.S. Territories											
CO_2 Emissions from Stationary Combustion - Coal - Commercial	CO_2		•		•						2.2
CO_2 Emissions from Stationary Combustion - Coal - Residential	CO_2						•				0.0
CH_4 Emissions from Natural Gas Systems	CH_4	•	•	•	•	•	•	•	•		163.5
Fugitive Emissions from Coal Mining	CH_4	•	•	•	•	•	•	•	•		53.8
CH_4 Emissions from Petroleum Systems	CH_4	•		•		•		•			38.6
CH_4 Emissions from Abandoned Oil and Gas Wells	CH_4					•		•			7.1
Non-CO_2 Emissions from Stationary Combustion - Residential	CH_4					•	•	•	•		3.4
CH_4 Emissions from Mobile Combustion: Other	CH_4						•				2.1
Non-CO_2 Emissions from Stationary Combustion - Electricity Generation	N_2O		•		•	•	•				14.9
N_2O Emissions from Mobile Combustion: Road	N_2O	•	•	•	•	•	•				13.2
Non-CO_2 Emissions from Stationary Combustion - Industrial	N_2O					•					2.5
International Bunker Fuels[b]	Several									•	117.7
Industrial Processes and Product Use											
CO_2 Emissions from Iron and Steel Production & Metallurgical Coke Production	CO_2	•	•	•	•	•	•	•	•		42.3
CO_2 Emissions from Cement Production	CO_2	•		•							39.4
CO_2 Emissions from Petrochemical Production	CO_2	•	•	•	•						28.1
N_2O Emissions from Adipic Acid Production	N_2O		•		•						7.0
Emissions from Substitutes for Ozone Depleting Substances	HiGWP	•	•	•	•	•	•	•	•		159.1
SF_6 Emissions from Electrical Transmission and Distribution	HiGWP		•		•		•				4.3

HFC-23 Emissions from HCFC-22 Production	HiGWP	•	•	•	•		•		•		2.8
PFC Emissions from Aluminum Production	HiGWP		•		•		•				1.4
Agriculture											
CH_4 Emissions from Enteric Fermentation	CH_4	•		•		•		•			170.1
CH_4 Emissions from Manure Management	CH_4	•	•	•	•	•	•	•	•		67.7
CH_4 Emissions from Rice Cultivation	CH_4					•	•				13.7
Direct N_2O Emissions from Agricultural Soil Management	N_2O	•	•	•	•	•	•	•			237.6
Indirect N_2O Emissions from Applied Nitrogen	N_2O	•	•	•	•	•	•	•	•		45.9
Waste											
CH_4 Emissions from Landfills	CH_4	•	•	•	•	•	•	•	•		107.7
Land Use, Land Use Change, and Forestry											
Net CO_2 Emissions from Land Converted to Settlements	CO_2			•	•			•	•		68.0
Net CO_2 Emissions from Land Converted to Cropland	CO_2			•	•			•	•		23.8
Net CO_2 Emissions from Land Converted to Grassland	CO_2							•	•		22.0
Net CO_2 Emissions from Grassland Remaining Grassland	CO_2							•	•		(1.6)
Net CO_2 Emissions from Cropland Remaining Cropland	CO_2			•	•			•	•		(9.9)
Net CO_2 Emissions from Land Converted to Forest Land	CO_2			•	•						(75.0)
Net CO_2 Emissions from Settlements Remaining Settlements	CO_2			•	•			•	•		(103.7)
Net CO_2 Emissions from Forest Land Remaining Forest Land	CO_2			•	•			•	•		(670.5)
CH_4 Emissions from Forest Fires	CH_4				•			•	•		18.5
N_2O Emissions from Forest Fires	N_2O				•			•	•		12.2
Subtotal Without LULUCF											**6,348.5**
Total Emissions Without LULUCF											**6,511.3**
Percent of Total Without LULUCF											**97%**
Subtotal With LULUCF											**5,610.8**
Total Emissions With LULUCF											**5,794.5**
Percent of Total With LULUCF											**97%**

[a] Qualitative criteria.
[b] Emissions from this source not included in totals.
Note: Parentheses indicate negative values (or sequestration).

1.6 Quality Assurance and Quality Control (QA/QC)

As part of efforts to achieve its stated goals for inventory quality, transparency, and credibility, the United States has developed a quality assurance and quality control plan designed to check, document and improve the quality of its inventory over time. QA/QC activities on the Inventory are undertaken within the framework of the U.S. *Quality Assurance/Quality Control and Uncertainty Management Plan* (QA/QC plan) *for the U.S. Greenhouse Gas Inventory: Procedures Manual for QA/QC and Uncertainty Analysis*.

Key attributes of the QA/QC plan are summarized in Figure 1-2. These attributes include:

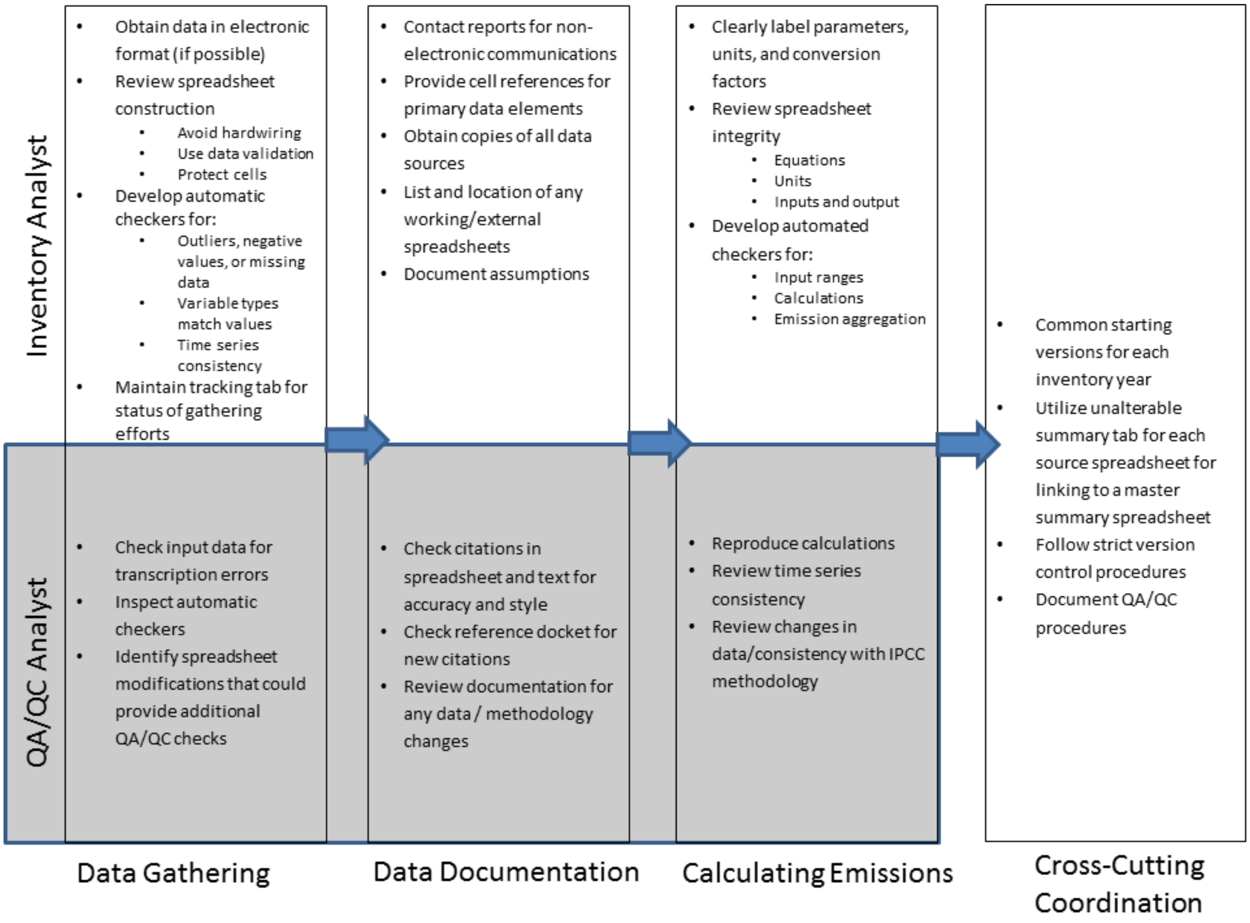
- *Procedures and Forms:* detailed and specific systems that serve to standardize the process of documenting and archiving information, as well as to guide the implementation of QA/QC and the analysis of uncertainty
- *Implementation of Procedures:* application of QA/QC procedures throughout the whole inventory development process from initial data collection, through preparation of the emission estimates, to publication of the Inventory
- *Quality Assurance:* expert and public reviews for both the inventory estimates and the Inventory report (which is the primary vehicle for disseminating the results of the inventory development process). The expert technical review conducted by the UNFCCC supplements these QA processes, consistent with the *2006 IPCC Guidelines* (IPCC 2006)
- *Quality Control*: consideration of secondary data and category-specific checks (Tier 2 QC) in parallel and coordination with the uncertainty assessment; the development of protocols and templates, which provides for more structured communication and integration with the suppliers of secondary information
- *General (Tier 1) and Category-specific (Tier 2) Checks:* quality controls and checks, as recommended by *IPCC Good Practice Guidance* and *2006 IPCC Guidelines* (IPCC 2006)
- *Record Keeping:* provisions to track which procedures have been followed, the results of the QA/QC, uncertainty analysis, and feedback mechanisms for corrective action based on the results of the investigations which provide for continual data quality improvement and guided research efforts
- *Multi-Year Implementation*: a schedule for coordinating the application of QA/QC procedures across multiple years, especially for category-specific QC, prioritizing key categories
- *Interaction and Coordination:* promoting communication within the EPA, across Federal agencies and departments, state government programs, and research institutions and consulting firms involved in supplying data or preparing estimates for the Inventory. The QA/QC Management Plan itself is intended to be revised and reflect new information that becomes available as the program develops, methods are improved, or additional supporting documents become necessary.

In addition, based on the national QA/QC plan for the Inventory, source-specific QA/QC plans have been developed for a number of sources. These plans follow the procedures outlined in the national QA/QC plan, tailoring the procedures to the specific text and spreadsheets of the individual sources. For each greenhouse gas emissions source or sink included in this Inventory, a minimum of general or Tier 1 QA/QC analysis has been undertaken. Where QA/QC activities for a particular category go beyond the minimum Tier 1 level, and include category-specific checks (Tier 2), further explanation is provided within the respective source category text. Similarly, responses or updates based on comments from the expert, public and the international technical expert reviews (e.g., UNFCCC) are also addressed within the respective source category sections in each chapter.

The quality control activities described in the U.S. QA/QC plan occur throughout the inventory process; QA/QC is not separate from, but is an integral part of, preparing the Inventory. Quality control—in the form of both good practices (such as documentation procedures) and checks on whether good practices and procedures are being followed—is applied at every stage of inventory development and document preparation. In addition, quality assurance occurs during the expert review and the public review, in addition to the UNFCCC expert technical review. While all phases significantly contribute to improving inventory quality, the public review phase is also essential for promoting the openness of the inventory development process and the transparency of the inventory data and methods.

The QA/QC plan guides the process of ensuring inventory quality by describing data and methodology checks, developing processes governing peer review and public comments, and developing guidance on conducting an analysis of the uncertainty surrounding the emission estimates. The QA/QC procedures also include feedback loops and provide for corrective actions that are designed to improve the inventory estimates over time.

Figure 1-2: U.S. QA/QC Plan Summary



1.7 Uncertainty Analysis of Emission Estimates

Uncertainty estimates are an essential element of a complete and transparent emissions inventory. Uncertainty information is not intended to dispute the validity of the Inventory estimates, but to help prioritize efforts to improve the accuracy of future Inventories and guide future decisions on methodological choice. While the U.S. Inventory calculates its emission estimates with the highest possible accuracy, uncertainties are associated to a varying degree with the development of emission estimates for any inventory. Some of the current estimates, such as those for CO_2

emissions from energy-related activities, are considered to have minimal uncertainty associated with them. For some other limited categories of emissions, however, a lack of data or an incomplete understanding of how emissions are generated increases the uncertainty or systematic error associated with the estimates presented. The UNFCCC reporting guidelines follow the recommendation in the *2006 IPCC Guidelines* (IPCC 2006) and require that countries provide single point estimates for each gas and emission or removal source category. Within the discussion of each emission source, specific factors affecting the uncertainty associated with the estimates are discussed.

Additional research in the following areas could help reduce uncertainty in the U.S. Inventory:

- *Incorporating excluded emission sources*. Quantitative estimates for some of the sources and sinks of greenhouse gas emissions are not available at this time. In particular, emissions from some land-use activities (e.g., emissions and removals from interior Alaska) and industrial processes are not included in the inventory either because data are incomplete or because methodologies do not exist for estimating emissions from these source categories. See Annex 5 of this report for a discussion of the sources of greenhouse gas emissions and sinks excluded from this report.
- *Improving the accuracy of emission factors*. Further research is needed in some cases to improve the accuracy of emission factors used to calculate emissions from a variety of sources. For example, the accuracy of current emission factors applied to CH_4 and N_2O emissions from stationary and mobile combustion is highly uncertain.
- *Collecting detailed activity data*. Although methodologies exist for estimating emissions for some sources, problems arise in obtaining activity data at a level of detail where more technology or process-specific emission factors can be applied.

The overall uncertainty estimate for total U.S. greenhouse gas emissions was developed using the IPCC Approach 2 uncertainty estimation methodology. Estimates of quantitative uncertainty for the total U.S. greenhouse gas emissions are shown below, in Table 1-5.

The IPCC provides good practice guidance on two approaches—Approach 1 and Approach 2—to estimating uncertainty for individual source categories. Approach 2 uncertainty analysis, employing the Monte Carlo Stochastic Simulation technique, was applied wherever data and resources permitted; further explanation is provided within the respective source category text and in Annex 7. Consistent with the *2006 IPCC Guidelines* (IPCC 2006), over a multi-year timeframe, the United States expects to continue to improve the uncertainty estimates presented in this report.

Table 1-5: Estimated Overall Inventory Quantitative Uncertainty (MMT CO_2 Eq. and Percent)

Gas	**2016 Emission Estimate (MMT CO_2 Eq.)**	**Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)**		**(%)**		**Mean[b] (MMT CO_2 Eq.)**	**Standard Deviation[b] (MMT CO_2 Eq.)**
		Lower Bound[c]	**Upper Bound[c]**	**Lower Bound**	**Upper Bound**		
CO_2	5,310.9	5,211.4	5,555.2	-2%	5%	5,379.4	88.4
CH_4[d]	657.4	637.0	780.8	-3%	19%	699.0	36.3
N_2O[d]	369.5	321.7	451.8	-13%	22%	375.1	33.4
PFC, HFC, SF_6, and NF_3[d]	173.5	168.4	192.1	-3%	11%	180.3	6.1
Total	**6,511.3**	**6,439.6**	**6,835.2**	**-1%**	**5%**	**6,633.8**	**101.2**
LULUCF Emissions[e]	**38.1**	**22.8**	**65.7**	**-40%**	**73%**	**38.4**	**11.2**
LULUCF Total Net Flux[f]	**(754.9)**	**(979.5)**	**(598.2)**	**-30%**	**21%**	**(790.5)**	**96.9**
LULUCF Sector Total[g]	**(716.8)**	**(940.3)**	**(560.5)**	**-31%**	**22%**	**(752.0)**	**97.4**
Net Emissions (Sources and Sinks)	**5,794.5**	**5,607.0**	**6,155.0**	**-3%**	**6%**	**5,881.8**	**140.9**

Notes: Total emissions (excluding emissions for which uncertainty was not quantified) is presented without LULUCF. Net emissions is presented with LULUCF.

[a] The lower and upper bounds for emission estimates correspond to a 95 percent confidence interval, with the lower bound corresponding to 2.5th percentile and the upper bound corresponding to 97.5th percentile.

[b] Mean value indicates the arithmetic average of the simulated emission estimates; standard deviation indicates the extent of deviation of the simulated values from the mean.

[c] The lower and upper bound emission estimates for the sub-source categories do not sum to total emissions because the low and high estimates for total emissions were calculated separately through simulations.

[d] The overall uncertainty estimates did not take into account the uncertainty in the GWP values for CH_4, N_2O and high GWP gases used in the Inventory emission calculations for 2016.

[e] LULUCF emissions include the CH_4 and N_2O emissions reported for Non-CO_2 Emissions from Forest Fires, Emissions from Drained Organic Soils, N_2O Fluxes from Forest Soils, Non-CO_2 Emissions from Grassland Fires, N_2O Fluxes from Settlement Soils, Coastal Wetlands Remaining Coastal Wetlands, Peatlands Remaining Peatlands, and CH_4 Emissions from Land Converted to Coastal Wetlands.

[f] Net CO_2 flux is the net C stock change from the following categories: *Forest Land Remaining Forest Land*, *Land Converted to Forest Land*, *Cropland Remaining Cropland*, *Land Converted to Cropland*, *Grassland Remaining Grassland*, *Land Converted to Grassland*, *Changes in Organic Soils Carbon Stocks*, *Changes in Urban Tree Carbon Stocks*, *Changes in Yard Trimmings and Food Scrap Carbon Stocks in Landfills*, *Land Converted to Settlements*, *Wetlands Remaining Wetlands*, and *Land Converted to Wetlands*.

[g] The LULUCF Sector Total is the net sum of all emissions (i.e., sources) of greenhouse gases to the atmosphere plus removals of CO_2 (i.e., sinks or negative emissions) from the atmosphere.

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Emissions calculated for the U.S. Inventory reflect current best estimates; in some cases, however, estimates are based on approximate methodologies, assumptions, and incomplete data. As new information becomes available in the future, the United States will continue to improve and revise its emission estimates. See Annex 7 of this report for further details on the U.S. process for estimating uncertainty associated with the emission estimates and for a more detailed discussion of the limitations of the current analysis and plans for improvement. Annex 7 also includes details on the uncertainty analysis performed for selected source categories.

1.8 Completeness

This report, along with its accompanying CRF tables, serves as a thorough assessment of the anthropogenic sources and sinks of greenhouse gas emissions for the United States for the time series 1990 through 2016. This report is intended to be comprehensive and includes the vast majority of emissions and removals identified as anthropogenic, consistent with IPCC and UNFCCC guidelines. In general, sources or sink categories not accounted for in this Inventory are excluded because they are not occurring in the United States, or because data are unavailable to develop an estimate and/or the categories were determined to be insignificant[7] in terms of overall national emissions per UNFCCC reporting guidelines.

The United States is continually working to improve upon the understanding of such sources and sinks and seeking to find the data required to estimate related emissions and removals. As such improvements are implemented, new emission and removal estimates are quantified and included in the Inventory, focusing on categories that are significant. For a list of sources and sink categories not included and more information on significance of these categories, see Annex 5 and the respective category sections in each chapter of this report.

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[7] See paragraph 32 of Decision 24/CP.19, the UNFCCC reporting guidelines on annual inventories for Parties included in Annex 1 to the Convention. Paragraph notes that "…An emission should only be considered insignificant if the likely level of emissions is below 0.05 per cent of the national total GHG emissions, and does not exceed 500 kt CO_2 Eq. The total national aggregate of estimated emissions for all gases and categories considered insignificant shall remain below 0.1 percent of the national total GHG emissions."

1.9 Organization of Report

In accordance with the revision of the UNFCCC reporting guidelines agreed to at the nineteenth Conference of the Parties (UNFCCC 2014), this *Inventory of U.S. Greenhouse Gas Emissions and Sinks* is segregated into five sector-specific chapters consistent with the UN Common Reporting Framework, listed below in Table 1-6. In addition, chapters on Trends in Greenhouse Gas Emissions and Other information to be considered as part of the U.S. Inventory submission are included.

Table 1-6: IPCC Sector Descriptions

Chapter/IPCC Sector	Activities Included
Energy	Emissions of all greenhouse gases resulting from stationary and mobile energy activities including fuel combustion and fugitive fuel emissions, and non-energy use of fossil fuels.
Industrial Processes and Product Use	Emissions resulting from industrial processes and product use of greenhouse gases.
Agriculture	Emissions from agricultural activities except fuel combustion, which is addressed under Energy.
Land Use, Land-Use Change, and Forestry	Emissions and removals of CO_2, and emissions of CH_4, and N_2O from land use, land-use change and forestry.
Waste	Emissions from waste management activities.

Within each chapter, emissions are identified by the anthropogenic activity that is the source or sink of the greenhouse gas emissions being estimated (e.g., coal mining). Overall, the following organizational structure is consistently applied throughout this report:

Chapter/IPCC Sector: Overview of emission trends for each IPCC defined sector.

CRF Source or Category: Description of category pathway and emission/removal trends based on IPCC methodologies, consistent with UNFCCC reporting guidelines.

Methodology: Description of analytical methods (e.g. from *2006 IPCC Guidelines*, or country-specific methods) employed to produce emission estimates and identification of data references, primarily for activity data and emission factors.

Uncertainty and Time Series Consistency: A discussion and quantification of the uncertainty in emission estimates and a discussion of time-series consistency.

QA/QC and Verification: A discussion on steps taken to QA/QC and verify the emission estimates, consistent with the U.S. QA/QC plan, and any key findings.

Recalculations: A discussion of any data or methodological changes that necessitate a recalculation of previous years' emission estimates, and the impact of the recalculation on the emission estimates, if applicable.

Planned Improvements: A discussion on any category-specific planned improvements, if applicable.

Special attention is given to CO_2 from fossil fuel combustion relative to other sources because of its share of emissions and its dominant influence on emission trends. For example, each energy consuming end-use sector (i.e., residential, commercial, industrial, and transportation), as well as the electricity generation sector, is described individually. Additional information for certain source categories and other topics is also provided in several Annexes listed in Table 1-7.

Table 1-7: List of Annexes

ANNEX 1 Key Category Analysis
ANNEX 2 Methodology and Data for Estimating CO_2 Emissions from Fossil Fuel Combustion
2.1. Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion
2.2. Methodology for Estimating the Carbon Content of Fossil Fuels
2.3. Methodology for Estimating Carbon Emitted from Non-Energy Uses of Fossil Fuels
ANNEX 3 Methodological Descriptions for Additional Source or Sink Categories
3.1. Methodology for Estimating Emissions of CH_4, N_2O, and Indirect Greenhouse Gases from Stationary

Combustion
3.2. Methodology for Estimating Emissions of CH_4, N_2O, and Indirect Greenhouse Gases from Mobile Combustion and Methodology for and Supplemental Information on Transportation-Related Greenhouse Gas Emissions
3.3. Methodology for Estimating Emissions from Commercial Aircraft Jet Fuel Consumption
3.4. Methodology for Estimating CH_4 Emissions from Coal Mining
3.5. Methodology for Estimating CH_4 and CO_2 Emissions from Petroleum Systems
3.6. Methodology for Estimating CH_4 Emissions from Natural Gas Systems
3.7. Methodology for Estimating CO_2 and N_2O Emissions from Incineration of Waste
3.8. Methodology for Estimating Emissions from International Bunker Fuels used by the U.S. Military
3.9. Methodology for Estimating HFC and PFC Emissions from Substitution of Ozone Depleting Substances
3.10. Methodology for Estimating CH_4 Emissions from Enteric Fermentation
3.11. Methodology for Estimating CH_4 and N_2O Emissions from Manure Management
3.12. Methodology for Estimating N_2O Emissions, CH_4 Emissions and Soil Organic C Stock Changes from Agricultural Lands (Cropland and Grassland)
3.13. Methodology for Estimating Net Carbon Stock Changes in *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*
3.14. Methodology for Estimating CH_4 Emissions from Landfills
ANNEX 4 IPCC Reference Approach for Estimating CO_2 Emissions from Fossil Fuel Combustion
ANNEX 5 Assessment of the Sources and Sinks of Greenhouse Gas Emissions Not Included
ANNEX 6 Additional Information
6.1. Global Warming Potential Values
6.2. Ozone Depleting Substance Emissions
6.3. Sulfur Dioxide Emissions
6.4. Complete List of Source Categories
6.5. Constants, Units, and Conversions
6.6. Abbreviations
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ANNEX 7 Uncertainty
7.1. Overview
7.2. Methodology and Results
7.3. Reducing Uncertainty
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7.5. Additional Information on Uncertainty Analyses by Source
ANNEX 8 QA/QC Procedures
8.1. Background
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8.3. Assessment Factors
8.4. Responses During the Review Process

2. Trends in Greenhouse Gas Emissions

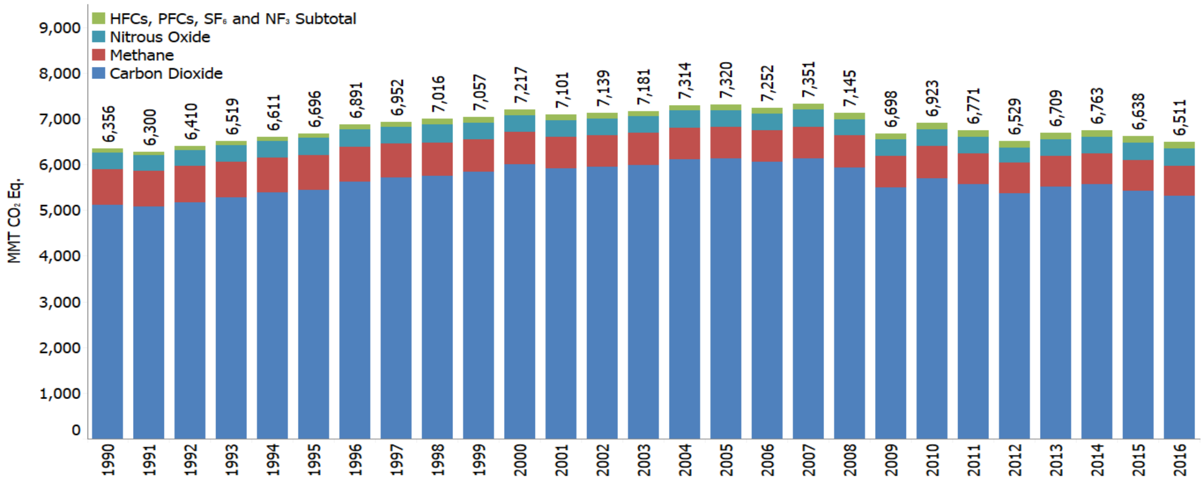
2.1 Recent Trends in U.S. Greenhouse Gas Emissions and Sinks

In 2016, total gross U.S. greenhouse gas emissions were 6,511.3 MMT, or million metric tons, carbon dioxide (CO_2) Eq.[1] Total U.S. emissions have increased by 2.4 percent from 1990 to 2016, and emissions decreased from 2015 to 2016 by 1.9 percent (126.8 MMT CO_2 Eq.). The decrease in total greenhouse gas emissions between 2015 and 2016 was driven in large part by a decrease in CO_2 emissions from fossil fuel combustion. The decrease in CO_2 emissions from fossil fuel combustion was a result of multiple factors, including:

(1) substitution from coal to natural gas and other non-fossil energy sources in the electric power sector; and
(2) warmer winter conditions in 2016 resulting in a decreased demand for heating fuel in the residential and commercial sectors.

Since 1990, U.S. emissions have increased at an average annual rate of 0.1 percent. Figure 2-1 through Figure 2-3 illustrate the overall trend in total U.S. emissions by gas, annual changes, and absolute changes since 1990. Overall, net emissions in 2016 were 12.1 percent below 2005 levels as shown in Table 2-1.

Figure 2-1: Gross U.S. Greenhouse Gas Emissions by Gas (MMT CO_2 Eq.)



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[1] The gross emissions total presented in this report for the United States excludes emissions and removals from Land Use, Land-Use Change, and Forestry (LULUCF). The net emissions total presented in this report for the United States includes emissions and removals from LULUCF.

Figure 2-2: Annual Percent Change in Gross U.S. Greenhouse Gas Emissions Relative to the Previous Year

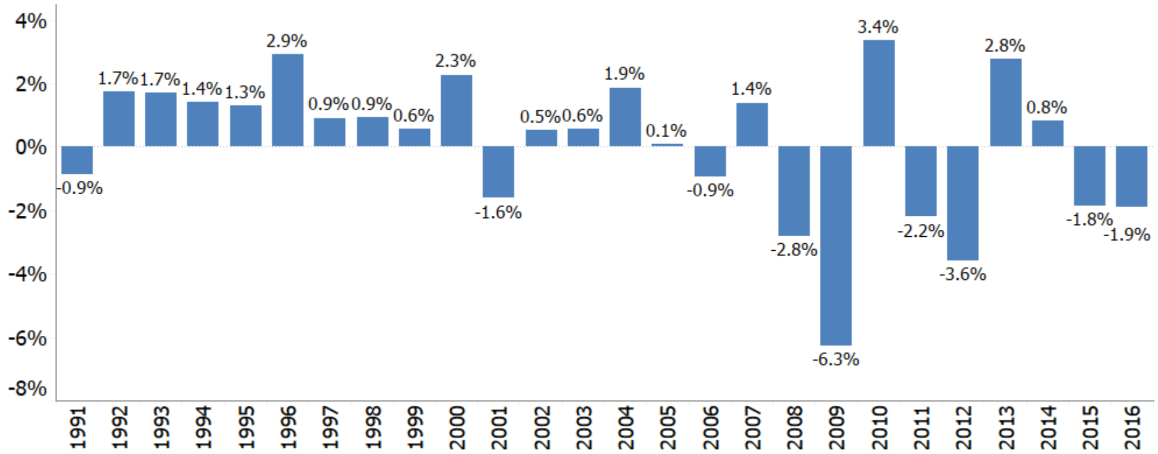
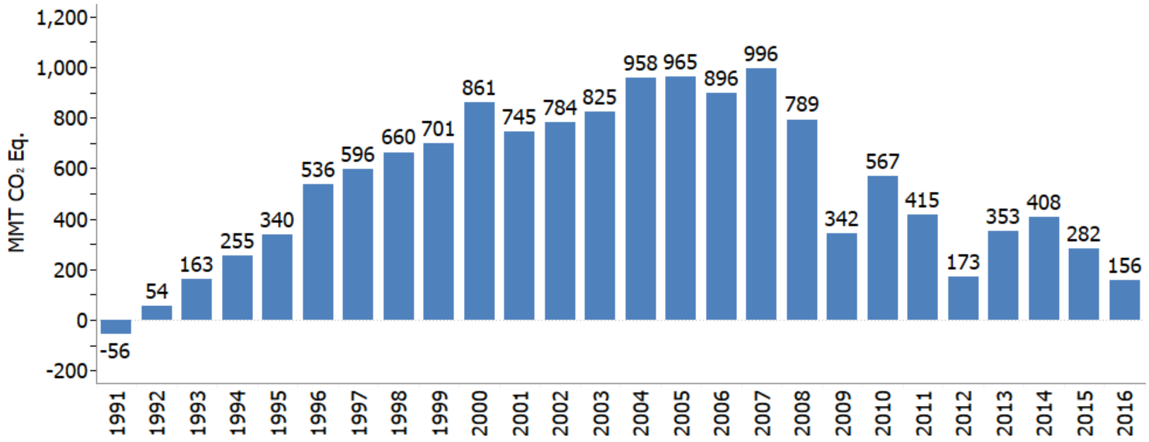


Figure 2-3: Cumulative Change in Annual Gross U.S. Greenhouse Gas Emissions Relative to 1990 (1990=0, MMT CO_2 Eq.)



Overall, from 1990 to 2016, total emissions of CO_2 increased by 189.6 MMT CO_2 Eq. (3.7 percent), while total emissions of methane (CH_4) decreased by 122.5 MMT CO_2 Eq. (15.7 percent), and total emissions of nitrous oxide (N_2O) increased by 14.8 MMT CO_2 Eq. (4.2 percent). During the same period, aggregate weighted emissions of hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6), and nitrogen trifluoride (NF_3) rose by 73.8 MMT CO_2 Eq. (74.0 percent). Despite being emitted in smaller quantities relative to the other principal greenhouse gases, emissions of HFCs, PFCs, SF_6, and NF_3 are significant because many of them have extremely high global warming potentials (GWPs), and, in the cases of PFCs, SF_6, and NF_3, long atmospheric lifetimes. Conversely, U.S. greenhouse gas emissions were partly offset by carbon (C) sequestration in managed forests, trees in urban areas, agricultural soils, landfilled yard trimmings, and coastal wetlands. These were estimated to offset 11.5 percent of total emissions in 2016.

Table 2-1 summarizes emissions and sinks from all U.S. anthropogenic sources in weighted units of MMT CO_2 Eq., while unweighted gas emissions and sinks in kilotons (kt) are provided in Table 2-2.

Table 2-1: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks (MMT CO_2 Eq.)

Gas/Source	1990	2005	2012	2013	2014	2015	2016
CO_2	**5,121.3**	**6,132.0**	**5,366.7**	**5,519.6**	**5,568.8**	**5,420.8**	**5,310.9**
Fossil Fuel Combustion	4,740.3	5,746.9	5,024.4	5,156.9	5,200.3	5,049.3	4,966.0
Electric Power	*1,820.8*	*2,400.9*	*2,022.2*	*2,038.1*	*2,038.0*	*1,900.7*	*1,809.3*
Transportation	*1,467.6*	*1,855.8*	*1,661.9*	*1,677.6*	*1,717.1*	*1,735.5*	*1,782.6*
Industrial	*858.8*	*855.7*	*812.9*	*843.3*	*824.9*	*809.5*	*809.1*
Residential	*338.3*	*357.8*	*282.5*	*329.7*	*345.3*	*316.8*	*292.5*
Commercial	*227.2*	*227.0*	*201.3*	*225.7*	*233.6*	*245.4*	*231.3*
U.S. Territories	*27.6*	*49.7*	*43.5*	*42.5*	*41.4*	*41.4*	*41.4*
Non-Energy Use of Fuels	119.5	138.9	108.0	123.5	118.9	125.6	112.2
Iron and Steel Production & Metallurgical Coke Production	101.6	68.2	55.6	53.5	58.4	47.8	42.3
Cement Production	33.5	46.2	35.3	36.4	39.4	39.9	39.4
Petrochemical Production	21.2	26.8	26.5	26.4	26.5	28.1	28.1
Natural Gas Systems	29.8	22.5	23.3	24.8	25.3	24.9	25.5
Petroleum Systems	7.7	11.7	19.3	22.6	26.3	28.8	22.8
Lime Production	11.7	14.6	13.8	14.0	14.2	13.3	12.9
Ammonia Production	13.0	9.2	9.4	10.0	9.6	10.9	12.2
Other Process Uses of Carbonates	6.3	7.6	9.1	11.5	13.0	12.3	11.0
Incineration of Waste	8.0	12.5	10.4	10.4	10.6	10.7	10.7
Urea Fertilization	2.4	3.5	4.3	4.4	4.5	4.9	5.1
Carbon Dioxide Consumption	1.5	1.4	4.0	4.2	4.5	4.5	4.5
Urea Consumption for Non-Agricultural Purposes	3.8	3.7	4.4	4.1	1.5	4.2	4.0
Liming	4.7	4.3	6.0	3.9	3.6	3.8	3.9
Ferroalloy Production	2.2	1.4	1.9	1.8	1.9	2.0	1.8
Soda Ash Production	1.4	1.7	1.7	1.7	1.7	1.7	1.7
Titanium Dioxide Production	1.2	1.8	1.5	1.7	1.7	1.6	1.6
Aluminum Production	6.8	4.1	3.4	3.3	2.8	2.8	1.3
Glass Production	1.5	1.9	1.2	1.3	1.3	1.3	1.2
Phosphoric Acid Production	1.5	1.3	1.1	1.1	1.0	1.0	1.0
Zinc Production	0.6	1.0	1.5	1.4	1.0	0.9	0.9
Lead Production	0.5	0.6	0.5	0.5	0.5	0.5	0.5
Silicon Carbide Production and Consumption	0.4	0.2	0.2	0.2	0.2	0.2	0.2
Abandoned Oil and Gas Wells	+	+	+	+	+	+	+
Magnesium Production and Processing	+	+	+	+	+	+	+
Wood Biomass, Ethanol, and Biodiesel Consumption[a]	*219.4*	*230.7*	*287.7*	*316.4*	*324.3*	*310.4*	*309.3*
International Bunker Fuels[b]	*103.5*	*113.1*	*105.8*	*99.8*	*103.4*	*110.9*	*116.6*
CH_4[c]	**779.9**	**688.6**	**662.5**	**662.6**	**664.0**	**665.4**	**657.4**
Enteric Fermentation	164.2	168.9	166.7	165.5	164.2	166.5	170.1
Natural Gas Systems	195.2	169.1	159.6	163.8	164.3	166.3	163.5
Landfills	179.6	132.7	117.0	113.3	112.7	111.7	107.7
Manure Management	37.2	56.3	65.6	63.3	62.9	66.3	67.7
Coal Mining	96.5	64.1	66.5	64.6	64.6	61.2	53.8
Petroleum Systems	39.8	32.1	32.7	36.6	38.6	38.1	38.6
Wastewater Treatment	15.7	15.8	15.1	14.9	15.0	15.1	14.8
Rice Cultivation	16.0	16.7	11.3	11.5	12.7	12.3	13.7
Stationary Combustion	8.6	7.8	7.4	8.8	8.9	7.9	7.3
Abandoned Oil and Gas Wells	6.5	6.9	7.0	7.0	7.1	7.2	7.1
Abandoned Underground Coal Mines	7.2	6.6	6.2	6.2	6.3	6.4	6.7
Mobile Combustion	12.7	9.4	5.1	4.7	4.2	3.8	3.6
Composting	0.4	1.9	1.9	2.0	2.1	2.1	2.1

Field Burning of Agricultural Residues	0.2	0.2	0.3	0.3	0.3	0.3	0.3
Petrochemical Production	0.2	0.1	0.1	0.1	0.1	0.2	0.2
Ferroalloy Production	+	+	+	+	+	+	+
Silicon Carbide Production and Consumption	+	+	+	+	+	+	+
Iron and Steel Production & Metallurgical Coke Production	+	+	+	+	+	+	+
Incineration of Waste	+	+	+	+	+	+	+
International Bunker Fuels[b]	*0.2*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*
N_2O[c]	**354.8**	**357.8**	**335.8**	**363.2**	**361.2**	**379.6**	**369.5**
Agricultural Soil Management	250.5	253.5	247.9	276.6	274.0	295.0	283.6
Stationary Combustion	11.1	17.5	16.9	18.7	19.0	18.1	18.6
Mobile Combustion	41.7	38.8	24.3	22.5	20.6	19.3	18.4
Manure Management	14.0	16.5	17.5	17.5	17.5	17.7	18.1
Nitric Acid Production	12.1	11.3	10.5	10.7	10.9	11.6	10.2
Adipic Acid Production	15.2	7.1	5.5	3.9	5.4	4.3	7.0
Wastewater Treatment	3.4	4.4	4.6	4.7	4.8	4.8	5.0
N_2O from Product Uses	4.2	4.2	4.2	4.2	4.2	4.2	4.2
Caprolactam, Glyoxal, and Glyoxylic Acid Production	1.7	2.1	2.0	2.0	2.0	2.0	2.0
Composting	0.3	1.7	1.7	1.8	1.9	1.9	1.9
Incineration of Waste	0.5	0.4	0.3	0.3	0.3	0.3	0.3
Semiconductor Manufacture	+	0.1	0.2	0.2	0.2	0.2	0.2
Field Burning of Agricultural Residues	0.1	0.1	0.1	0.1	0.1	0.1	0.1
International Bunker Fuels[b]	*0.9*	*1.0*	*0.9*	*0.9*	*0.9*	*0.9*	*1.0*
HFCs	**46.6**	**123.0**	**150.5**	**151.1**	**156.7**	**160.8**	**162.3**
Substitution of Ozone Depleting Substances[d]	0.3	102.7	144.8	146.8	151.3	156.1	159.1
HCFC-22 Production	46.1	20.0	5.5	4.1	5.0	4.3	2.8
Semiconductor Manufacture	0.2	0.2	0.2	0.2	0.3	0.3	0.3
Magnesium Production and Processing	0.0	0.0	+	0.1	0.1	0.1	0.1
PFCs	**24.3**	**6.7**	**5.9**	**5.8**	**5.6**	**5.1**	**4.3**
Semiconductor Manufacture	2.8	3.3	3.0	2.8	3.1	3.1	3.0
Aluminum Production	21.5	3.4	2.9	3.0	2.5	2.0	1.4
Substitution of Ozone Depleting Substances	0.0	+	+	+	+	+	+
SF_6	**28.8**	**11.8**	**6.7**	**6.3**	**6.4**	**5.9**	**6.2**
Electrical Transmission and Distribution	23.1	8.3	4.7	4.5	4.7	4.3	4.3
Magnesium Production and Processing	5.2	2.7	1.6	1.5	1.0	0.9	1.0
Semiconductor Manufacture	0.5	0.7	0.3	0.4	0.7	0.7	0.8
NF_3	**+**	**0.5**	**0.6**	**0.6**	**0.5**	**0.6**	**0.6**
Semiconductor Manufacture	+	0.5	0.6	0.6	0.5	0.6	0.6
Total Emissions	**6,355.6**	**7,320.3**	**6,528.8**	**6,709.1**	**6,763.1**	**6,638.1**	**6,511.3**
LULUCF Emissions[c]	**10.6**	**23.0**	**26.1**	**19.2**	**19.6**	**38.2**	**38.1**
LULUCF CH_4 Emissions	6.7	13.3	15.0	10.9	11.2	22.4	22.4
LULUCF N_2O Emissions	3.9	9.7	11.1	8.3	8.4	15.8	15.7
LULUCF Carbon Stock Change[e]	**(830.2)**	**(754.2)**	**(779.5)**	**(755.0)**	**(760.0)**	**(733.4)**	**(754.9)**
LULUCF Sector Net Total[f]	**(819.6)**	**(731.1)**	**(753.5)**	**(735.8)**	**(740.4)**	**(695.2)**	**(716.8)**
Net Emissions (Sources and Sinks)	**5,536.0**	**6,589.1**	**5,775.3**	**5,973.3**	**6,022.8**	**5,942.9**	**5,794.5**

Notes: Total emissions presented without LULUCF. Net emissions presented with LULUCF. Totals may not sum due to independent rounding. Parentheses indicate negative values or sequestration.

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Emissions from Wood Biomass, Ethanol, and Biodiesel Consumption are not included specifically in summing Energy sector totals. Net carbon fluxes from changes in biogenic carbon reservoirs are accounted for in the estimates for LULUCF.

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[b] Emissions from International Bunker Fuels are not included in totals.

[c] LULUCF emissions of CH_4 and N_2O are reported separately from gross emissions totals. LULUCF emissions include the CH_4 and N_2O emissions reported for *Peatlands Remaining Peatlands*, Forest Fires, Drained Organic Soils, Grassland Fires, and *Coastal Wetlands Remaining Coastal Wetlands*; CH_4 emissions from *Land Converted to Coastal Wetlands*; and N_2O emissions from Forest Soils and Settlement Soils. Refer to Table 2-8 for a breakout of emissions and removals for LULUCF by gas and source category.

[d] Small amounts of PFC emissions also result from this source.

[e] LULUCF Carbon Stock Change is the net C stock change from the following categories: *Forest Land Remaining Forest Land*, *Land Converted to Forest Land*, *Cropland Remaining Cropland*, *Land Converted to Cropland*, *Grassland Remaining Grassland*, *Land Converted to Grassland*, *Wetlands Remaining Wetlands*, *Land Converted to Wetlands*, *Settlements Remaining Settlements*, and *Land Converted to Settlements*. Refer to Table 2-8 for a breakout of emissions and removals for LULUCF by gas and source category.

[f] The LULUCF Sector Net Total is the net sum of all CH_4 and N_2O emissions to the atmosphere plus net carbon stock changes.

Table 2-2: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks (kt)

Gas/Source	1990	2005	2012	2013	2014	2015	2016
CO_2	**5,121,264**	**6,132,006**	**5,366,730**	**5,519,613**	**5,568,759**	**5,420,804**	**5,310,861**
Fossil Fuel Combustion	4,740,344	5,746,942	5,024,373	5,156,898	5,200,297	5,049,254	4,966,049
Electric Power	*1,820,818*	*2,400,874*	*2,022,181*	*2,038,122*	*2,038,018*	*1,900,673*	*1,809,252*
Transportation	*1,467,564*	*1,855,751*	*1,661,895*	*1,677,593*	*1,717,132*	*1,735,469*	*1,782,585*
Industrial	*858,840*	*855,719*	*812,945*	*843,252*	*824,929*	*809,495*	*809,062*
Residential	*338,347*	*357,834*	*282,501*	*329,742*	*345,296*	*316,821*	*292,501*
Commercial	*227,219*	*227,041*	*201,325*	*225,722*	*233,557*	*245,416*	*231,269*
U.S. Territories	*27,555*	*49,723*	*43,527*	*42,467*	*41,365*	*41,380*	*41,380*
Non-Energy Use of Fuels	119,546	138,885	107,987	123,485	118,877	125,634	112,199
Iron and Steel Production & Metallurgical Coke Production	101,630	68,210	55,600	53,471	58,353	47,825	42,306
Cement Production	33,484	46,194	35,270	36,369	39,439	39,907	39,439
Petrochemical Production	21,203	26,794	26,501	26,395	26,496	28,062	28,110
Natural Gas Systems	29,831	22,512	23,276	24,827	25,336	24,888	25,516
Petroleum Systems	7,689	11,700	19,300	22,611	26,324	28,752	22,767
Lime Production	11,700	14,552	13,785	14,028	14,210	13,342	12,942
Ammonia Production	13,047	9,196	9,377	9,962	9,619	10,883	12,194
Other Process Uses of Carbonates	6,297	7,644	9,119	11,524	12,954	12,312	10,986
Incineration of Waste	7,950	12,469	10,392	10,361	10,604	10,670	10,676
Urea Fertilization	2,417	3,504	4,282	4,443	4,538	4,888	5,098
Carbon Dioxide Consumption	1,472	1,375	4,019	4,188	4,471	4,471	4,471
Urea Consumption for Non-Agricultural Purposes	3,784	3,653	4,392	4,074	1,541	4,169	3,959
Liming	4,667	4,349	5,978	3,907	3,609	3,777	3,863
Ferroalloy Production	2,152	1,392	1,903	1,785	1,914	1,960	1,796
Soda Ash Production	1,431	1,655	1,665	1,694	1,685	1,714	1,723
Titanium Dioxide Production	1,195	1,755	1,528	1,715	1,688	1,635	1,608
Aluminum Production	6,831	4,142	3,439	3,255	2,833	2,767	1,334
Glass Production	1,535	1,928	1,248	1,317	1,336	1,299	1,243
Phosphoric Acid Production	1,529	1,342	1,118	1,149	1,038	999	992
Zinc Production	632	1,030	1,486	1,429	956	933	925
Lead Production	516	553	527	546	459	473	482
Silicon Carbide Production and Consumption	375	219	158	169	173	180	174
Abandoned Oil and Gas Wells	6	7	7	7	7	7	7
Magnesium Production and Processing	1	3	2	2	2	3	3

Wood Biomass, Ethanol, and Biodiesel Consumption[a]	*219,413*	*230,700*	*287,732*	*316,405*	*324,308*	*310,430*	*309,252*
International Bunker Fuels[b]	*103,463*	*113,139*	*105,805*	*99,763*	*103,400*	*110,887*	*116,594*
CH_4[c]	**31,198**	**27,544**	**26,500**	**26,502**	**26,558**	**26,615**	**26,298**
Enteric Fermentation	6,566	6,755	6,670	6,619	6,567	6,661	6,805
Natural Gas Systems	7,806	6,765	6,384	6,553	6,572	6,651	6,541
Landfills	7,182	5,310	4,680	4,531	4,509	4,467	4,306
Manure Management	1,486	2,254	2,625	2,530	2,514	2,651	2,709
Coal Mining	3,860	2,565	2,658	2,584	2,583	2,449	2,153
Petroleum Systems	1,592	1,284	1,307	1,463	1,543	1,523	1,544
Wastewater Treatment	627	631	604	596	598	605	593
Rice Cultivation	641	667	453	462	510	493	549
Stationary Combustion	345	313	295	351	356	317	293
Abandoned Oil and Gas Wells	260	275	279	280	282	286	284
Abandoned Underground Coal Mines	288	264	249	249	253	256	268
Mobile Combustion	508	374	204	188	170	152	146
Composting	15	75	77	81	84	84	85
Field Burning of Agricultural Residues	9	8	11	11	11	11	11
Petrochemical Production	9	3	3	3	5	7	10
Ferroalloy Production	1	+	1	+	1	1	1
Silicon Carbide Production and Consumption	1	+	+	+	+	+	+
Iron and Steel Production & Metallurgical Coke Production	1	1	+	+	+	+	+
Incineration of Waste	+	+	+	+	+	+	+
International Bunker Fuels[b]	*7*	*5*	*4*	*3*	*3*	*3*	*4*
N_2O[c]	**1,190**	**1,201**	**1,127**	**1,219**	**1,212**	**1,274**	**1,240**
Agricultural Soil Management	840	851	832	928	920	990	952
Stationary Combustion	37	59	57	63	64	61	62
Mobile Combustion	140	130	81	75	69	65	62
Manure Management	47	55	59	59	59	59	61
Nitric Acid Production	41	38	35	36	37	39	34
Adipic Acid Production	51	24	19	13	18	14	23
Wastewater Treatment	11	15	16	16	16	16	17
N_2O from Product Uses	14	14	14	14	14	14	14
Caprolactam, Glyoxal, and Glyoxylic Acid Production	6	7	7	7	7	7	7
Composting	1	6	6	6	6	6	6
Incineration of Waste	2	1	1	1	1	1	1
Semiconductor Manufacture	+	+	1	1	1	1	1
Field Burning of Agricultural Residues	+	+	+	+	+	+	+
International Bunker Fuels[b]	*3*	*3*	*3*	*3*	*3*	*3*	*3*
HFCs	**M**	**M**	**M**	**M**	**M**	**M**	**M**
Substitution of Ozone Depleting Substances[d]	M	M	M	M	M	M	M
HCFC-22 Production	3	1	+	+	+	+	+
Semiconductor Manufacture	M	M	M	M	M	M	M
Magnesium Production and Processing	0	0	+	+	+	+	+
PFCs	**M**	**M**	**M**	**M**	**M**	**M**	**M**
Semiconductor Manufacture	M	M	M	M	M	M	M
Aluminum Production	M	M	M	M	M	M	M
Substitution of Ozone Depleting Substances	0	+	+	+	+	+	+

SF_6	**1**	**1**	+	+	+	+	+
Electrical Transmission and Distribution	1	+	+	+	+	+	+
Magnesium Production and Processing	+	+	+	+	+	+	+
Semiconductor Manufacture	+	+	+	+	+	+	+
NF_3	+	+	+	+	+	+	+
Semiconductor Manufacture	+	+	+	+	+	+	+

+ Does not exceed 0.5 kt.

M - Mixture of multiple gases

[a] Emissions from Wood Biomass, Ethanol, and Biodiesel Consumption are not included specifically in summing Energy sector totals. Net carbon fluxes from changes in biogenic carbon reservoirs are accounted for in the estimates for LULUCF.

[b] Emissions from International Bunker Fuels are not included in totals.

[c] LULUCF emissions of CH_4 and N_2O are reported separately from gross emissions totals. Refer to Table 2-8 for a breakout of emissions and removals for LULUCF by gas and source category.

[d] Small amounts of PFC emissions also result from this source.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or sequestration.

Emissions of all gases can be summed from each source category into a set of five sectors defined by the Intergovernmental Panel on Climate Change (IPCC). Figure 2-4 and Table 2-3 illustrate that over the twenty-seven-year period of 1990 to 2016, total emissions from the Energy, Industrial Processes and Product Use, and Agriculture sectors grew by 130.1 MMT CO_2 Eq. (2.4 percent), 20.0 MMT CO_2 Eq. (5.9 percent), and 73.4 MMT CO_2 Eq. (15.0 percent), respectively. Emissions from the Waste sector decreased by 67.9 MMT CO_2 Eq. (34.1 percent). Over the same period, total C sequestration in the Land Use, Land-Use Change, and Forestry (LULUCF) sector decreased by 75.4 MMT CO_2 (9.1 percent decrease in total C sequestration), and emissions from the LULUCF sector increased by 27.4 MMT CO_2 Eq. (258 percent).

Figure 2-4: U.S. Greenhouse Gas Emissions and Sinks by Chapter/IPCC Sector (MMT CO_2 Eq.)

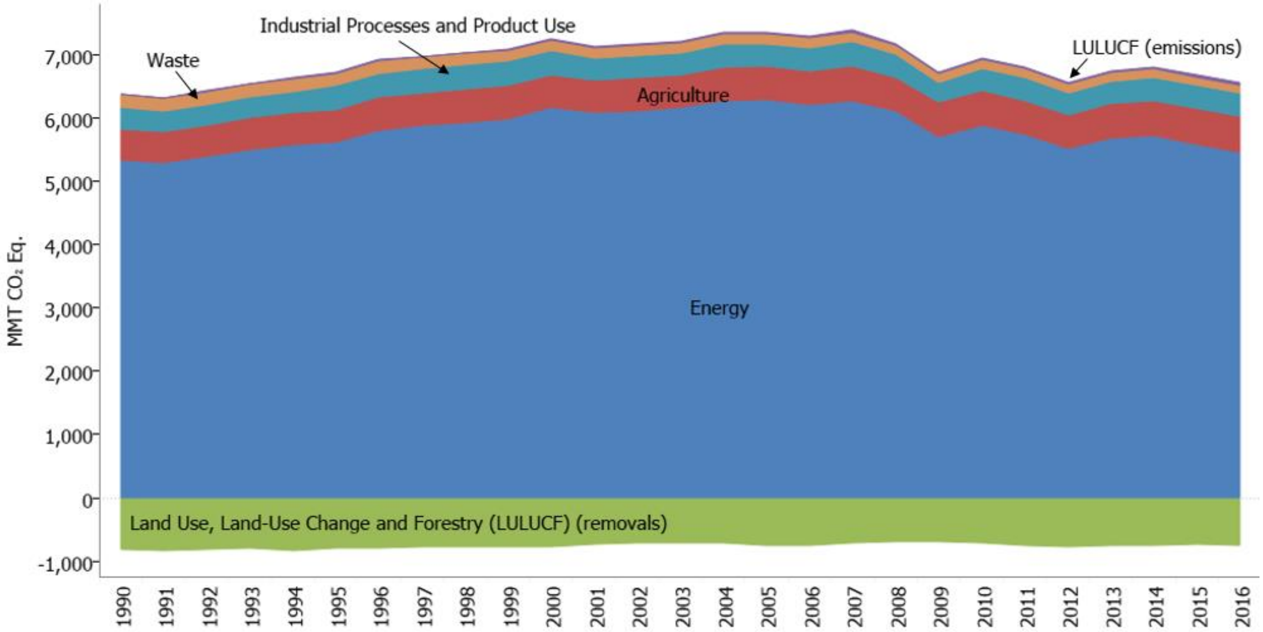


Table 2-3: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks by Chapter/IPCC Sector (MMT CO_2 Eq.)

Chapter/IPCC Sector	1990	2005	2012	2013	2014	2015	2016
Energy	**5,325.1**	**6,285.2**	**5,511.2**	**5,671.4**	**5,715.4**	**5,567.8**	**5,455.2**

Fossil Fuel Combustion	4,740.3	5,746.9	5,024.4	5,156.9	5,200.3	5,049.3	4,966.0
Natural Gas Systems	225.0	191.6	182.9	188.6	189.6	191.2	189.0
Non-Energy Use of Fuels	119.5	138.9	108.0	123.5	118.9	125.6	112.2
Petroleum Systems	47.5	43.8	52.0	59.2	64.9	66.8	61.4
Coal Mining	96.5	64.1	66.5	64.6	64.6	61.2	53.8
Stationary Combustion	19.7	25.3	24.3	27.5	28.0	26.1	25.9
Mobile Combustion	54.4	48.2	29.4	27.2	24.9	23.1	22.0
Incineration of Waste	8.4	12.9	10.7	10.7	10.9	11.0	11.0
Abandoned Oil and Gas Wells	6.5	6.9	7.0	7.0	7.1	7.2	7.1
Abandoned Underground Coal Mines	7.2	6.6	6.2	6.2	6.3	6.4	6.7
Industrial Processes and Product Use	**342.0**	**358.6**	**357.4**	**357.9**	**371.4**	**367.8**	**362.1**
Substitution of Ozone Depleting Substances	0.3	102.7	144.9	146.8	151.3	156.1	159.1
Iron and Steel Production & Metallurgical Coke Production	101.7	68.2	55.6	53.5	58.4	47.8	42.3
Cement Production	33.5	46.2	35.3	36.4	39.4	39.9	39.4
Petrochemical Production	21.4	26.9	26.6	26.5	26.6	28.2	28.4
Lime Production	11.7	14.6	13.8	14.0	14.2	13.3	12.9
Ammonia Production	13.0	9.2	9.4	10.0	9.6	10.9	12.2
Other Process Uses of Carbonates	6.3	7.6	9.1	11.5	13.0	12.3	11.0
Nitric Acid Production	12.1	11.3	10.5	10.7	10.9	11.6	10.2
Adipic Acid Production	15.2	7.1	5.5	3.9	5.4	4.3	7.0
Semiconductor Manufacture	3.6	4.7	4.4	4.0	4.9	5.0	5.0
Carbon Dioxide Consumption	1.5	1.4	4.0	4.2	4.5	4.5	4.5
Electrical Transmission and Distribution	23.1	8.3	4.7	4.5	4.7	4.3	4.3
N_2O from Product Uses	4.2	4.2	4.2	4.2	4.2	4.2	4.2
Urea Consumption for Non-Agricultural Purposes	3.8	3.7	4.4	4.1	1.5	4.2	4.0
HCFC-22 Production	46.1	20.0	5.5	4.1	5.0	4.3	2.8
Aluminum Production	28.3	7.6	6.4	6.2	5.4	4.8	2.7
Caprolactam, Glyoxal, and Glyoxylic Acid Production	1.7	2.1	2.0	2.0	2.0	2.0	2.0
Ferroalloy Production	2.2	1.4	1.9	1.8	1.9	2.0	1.8
Soda Ash Production	1.4	1.7	1.7	1.7	1.7	1.7	1.7
Titanium Dioxide Production	1.2	1.8	1.5	1.7	1.7	1.6	1.6
Glass Production	1.5	1.9	1.2	1.3	1.3	1.3	1.2
Magnesium Production and Processing	5.2	2.7	1.7	1.5	1.1	1.0	1.1
Phosphoric Acid Production	1.5	1.3	1.1	1.1	1.0	1.0	1.0
Zinc Production	0.6	1.0	1.5	1.4	1.0	0.9	0.9
Lead Production	0.5	0.6	0.5	0.5	0.5	0.5	0.5
Silicon Carbide Production and Consumption	0.4	0.2	0.2	0.2	0.2	0.2	0.2
Agriculture	**489.2**	**520.0**	**519.8**	**543.1**	**539.8**	**566.9**	**562.6**
Agricultural Soil Management	250.5	253.5	247.9	276.6	274.0	295.0	283.6
Enteric Fermentation	164.2	168.9	166.7	165.5	164.2	166.5	170.1
Manure Management	51.1	72.9	83.2	80.8	80.4	84.0	85.9
Rice Cultivation	16.0	16.7	11.3	11.5	12.7	12.3	13.7
Urea Fertilization	2.4	3.5	4.3	4.4	4.5	4.9	5.1
Liming	4.7	4.3	6.0	3.9	3.6	3.8	3.9
Field Burning of Agricultural Residues	0.3	0.3	0.4	0.4	0.4	0.4	0.4
Waste	**199.3**	**156.4**	**140.4**	**136.7**	**136.5**	**135.6**	**131.5**
Landfills	179.6	132.7	117.0	113.3	112.7	111.7	107.7
Wastewater Treatment	19.1	20.2	19.7	19.6	19.8	20.0	19.8
Composting	0.7	3.5	3.7	3.9	4.0	4.0	4.0
Total Emissions[a]	**6,355.6**	**7,320.3**	**6,528.8**	**6,709.1**	**6,763.1**	**6,638.1**	**6,511.3**

Land Use, Land-Use Change, and Forestry	**(819.6)**	**(731.1)**	**(753.5)**	**(735.8)**	**(740.4)**	**(695.2)**	**(716.8)**
Forest land	(784.3)	(730.0)	(723.3)	(733.3)	(731.7)	(709.9)	(714.2)
Cropland	2.4	(0.7)	1.3	11.9	11.2	16.8	13.8
Grassland	13.8	25.3	0.8	18.5	14.7	33.6	21.0
Wetlands	(4.0)	(5.3)	(4.1)	(4.1)	(4.1)	(4.1)	(4.2)
Settlements	(47.6)	(20.5)	(28.3)	(28.8)	(30.5)	(31.5)	(33.2)
Net Emission (Sources and Sinks)[b]	**5,536.0**	**6,589.1**	**5,775.3**	**5,973.3**	**6,022.8**	**5,942.9**	**5,794.5**

Notes: Total emissions presented without LULUCF. Net emissions presented with LULUCF. Totals may not sum due to independent rounding. Parentheses indicate negative values or sequestration.

[a] Total emissions without LULUCF.

[b] Net emissions with LULUCF.

Energy

Energy-related activities, primarily fossil fuel combustion, accounted for the vast majority of U.S. CO_2 emissions for the period of 1990 through 2016. Fossil fuel combustion is the largest source of energy-related emissions, with CO_2 being the primary gas emitted (see Figure 2-5). Due to their relative importance, fossil fuel combustion-related CO_2 emissions are considered in detail in the Energy chapter (see Figure 2-6).

In 2016, approximately 81 percent of the energy consumed in the United States (on a Btu basis) was produced through the combustion of fossil fuels. The remaining 19 percent came from other energy sources such as hydropower, biomass, nuclear, wind, and solar energy. A discussion of specific trends related to CO_2 as well as other greenhouse gas emissions from energy use is presented in the Energy chapter. Energy-related activities are also responsible for CH_4 and N_2O emissions (43 percent and 10 percent of total U.S. emissions of each gas, respectively). Table 2-4 presents greenhouse gas emissions from the Energy chapter, by source and gas.

Figure 2-5: 2016 Energy Chapter Greenhouse Gas Sources (MMT CO_2 Eq.)

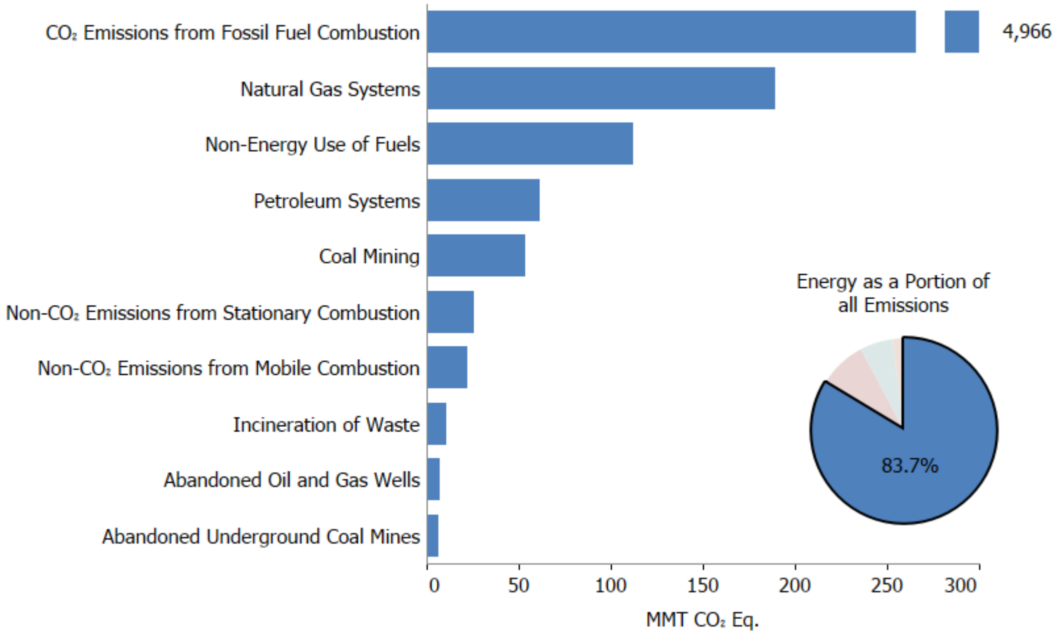
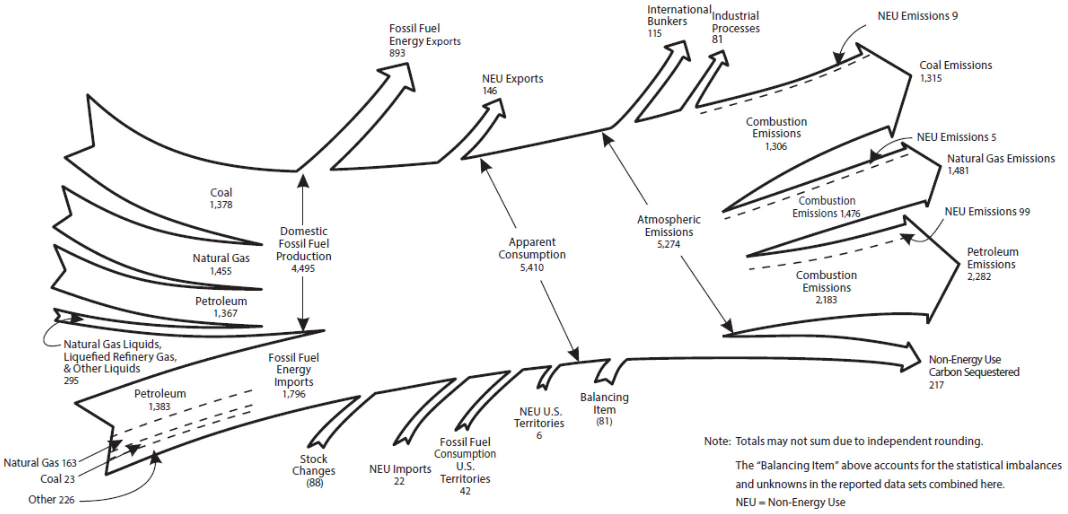


Figure 2-6: 2016 U.S. Fossil Carbon Flows (MMT CO_2 Eq.)



Note: Totals may not sum due to independent rounding.

The "Balancing Item" above accounts for the statistical imbalances and unknowns in the reported data sets combined here.

NEU = Non-Energy Use

Table 2-4: Emissions from Energy (MMT CO_2 Eq.)

Gas/Source	1990	2005	2012	2013	2014	2015	2016
CO_2	**4,905.4**	**5,932.5**	**5,185.3**	**5,338.2**	**5,381.4**	**5,239.2**	**5,137.2**
Fossil Fuel Combustion	4,740.3	5,746.9	5,024.4	5,156.9	5,200.3	5,049.3	4,966.0
Electric Power	*1,820.8*	*2,400.9*	*2,022.2*	*2,038.1*	*2,038.0*	*1,900.7*	*1,809.3*
Transportation	*1,467.6*	*1,855.8*	*1,661.9*	*1,677.6*	*1,717.1*	*1,735.5*	*1,782.6*
Industrial	*858.8*	*855.7*	*812.9*	*843.3*	*824.9*	*809.5*	*809.1*
Residential	*338.3*	*357.8*	*282.5*	*329.7*	*345.3*	*316.8*	*292.5*
Commercial	*227.2*	*227.0*	*201.3*	*225.7*	*233.6*	*245.4*	*231.3*
U.S. Territories	*27.6*	*49.7*	*43.5*	*42.5*	*41.4*	*41.4*	*41.4*
Non-Energy Use of Fuels	119.5	138.9	108.0	123.5	118.9	125.6	112.2
Natural Gas Systems	29.8	22.5	23.3	24.8	25.3	24.9	25.5
Petroleum Systems	7.7	11.7	19.3	22.6	26.3	28.8	22.8
Incineration of Waste	8.0	12.5	10.4	10.4	10.6	10.7	10.7
Abandoned Oil and Gas Wells	+	+	+	+	+	+	+
Biomass-Wood[a]	*215.2*	*206.9*	*206.4*	*228.2*	*234.9*	*217.4*	*208.4*
International Bunker Fuels[b]	*103.5*	*113.1*	*105.8*	*99.8*	*103.4*	*110.9*	*116.6*
Biofuels-Ethanol[a]	*4.2*	*22.9*	*72.8*	*74.7*	*76.1*	*78.9*	*81.2*
Biofuels-Biodiesel[a]	*0.0*	*0.9*	*8.5*	*13.5*	*13.3*	*14.1*	*19.6*
CH_4	**366.5**	**296.0**	**284.4**	**291.7**	**294.0**	**290.9**	**280.7**
Natural Gas Systems	195.2	169.1	159.6	163.8	164.3	166.3	163.5
Coal Mining	96.5	64.1	66.5	64.6	64.6	61.2	53.8
Petroleum Systems	39.8	32.1	32.7	36.6	38.6	38.1	38.6
Stationary Combustion	8.6	7.8	7.4	8.8	8.9	7.9	7.3
Abandoned Oil and Gas Wells	6.5	6.9	7.0	7.0	7.1	7.2	7.1
Abandoned Underground Coal Mines	7.2	6.6	6.2	6.2	6.3	6.4	6.7
Mobile Combustion	12.7	9.4	5.1	4.7	4.2	3.8	3.6
Incineration of Waste	+	+	+	+	+	+	+
International Bunker Fuels[b]	*0.2*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*
N_2O	**53.2**	**56.7**	**41.5**	**41.5**	**40.0**	**37.7**	**37.3**
Stationary Combustion	11.1	17.5	16.9	18.7	19.0	18.1	18.6
Mobile Combustion	41.7	38.8	24.3	22.5	20.6	19.3	18.4
Incineration of Waste	0.5	0.4	0.3	0.3	0.3	0.3	0.3
International Bunker Fuels[b]	*0.9*	*1.0*	*0.9*	*0.9*	*0.9*	*0.9*	*1.0*
Total	**5,325.1**	**6,285.2**	**5,511.2**	**5,671.4**	**5,715.4**	**5,567.8**	**5,455.2**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Emissions from Wood Biomass and Biofuel Consumption are not included specifically in summing energy sector totals. Net carbon fluxes from changes in biogenic carbon reservoirs are accounted for in the estimates for LULUCF.

[b] Emissions from International Bunker Fuels are not included in totals.

Note: Totals may not sum due to independent rounding.

CO_2 Emissions from Fossil Fuel Combustion

As the largest contributor to U.S. greenhouse gas emissions, CO_2 from fossil fuel combustion has accounted for approximately 77 percent of GWP-weighted emissions for the entire time series since 1990. Emissions from this source category grew by 4.8 percent (225.7 MMT CO_2 Eq.) from 1990 to 2016 and were responsible for most of the increase in national emissions during this period. Conversely, CO_2 emissions from fossil fuel combustion decreased from 2005 levels by 780.9 MMT CO_2 Eq., a decrease of approximately 13.6 percent between 2005 and 2016. From 2015 to 2016, these emissions decreased by 1.6 percent (83.2 MMT CO_2 Eq.). Historically, changes in emissions from fossil fuel combustion have been the dominant factor affecting U.S. emission trends.

Changes in CO_2 emissions from fossil fuel combustion are influenced by many long-term and short-term factors, including population and economic growth, energy price fluctuations and market trends, technological changes, energy fuel choices, and seasonal temperatures. On an annual basis, the overall consumption and mix of fossil fuels in the United States fluctuates primarily in response to changes in general economic conditions, overall energy prices, the relative price of different fuels, weather, and the availability of non-fossil alternatives. For example, coal consumption for electric power is influenced by a number of factors including the relative price of coal and alternative sources, the ability to switch fuels, and longer term trends in coal markets. Likewise, warmer winters will lead to a decrease in heating degree days and result in a decreased demand for heating fuel and electricity for heat in the residential and commercial sector, which leads to a decrease in emissions from reduced fuel consumption.

Energy-related CO_2 emissions also depend on the type of fuel consumed or energy used and its C intensity. Producing a unit of heat or electricity using natural gas instead of coal, for example, can reduce the CO_2 emissions because of the lower C content of natural gas (see Table A-40 in Annex 2.1 for more detail on the C Content Coefficient of different fossil fuels).

Trends in CO_2 emissions from fossil fuel combustion over the past decade have been strongly influenced by the electric power sector, which historically has accounted for the largest share of emissions from this source (see Figure 2-7). In recent years, the types of fuel consumed to produce electricity have changed. Carbon dioxide emissions from coal consumption for electric power generation decreased by 36.6 percent since 2008, and there has been a shift to the use of less-CO_2-intensive natural gas to supply electricity. There has also been a rapid increase in renewable energy capacity additions in the electric power sector in recent years. In 2016, renewable energy sources accounted for 63 percent of capacity additions with natural gas accounting for the majority of the remaining additions. The share of renewable energy capacity additions has grown significantly since 2010, when renewable energy sources accounted for only 28 percent of total capacity additions (EIA 2017c). Electricity generation from renewable sources increased by 14 percent from 2015 to 2016. The decrease in coal-powered electricity generation and increase in renewable energy electricity generation have contributed to a 4.8 percent decrease in emissions from electric power generation from 2015 to 2016 (see Figure 2-9), and lower CO_2 emissions from fossil fuel combustion over the time series (i.e., 1990 through 2016).

Total petroleum use is another major driver of CO_2 emissions from fossil fuel combustion, particularly in the transportation sector, which represents the second largest source of CO_2 emissions from fossil fuel combustion. Emissions from petroleum consumption for transportation have increased by 21.7 percent since 1990, which can be primarily attributed to a 48.0 percent increase in vehicle miles traveled (VMT) over the time series. Fuel economy of light-duty vehicles is another important factor. The decline in new light-duty vehicle fuel economy between 1990 and 2004 reflected the increasing market share of light-duty trucks, which grew from about 30 percent of new vehicle sales in 1990 to 48 percent in 2004. Since 2005, average new vehicle fuel economy has increased while the market share of light-duty trucks has decreased. Total transportation sector CO_2 emissions have increased by 5.2 percent since 2010.

The overall trends in CO_2 emissions from fossil fuel combustion in the residential and commercial sectors closely align with heating degree days. Emissions from the residential and commercial sectors decreased by 7.7 percent and 5.8 percent from 2015 to 2016, respectively. This trend can be largely attributed to a 5 percent decrease in heating degree days which led to a decreased demand for heating fuel and electricity for heat in the residential and commercial sectors. In addition, an increase in energy efficiency standards and the use of energy efficient products in residential and commercial buildings has resulted in an overall reduction in energy use, contributing to a decrease in emissions in both of these sectors (EIA 2017a). Combined residential and commercial sector emissions have decreased by 6.5 percent since 2010.

The increase in transportation sector petroleum CO_2 emissions from 2015 to 2016 offset some of the emission reductions from decreased coal use in the electric power sector and decreased demand for heating fuel in the residential and commercial sectors. Although emissions from the transportation sector have increased, emissions from all other sectors and U.S. Territories have decreased in recent years, contributing to a 1.6 percent decrease in total CO_2 emissions from fossil fuel combustion from 2015 to 2016 and a 7.3 percent reduction since 2010.

Carbon dioxide emissions from fossil fuel combustion are presented in Table 2-5 based on the underlying U.S. energy consumer data collected by the U.S. Energy Information Administration (EIA). Estimates of CO_2 emissions from fossil fuel combustion are calculated from these EIA “end-use sectors” based on total fuel consumption and appropriate fuel properties described below. (Any additional analysis and refinement of the EIA data is further explained in the Energy chapter of this report.)

- *Electric Power.* EIA’s fuel consumption data for the electric power sector are comprised of electricity-only and combined-heat-and-power (CHP) plants within the North American Industry Classification System (NAICS) 22 category whose primary business is to sell electricity, or electricity and heat, to the public. (Non-utility power producers are included in this sector as long as they meet the electric power sector definition.)
- *Industry.* EIA statistics for the industrial sector include fossil fuel consumption that occurs in the fields of manufacturing, agriculture, mining, and construction. EIA’s fuel consumption data for the industrial sector consist of all facilities and equipment used for producing, processing, or assembling goods. (EIA includes generators that produce electricity and/or useful thermal output primarily to support on-site industrial activities in this sector.)
- *Transportation.* EIA’s fuel consumption data for the transportation sector consists of all vehicles whose primary purpose is transporting people and/or goods from one physical location to another.
- *Residential.* EIA’s fuel consumption data for the residential sector consist of living quarters for private households.
- *Commercial.* EIA’s fuel consumption data for the commercial sector consist of service-providing facilities and equipment from private and public organizations and businesses. (EIA includes generators that produce electricity and/or useful thermal output primarily to support the activities at commercial establishments in this sector.)

Table 2-5 and Figure 2-7 summarize CO_2 emissions from fossil fuel combustion by end-use sector. Figure 2-8 further describes the total emissions from fossil fuel combustion, separated by end-use sector, including CH_4 and N_2O in addition to CO_2.

Table 2-5: CO_2 Emissions from Fossil Fuel Combustion by End-Use Sector (MMT CO_2 Eq.)

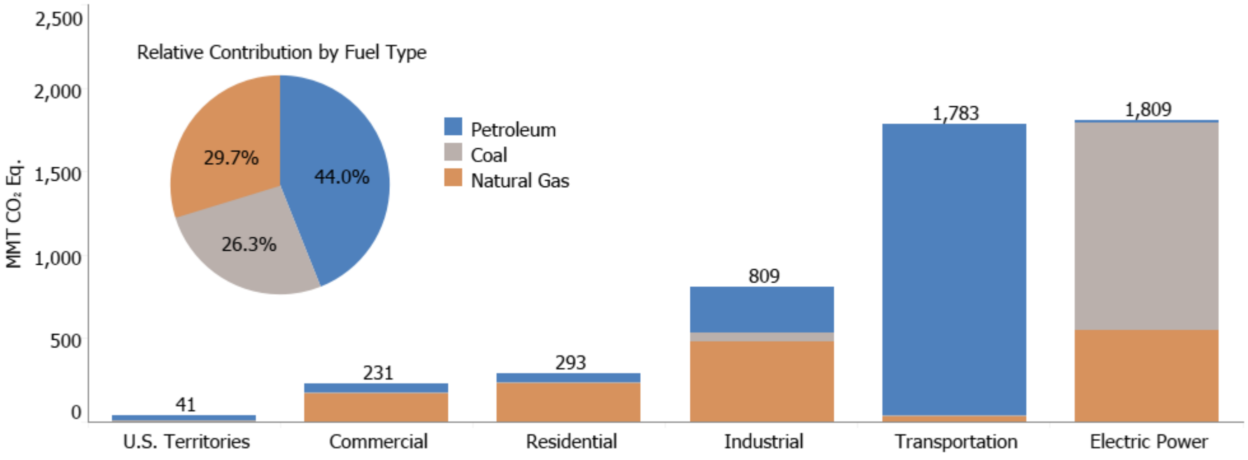
End-Use Sector	1990	2005	2012	2013	2014	2015	2016
Transportation	**1,470.6**	**1,860.5**	**1,665.8**	**1,681.6**	**1,721.2**	**1,739.2**	**1,786.1**
Combustion	1,467.6	1,855.8	1,661.9	1,677.6	1,717.1	1,735.5	1,782.6
Electricity	3.0	4.7	3.9	4.0	4.1	3.7	3.5
Industrial	**1,545.6**	**1,592.3**	**1,405.7**	**1,438.0**	**1,418.1**	**1,359.0**	**1,326.7**
Combustion	858.8	855.7	812.9	843.3	824.9	809.5	809.1
Electricity	686.7	736.6	592.8	594.7	593.2	549.6	517.7
Residential	**931.4**	**1,214.1**	**1,007.8**	**1,064.6**	**1,080.0**	**1,001.1**	**946.7**
Combustion	338.3	357.8	282.5	329.7	345.3	316.8	292.5
Electricity	593.0	856.3	725.3	734.9	734.7	684.3	654.2
Commercial	**765.2**	**1,030.3**	**901.6**	**930.2**	**939.6**	**908.6**	**865.2**
Combustion	227.2	227.0	201.3	225.7	233.6	245.4	231.3
Electricity	538.0	803.3	700.3	704.5	706.0	663.1	633.9

U.S. Territories[a]	**27.6**	**49.7**	**43.5**	**42.5**	**41.4**	**41.4**	**41.4**
Total	**4,740.3**	**5,746.9**	**5,024.4**	**5,156.9**	**5,200.3**	**5,049.3**	**4,966.0**
Electric Power	**1,820.8**	**2,400.9**	**2,022.2**	**2,038.1**	**2,038.0**	**1,900.7**	**1,809.3**

[a] Fuel consumption by U.S. Territories (i.e., American Samoa, Guam, Puerto Rico, U.S. Virgin Islands, Wake Island, and other U.S. Pacific Islands) is included in this report.

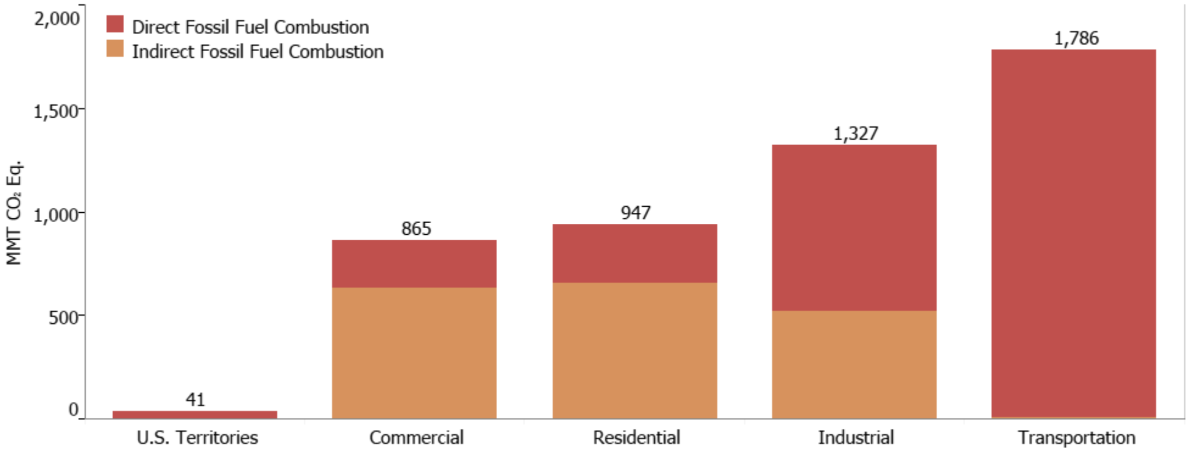
Notes: Combustion-related emissions from electric power are allocated based on aggregate national electricity use by each end-use sector. Totals may not sum due to independent rounding.

Figure 2-7: 2016 CO_2 Emissions from Fossil Fuel Combustion by Sector and Fuel Type (MMT CO_2 Eq.)



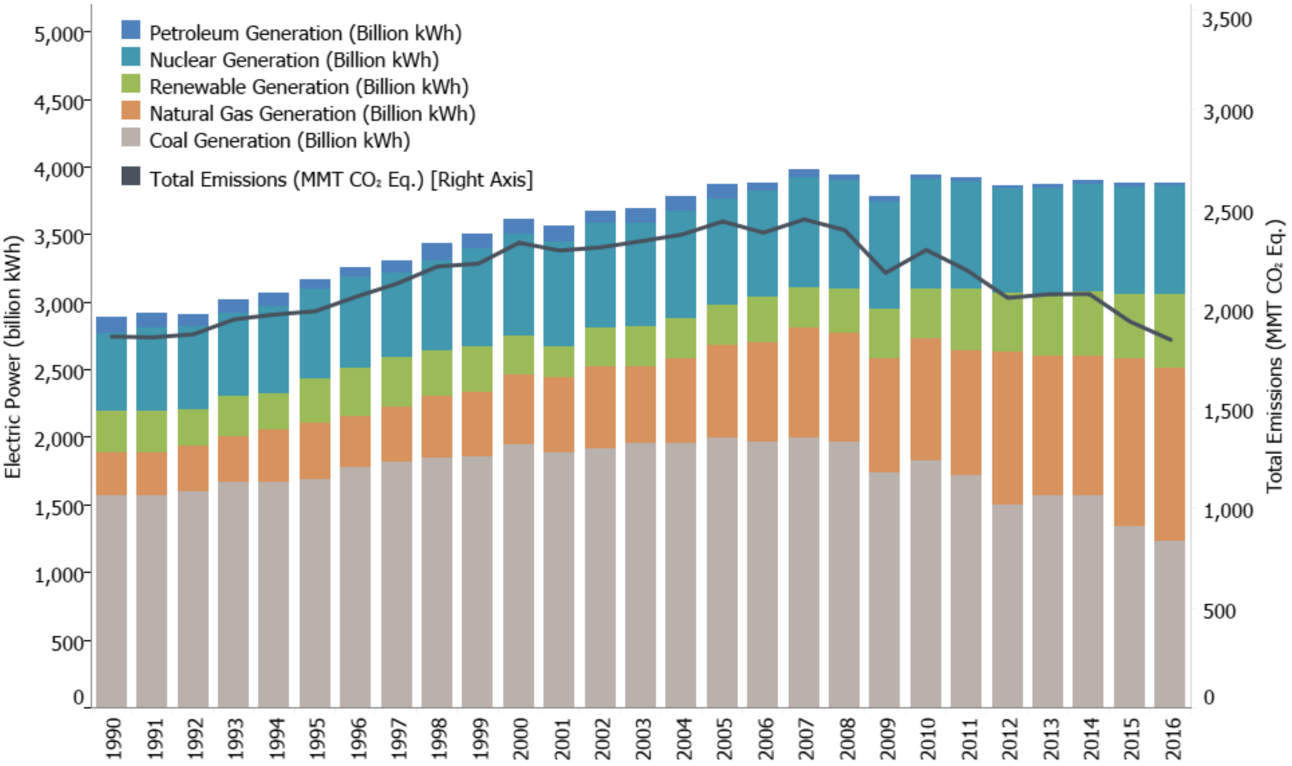
Note on Figure 2-7: Fossil Fuel Combustion for electric power also includes emissions of less than 0.5 MMT CO_2 Eq. from geothermal-based generation.

Figure 2-8: 2016 End-Use Sector Emissions of CO_2 from Fossil Fuel Combustion (MMT CO_2 Eq.)



The main driver of emissions in the Energy sector is CO_2 from fossil fuel combustion. Electric power is the largest emitter of CO_2, and electricity generators used 33 percent of U.S. energy from fossil fuels and emitted 36 percent of the CO_2 from fossil fuel combustion in 2016. Changes in electricity demand and the carbon intensity of fuels used for electric power have a significant impact on CO_2 emissions. Total greenhouse gas emissions from the electric power sector have decreased by approximately 0.1 percent since 1990, and the carbon intensity of the electric power sector, in terms of CO_2 Eq. per QBtu input has significantly decreased by 12 percent during that same timeframe. This decoupling of electric power and the resulting emissions is shown below in Figure 2-9.

Figure 2-9: Electric Power Generation (Billion kWh) and Emissions (MMT CO_2 Eq.)



Electric power emissions can also be allocated to the end-use sectors that are using that electricity, as presented in Table 2-5. The transportation end-use sector accounted for 1,786.1 MMT CO_2 Eq. in 2016 or approximately 36 percent of total CO_2 emissions from fossil fuel combustion. The industrial end-use sector accounted for 27 percent of CO_2 emissions from fossil fuel combustion. The residential and commercial end-use sectors accounted for 19 and 17 percent, respectively, of CO_2 emissions from fossil fuel combustion. Both of these end-use sectors were heavily reliant on electricity for meeting energy needs, with electricity use for lighting, heating, air conditioning, and operating appliances contributing 69 and 73 percent of emissions from the residential and commercial end-use sectors, respectively.

Other Significant Trends in Energy

Other significant trends in emissions from energy source categories over the twenty-seven-year period from 1990 through 2016 included the following:

- Methane emissions from natural gas systems and petroleum systems (combined here) decreased from 235.0 MMT CO_2 Eq. in 1990 to 202.1 MMT CO_2 Eq. in 2016 (32.8 MMT CO_2 Eq. or 14.0 percent decrease from 1990 to 2016). Natural gas systems CH_4 emissions decreased by 31.6 MMT CO_2 Eq. (16.2 percent) since 1990, largely due to a decrease in emissions from distribution, transmission and storage, processing, and exploration. The decrease in distribution emissions is largely attributed to increased use of plastic piping, which has lower emissions than other pipe materials, and station upgrades at metering and regulating (M&R) stations. The decrease in transmission and storage emissions is largely due to reduced compressor station emissions (including emissions from compressors and leaks). Petroleum systems CH_4 emissions decreased by 1.2 MMT CO_2 Eq. (or 3.0 percent) since 1990. This decrease is due primarily to decreases in tank emissions and associated gas venting. Carbon dioxide emissions from natural gas and petroleum systems increased by 29 percent from 1990 to 2016, due to increases in flaring emissions.
- Carbon dioxide emissions from non-energy uses of fossil fuels decreased by 7.3 MMT CO_2 Eq. (6.1 percent) from 1990 through 2016. Emissions from non-energy uses of fossil fuels were 112.2 MMT CO_2

Eq. in 2016, which constituted 2.1 percent of total national CO_2 emissions, approximately the same proportion as in 1990.

- Nitrous oxide emissions from stationary combustion increased by 7.5 MMT CO_2 Eq. (67.5 percent) from 1990 through 2016. Nitrous oxide emissions from this source increased primarily as a result of an increase in the number of coal fluidized bed boilers in the electric power sector.
- Nitrous oxide emissions from mobile combustion decreased by 23.3 MMT CO_2 Eq. (55.9 percent) from 1990 through 2016, primarily as a result of N_2O national emission control standards and emission control technologies for on-road vehicles.
- Carbon dioxide emissions from incineration of waste (10.7 MMT CO_2 Eq. in 2016) increased by 2.7 MMT CO_2 Eq. (34.3 percent) from 1990 through 2016, as the volume of scrap tires and other fossil C-containing materials in waste increased.

Industrial Processes and Product Use

The Industrial Processes and Product Use (IPPU) chapter includes greenhouse gas emissions occurring from industrial processes and from the use of greenhouse gases in products.

In many cases, greenhouse gas emissions are produced as the byproducts of many non-energy-related industrial activities. For example, industrial processes can chemically transform raw materials, which often release waste gases such as CO_2, CH_4, N_2O, and fluorinated gases (e.g., HFC-23). These processes are shown in Figure 2-10. Industrial manufacturing processes and use by end-consumers also release HFCs, PFCs, SF_6, and NF_3 and other fluorinated compounds. In addition to the use of HFCs and some PFCs as substitutes for ozone depleting substances (ODS), fluorinated compounds such as HFCs, PFCs, SF_6, NF_3, and others are employed and emitted by a number of other industrial sources in the United States. These industries include semiconductor manufacture, electric power transmission and distribution, and magnesium metal production and processing. In addition, N_2O is used in and emitted by semiconductor manufacturing and anesthetic and aerosol applications. Table 2-6 presents greenhouse gas emissions from industrial processes by source category.

Figure 2-10: 2016 Industrial Processes and Product Use Chapter Greenhouse Gas Sources (MMT CO_2 Eq.)

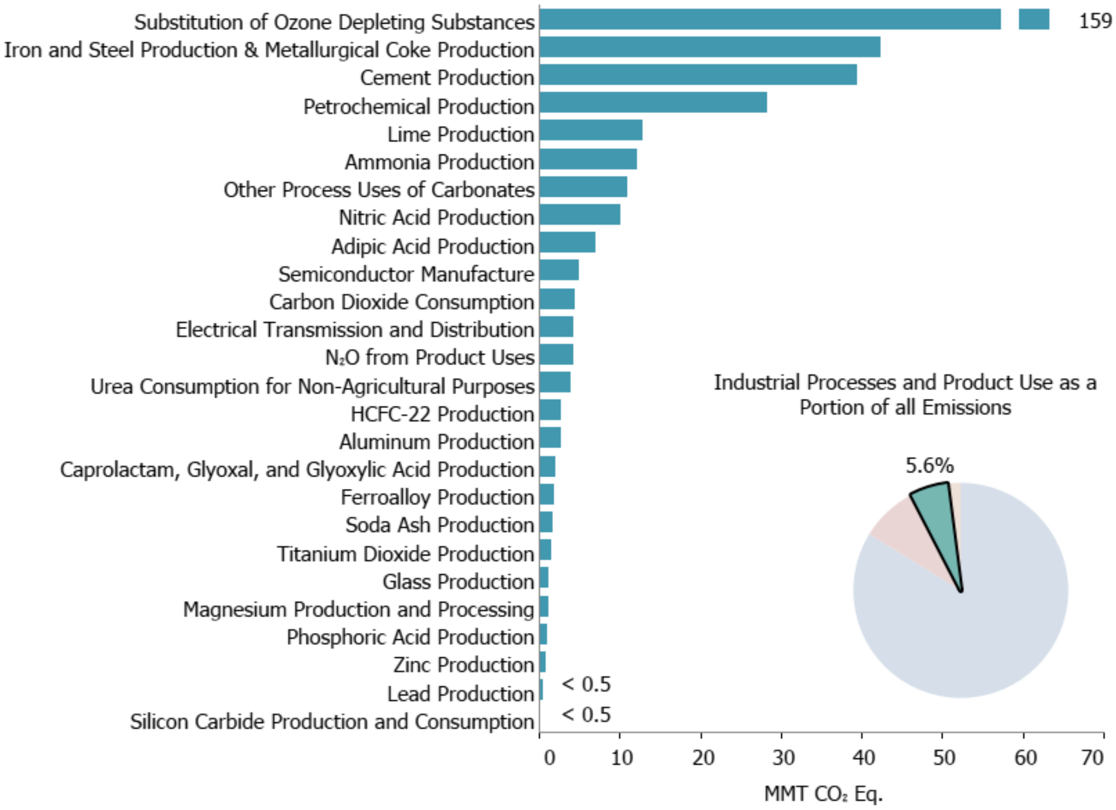


Table 2-6: Emissions from Industrial Processes and Product Use (MMT CO_2 Eq.)

Gas/Source	1990	2005	2012	2013	2014	2015	2016
CO_2	**208.8**	**191.6**	**171.1**	**173.1**	**179.2**	**172.9**	**164.7**
Iron and Steel Production & Metallurgical Coke Production	101.6	68.2	55.6	53.5	58.4	47.8	42.3
Iron and Steel Production	*99.1*	*66.2*	*55.1*	*51.6*	*56.3*	*45.0*	*41.0*
Metallurgical Coke Production	*2.5*	*2.1*	*0.5*	*1.8*	*2.0*	*2.8*	*1.3*
Cement Production	33.5	46.2	35.3	36.4	39.4	39.9	39.4
Petrochemical Production	21.2	26.8	26.5	26.4	26.5	28.1	28.1
Lime Production	11.7	14.6	13.8	14.0	14.2	13.3	12.9
Ammonia Production	13.0	9.2	9.4	10.0	9.6	10.9	12.2
Other Process Uses of Carbonates	6.3	7.6	9.1	11.5	13.0	12.3	11.0
Carbon Dioxide Consumption	1.5	1.4	4.0	4.2	4.5	4.5	4.5
Urea Consumption for Non-Agricultural Purposes	3.8	3.7	4.4	4.1	1.5	4.2	4.0
Ferroalloy Production	2.2	1.4	1.9	1.8	1.9	2.0	1.8
Soda Ash Production	1.4	1.7	1.7	1.7	1.7	1.7	1.7
Titanium Dioxide Production	1.2	1.8	1.5	1.7	1.7	1.6	1.6
Aluminum Production	6.8	4.1	3.4	3.3	2.8	2.8	1.3
Glass Production	1.5	1.9	1.2	1.3	1.3	1.3	1.2
Phosphoric Acid Production	1.5	1.3	1.1	1.1	1.0	1.0	1.0
Zinc Production	0.6	1.0	1.5	1.4	1.0	0.9	0.9
Lead Production	0.5	0.6	0.5	0.5	0.5	0.5	0.5
Silicon Carbide Production and Consumption	0.4	0.2	0.2	0.2	0.2	0.2	0.2
Magnesium Production and Processing	+	+	+	+	+	+	+

CH_4	**0.3**	**0.1**	**0.1**	**0.1**	**0.2**	**0.2**	**0.3**
Petrochemical Production	0.2	0.1	0.1	0.1	0.1	0.2	0.2
Ferroalloy Production	+	+	+	+	+	+	+
Silicon Carbide Production and Consumption	+	+	+	+	+	+	+
Iron and Steel Production & Metallurgical Coke Production	+	+	+	+	+	+	+
Iron and Steel Production	+	+	+	+	+	+	+
Metallurgical Coke Production	0.0	0.0	0.0	0.0	0.0	0.0	0.0
N_2O	**33.3**	**24.9**	**22.4**	**21.0**	**22.8**	**22.3**	**23.6**
Nitric Acid Production	12.1	11.3	10.5	10.7	10.9	11.6	10.2
Adipic Acid Production	15.2	7.1	5.5	3.9	5.4	4.3	7.0
N_2O from Product Uses	4.2	4.2	4.2	4.2	4.2	4.2	4.2
Caprolactam, Glyoxal, and Glyoxylic Acid	1.7	2.1	2.0	2.0	2.0	2.0	2.0
Semiconductor Manufacturing	+	0.1	0.2	0.2	0.2	0.2	0.2
HFCs	**46.6**	**123.0**	**150.5**	**151.1**	**156.7**	**160.8**	**162.3**
Substitution of Ozone Depleting Substances[a]	0.3	102.7	144.8	146.8	151.3	156.1	159.1
HCFC-22 Production	46.1	20.0	5.5	4.1	5.0	4.3	2.8
Semiconductor Manufacturing	0.2	0.2	0.2	0.2	0.3	0.3	0.3
Magnesium Production and Processing	0.0	0.0	+	0.1	0.1	0.1	0.1
PFCs	**24.3**	**6.7**	**5.9**	**5.8**	**5.6**	**5.1**	**4.3**
Semiconductor Manufacturing	2.8	3.3	3.0	2.8	3.1	3.1	3.0
Aluminum Production	21.5	3.4	2.9	3.0	2.5	2.0	1.4
Substitution of Ozone Depleting Substances	0.0	+	+	+	+	+	+
SF_6	**28.8**	**11.8**	**6.7**	**6.3**	**6.4**	**5.9**	**6.2**
Electrical Transmission and Distribution	23.1	8.3	4.7	4.5	4.7	4.3	4.3
Magnesium Production and Processing	5.2	2.7	1.6	1.5	1.0	0.9	1.0
Semiconductor Manufacturing	0.5	0.7	0.3	0.4	0.7	0.7	0.8
NF_3	**+**	**0.5**	**0.6**	**0.6**	**0.5**	**0.6**	**0.6**
Semiconductor Manufacturing	+	0.5	0.6	0.6	0.5	0.6	0.6
Total	**342.0**	**358.6**	**357.4**	**357.9**	**371.4**	**367.8**	**362.1**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Small amounts of PFC emissions also result from this source.

Note: Totals may not sum due to independent rounding.

Overall, emissions from the IPPU sector increased by 5.9 percent from 1990 to 2016. Significant trends in emissions from IPPU source categories over the twenty-seven-year period from 1990 through 2016 included the following:

- Hydrofluorocarbon and perfluorocarbon emissions from ODS substitutes have been increasing from small amounts in 1990 to 159.1 MMT CO_2 Eq. in 2016. This increase was in large part the result of efforts to phase out chlorofluorocarbons (CFCs) and other ODSs in the United States. In the short term, this trend is expected to continue, and will likely continue over the next decade as hydrochlorofluorocarbons (HCFCs), which are interim substitutes in many applications, are themselves phased-out under the provisions of the Copenhagen Amendments to the Montreal Protocol.
- Combined CO_2 and CH_4 emissions from iron and steel production and metallurgical coke production decreased by 11.5 percent to 42.3 MMT CO_2 Eq. from 2015 to 2016, and have declined overall by 59.3 MMT CO_2 Eq. (58.4 percent) from 1990 through 2016, due to restructuring of the industry, technological improvements, and increased scrap steel utilization.
- Carbon dioxide emissions from ammonia production (12.2 MMT CO_2 Eq. in 2016) decreased by 0.9 MMT CO_2 Eq. (6.5 percent) since 1990. Ammonia production relies on natural gas as both a feedstock and a fuel, and as such, market fluctuations and volatility in natural gas prices affect the production of ammonia.
- Nitrous oxide emissions from adipic acid production were 7.0 MMT CO_2 Eq. in 2016, and have decreased significantly since 1990 due to both the widespread installation of pollution control measures in the late 1990s and plant idling in the late 2000s. Emissions from adipic acid production have decreased by 53.9 percent since 1990 and by 58.5 percent since a peak in 1995.

- PFC emissions from aluminum production decreased by 93.7 percent (20.1 MMT CO_2 Eq.) from 1990 to 2016, due to both industry emission reduction efforts and lower domestic aluminum production.

Agriculture

Agricultural activities contribute directly to emissions of greenhouse gases through a variety of processes, including the following source categories: enteric fermentation in domestic livestock, livestock manure management, rice cultivation, agricultural soil management, liming, urea fertilization, and field burning of agricultural residues. Methane, N_2O, and CO_2 were the primary greenhouse gases emitted by agricultural activities.

In 2016, agricultural activities were responsible for emissions of 562.6 MMT CO_2 Eq., or 8.6 percent of total U.S. greenhouse gas emissions. Methane emissions from enteric fermentation and manure management represented approximately 25.9 percent and 10.3 percent of total CH_4 emissions from anthropogenic activities, respectively, in 2016. Agricultural soil management activities, such as application of synthetic and organic fertilizers, deposition of livestock manure, and growing N-fixing plants, were the largest source of U.S. N_2O emissions in 2016, accounting for 76.7 percent. Carbon dioxide emissions from the application of crushed limestone and dolomite (i.e., soil liming) and urea fertilization represented 0.2 percent of total CO_2 emissions from anthropogenic activities. Figure 2-11 and Table 2-7 illustrate agricultural greenhouse gas emissions by source.

Figure 2-11: 2016 Agriculture Chapter Greenhouse Gas Sources (MMT CO_2 Eq.)

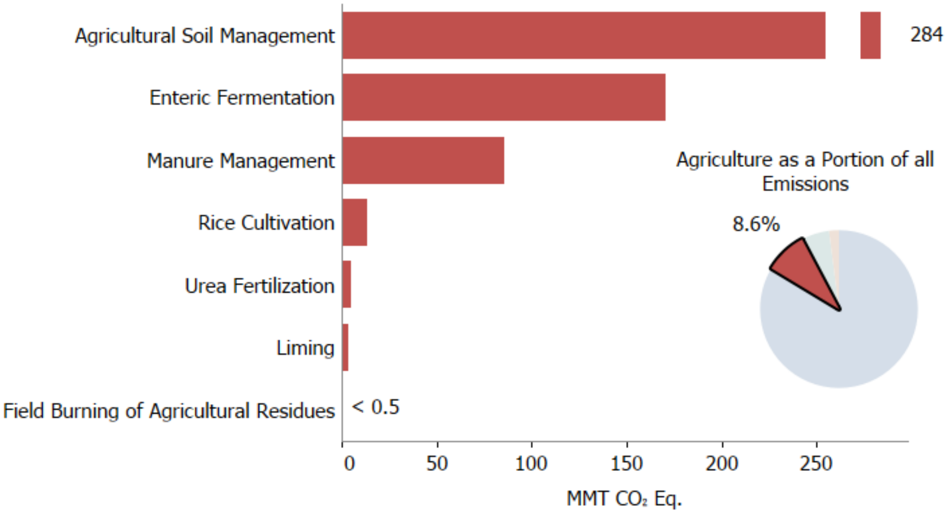


Table 2-7: Emissions from Agriculture (MMT CO_2 Eq.)

Gas/Source	1990	2005	2012	2013	2014	2015	2016
CO_2	**7.1**	**7.9**	**10.3**	**8.4**	**8.1**	**8.7**	**9.0**
Urea Fertilization	2.4	3.5	4.3	4.4	4.5	4.9	5.1
Liming	4.7	4.3	6.0	3.9	3.6	3.8	3.9
CH_4	**217.6**	**242.1**	**244.0**	**240.6**	**240.1**	**245.4**	**251.8**
Enteric Fermentation	164.2	168.9	166.7	165.5	164.2	166.5	170.1
Manure Management	37.2	56.3	65.6	63.3	62.9	66.3	67.7
Rice Cultivation	16.0	16.7	11.3	11.5	12.7	12.3	13.7
Field Burning of Agricultural Residues	0.2	0.2	0.3	0.3	0.3	0.3	0.3
N_2O	**264.5**	**270.1**	**265.5**	**294.2**	**291.6**	**312.8**	**301.8**
Agricultural Soil Management	250.5	253.5	247.9	276.6	274.0	295.0	283.6
Manure Management	14.0	16.5	17.5	17.5	17.5	17.7	18.1
Field Burning of Agricultural Residues	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Total	**489.2**	**520.0**	**519.8**	**543.1**	**539.8**	**566.9**	**562.6**

Note: Totals may not sum due to independent rounding.

Some significant trends in U.S. emissions from Agriculture source categories include the following:

- Agricultural soils is the largest anthropogenic source of N_2O emissions in the United States, accounting for approximately 76.7 percent of N_2O emissions in 2016. Estimated emissions from this source in 2016 were 283.6 MMT CO_2 Eq. Annual N_2O emissions from agricultural soils fluctuated between 1990 and 2016, although overall emissions were 13.2 percent higher in 2016 than in 1990. Year-to-year fluctuations are largely a reflection of annual variation in weather patterns, synthetic fertilizer use, and crop production.
- Enteric fermentation is the largest anthropogenic source of CH_4 emissions in the United States. In 2016, enteric fermentation CH_4 emissions were 170.1 MMT CO_2 Eq. (25.9 percent of total CH_4 emissions), which represents an increase of 6.0 MMT CO_2 Eq. (3.6 percent) since 1990. This increase in emissions from 1990 to 2016 in enteric fermentation generally follows the increasing trends in cattle populations. From 1990 to 1995, emissions increased and then generally decreased from 1996 to 2004, mainly due to fluctuations in beef cattle populations and increased digestibility of feed for feedlot cattle. Emissions increased from 2005 to 2007, as both dairy and beef populations increased. Research indicates that the feed digestibility of dairy cow diets decreased during this period. Emissions decreased again from 2008 to 2014 as beef cattle populations again decreased. Emissions increased from 2014 to 2016, consistent with an increase in beef cattle population over those same years.
- Liming and urea fertilization are the only source of CO_2 emissions reported in the Agriculture sector. Estimated emissions from these sources were 3.9 and 5.1 MMT CO_2 Eq., respectively. Liming and urea fertilization emissions increased by 2.3 percent and 4.3 percent, respectively, relative to 2015, and decreased by 17.2 percent and increased by 110.9 percent, respectively since 1990.
- Overall, emissions from manure management increased 67.8 percent between 1990 and 2016. This encompassed an increase of 82.2 percent for CH_4, from 37.2 MMT CO_2 Eq. in 1990 to 67.7 MMT CO_2 Eq. in 2016; and an increase of 29.6 percent for N_2O, from 14.0 MMT CO_2 Eq. in 1990 to 18.1 MMT CO_2 Eq. in 2016. The majority of the increase observed in CH_4 resulted from swine and dairy cattle manure, where emissions increased 63 and 140 percent, respectively, from 1990 to 2016. From 2015 to 2016, there was a 2.2 percent increase in total CH_4 emissions from manure management, mainly due to minor shifts in the animal populations and the resultant effects on manure management system allocations.

Land Use, Land-Use Change, and Forestry

When humans alter the terrestrial biosphere through land use, changes in land use, and land management practices, they also influence the carbon (C) stock fluxes on these lands and cause emissions of CH_4 and N_2O. Overall, managed land is a net sink for CO_2 (C sequestration) in the United States. The drivers of fluxes on managed lands include, for example, forest management practices, tree planting in urban areas, the management of agricultural soils, the landfilling of yard trimmings and food scraps, and activities that cause changes in C stocks in coastal wetlands. The main drivers for net forest sequestration include net forest growth, increasing forest area, and a net accumulation of C stocks in harvested wood pools. The net sequestration in *Settlements Remaining Settlements*, is driven primarily by C stock gains in urban forests through net tree growth and increased urban area, as well as long-term accumulation of C in landfills from additions of yard trimmings and food scraps.

The LULUCF sector in 2016 resulted in a net increase in C stocks (i.e., net CO_2 removals) of 754.9 MMT CO_2 Eq. (Table 2-8).[2] This represents an offset of approximately 11.6 percent of total (i.e., gross) greenhouse gas emissions in 2016. Emissions of CH_4 and N_2O from LULUCF activities in 2016 were 38.1 MMT CO_2 Eq. and represent 0.6 percent of total greenhouse gas emissions.[3] Between 1990 and 2016, total C sequestration in the LULUCF sector decreased by 9.1 percent, primarily due to a decrease in the rate of net C accumulation in forests and *Cropland Remaining Cropland*, as well as an increase in CO_2 emissions from *Land Converted to Settlements*.

Forest fires were the largest source of CH_4 emissions from LULUCF in 2016, totaling 18.5 MMT CO_2 Eq. (740 kt of CH_4). *Coastal Wetlands Remaining Coastal Wetlands* resulted in CH_4 emissions of 3.6 MMT CO_2 Eq. (143 kt of CH_4). Grassland fires resulted in CH_4 emissions of 0.3 MMT CO_2 Eq. (11 kt of CH_4). *Peatlands Remaining Peatlands*, *Land Converted to Wetlands*, and *Drained Organic Soils* resulted in CH_4 emissions of less than 0.05 MMT CO_2 Eq. each.

Forest fires were also the largest source of N_2O emissions from LULUCF in 2016, totaling 12.2 MMT CO_2 Eq. (41 kt of N_2O). Nitrous oxide emissions from fertilizer application to settlement soils in 2016 totaled to 2.5 MMT CO_2 Eq. (8 kt of N_2O). Additionally, the application of synthetic fertilizers to forest soils in 2016 resulted in N_2O emissions of 0.5 MMT CO_2 Eq. (2 kt of N_2O). Grassland fires resulted in N_2O emissions of 0.3 MMT CO_2 Eq. (1 kt of N_2O). *Coastal Wetlands Remaining Coastal Wetlands* and *Drained Organic Soils* resulted in N_2O emissions of 0.1 MMT CO_2 Eq. each (less than 0.5 kt of N_2O). *Peatlands Remaining Peatlands* resulted in N_2O emissions of less than 0.05 MMT CO_2 Eq.

Carbon dioxide removals from C stock changes are presented in Figure 2-12 and Table 2-8 along with CH_4 and N_2O emissions for LULUCF source categories.

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[2] LULUCF Carbon Stock Change is the net C stock change from the following categories: *Forest Land Remaining Forest Land, Land Converted to Forest Land, Cropland Remaining Cropland, Land Converted to Cropland, Grassland Remaining Grassland, Land Converted to Grassland, Wetlands Remaining Wetlands, Land Converted to Wetlands, Settlements Remaining Settlements,* and *Land Converted to Settlements.*

[3] LULUCF emissions include the CH_4 and N_2O emissions reported for *Peatlands Remaining Peatlands,* Forest Fires, Drained Organic Soils, Grassland Fires, and *Coastal Wetlands Remaining Coastal Wetlands*; CH_4 emissions from *Land Converted to Coastal Wetlands*; and N_2O emissions from Forest Soils and Settlement Soils.

Figure 2-12: 2016 LULUCF Chapter Greenhouse Gas Sources and Sinks (MMT CO_2 Eq.)

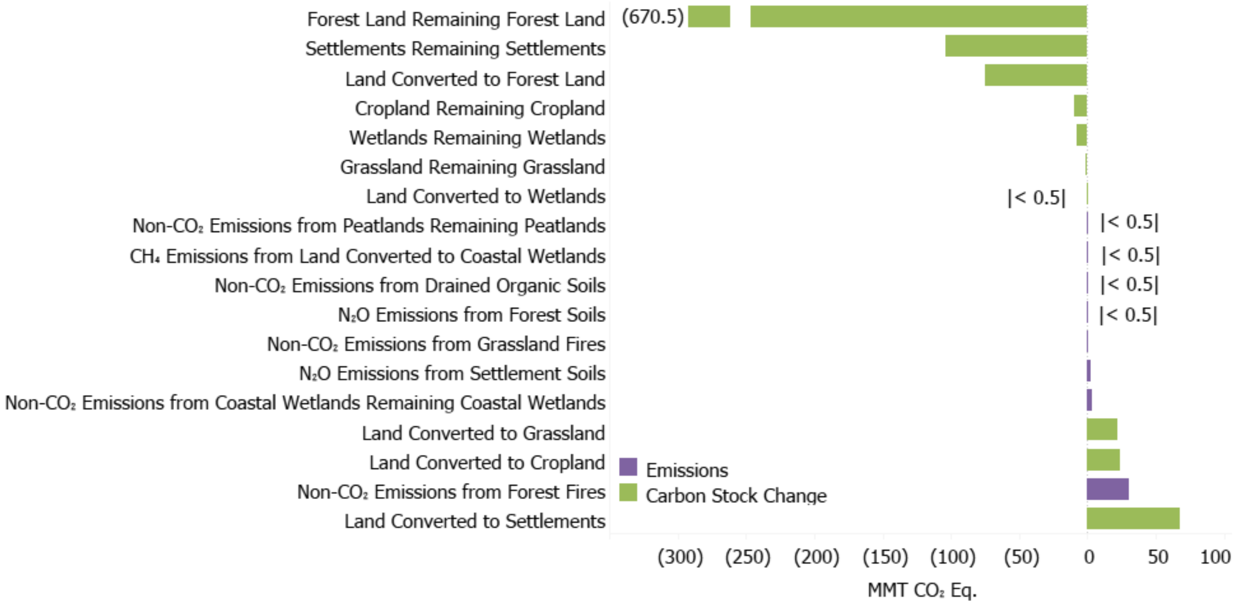


Table 2-8: U.S. Greenhouse Gas Emissions and Removals (Net Flux) from Land Use, Land-Use Change, and Forestry (MMT CO_2 Eq.)

Gas/Land-Use Category	1990	2005	2012	2013	2014	2015	2016
Carbon Stock Change[a]	**(830.2)**	**(754.2)**	**(779.5)**	**(755.0)**	**(760.0)**	**(733.4)**	**(754.9)**
Forest Land Remaining Forest Land	(697.7)	(664.6)	(666.9)	(670.9)	(669.3)	(666.2)	(670.5)
Land Converted to Forest Land	(92.0)	(81.6)	(74.9)	(74.9)	(75.0)	(75.0)	(75.0)
Cropland Remaining Cropland	(40.9)	(26.5)	(21.4)	(11.4)	(12.0)	(6.3)	(9.9)
Land Converted to Cropland	43.3	25.9	22.7	23.3	23.2	23.2	23.8
Grassland Remaining Grassland	(4.2)	5.5	(20.8)	(3.7)	(7.5)	9.6	(1.6)
Land Converted to Grassland	17.9	19.2	20.4	21.9	21.5	23.3	22.0
Wetlands Remaining Wetlands	(7.6)	(8.9)	(7.7)	(7.8)	(7.8)	(7.8)	(7.9)
Land Converted to Wetlands	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Settlements Remaining Settlements	(86.2)	(91.4)	(99.2)	(99.8)	(101.2)	(102.2)	(103.7)
Land Converted to Settlements	37.2	68.4	68.3	68.3	68.2	68.1	68.0
CH_4	**6.7**	**13.3**	**15.0**	**10.9**	**11.2**	**22.4**	**22.4**
Forest Land Remaining Forest Land: Forest Fires	3.2	9.4	10.8	7.2	7.2	18.5	18.5
Wetlands Remaining Wetlands: Coastal Wetlands Remaining Coastal Wetlands	3.4	3.5	3.5	3.6	3.6	3.6	3.6
Grassland Remaining Grassland: Grassland Fires	0.1	0.3	0.6	0.2	0.4	0.3	0.3
Forest Land Remaining Forest Land: Drained Organic Soils	+	+	+	+	+	+	+
Land Converted to Wetlands: Land Converted to Coastal Wetlands	+	+	+	+	+	+	+
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	+	+	+	+	+	+	+
N_2O	**3.9**	**9.7**	**11.1**	**8.3**	**8.4**	**15.8**	**15.7**
Forest Land Remaining Forest Land: Forest Fires	2.1	6.2	7.1	4.8	4.7	12.2	12.2
Settlements Remaining Settlements: Settlement Soils[b]	1.4	2.5	2.7	2.6	2.6	2.5	2.5
Forest Land Remaining Forest Land: Forest Soils[c]	0.1	0.5	0.5	0.5	0.5	0.5	0.5
Grassland Remaining Grassland:	0.1	0.3	0.6	0.2	0.4	0.3	0.3

Grassland Fires							
Wetlands Remaining Wetlands: Coastal Wetlands Remaining Coastal Wetlands	0.1	0.2	0.1	0.1	0.1	0.1	0.1
Forest Land Remaining Forest Land: Drained Organic Soils	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	+	+	+	+	+	+	+
LULUCF Emissions[d]	**10.6**	**23.0**	**26.1**	**19.2**	**19.6**	**38.2**	**38.1**
LULUCF Carbon Stock Change[a]	**(830.2)**	**(754.2)**	**(779.5)**	**(755.0)**	**(760.0)**	**(733.4)**	**(754.9)**
LULUCF Sector Net Total[e]	**(819.6)**	**(731.1)**	**(753.5)**	**(735.8)**	**(740.4)**	**(695.2)**	**(716.8)**

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

[a] LULUCF Carbon Stock Change is the net C stock change from the following categories: *Forest Land Remaining Forest Land, Land Converted to Forest Land, Cropland Remaining Cropland, Land Converted to Cropland, Grassland Remaining Grassland, Land Converted to Grassland, Wetlands Remaining Wetlands, Land Converted to Wetlands, Settlements Remaining Settlements*, and *Land Converted to Settlements*.

[b] Estimates include emissions from N fertilizer additions on both *Settlements Remaining Settlements* and *Land Converted to Settlements*.

[c] Estimates include emissions from N fertilizer additions on both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.

[d] LULUCF emissions include the CH_4 and N_2O emissions reported for *Peatlands Remaining Peatlands*, Forest Fires, Drained Organic Soils, Grassland Fires, and *Coastal Wetlands Remaining Coastal Wetlands*; CH_4 emissions from *Land Converted to Coastal Wetlands*; and N_2O emissions from Forest Soils and Settlement Soils.

[e] The LULUCF Sector Net Total is the net sum of all CH_4 and N_2O emissions to the atmosphere plus net carbon stock changes.

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Other significant trends from 1990 to 2016 in emissions from LULUCF categories include:

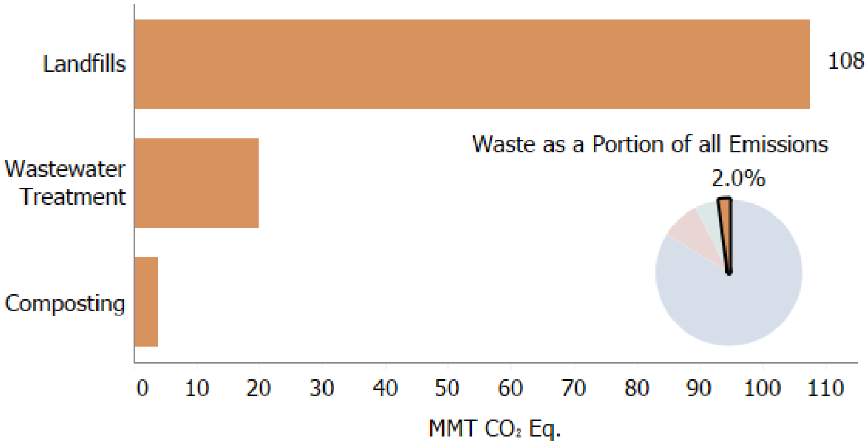
- Annual C sequestration by forest land (i.e., annual C stock accumulation in the five C pools and harvested wood products for *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*) has decreased by approximately 5.6 percent since 1990. This is primarily due to decreased C stock gains in *Land Converted to Forest Land* and the harvested wood products pools within *Forest Land Remaining Forest Land*.
- Annual C sequestration from *Settlements Remaining Settlements* (which includes organic soils, urban trees, and landfilled yard trimmings and food scraps) has increased by 20.2 percent over the period from 1990 to 2016. This is primarily due to an increase in urbanized land area in the United States.
- Annual emissions from *Land Converted to Grassland* increased by approximately 23.3 percent from 1990 to 2016 due to losses in aboveground biomass, belowground biomass, dead wood, and litter C stocks from *Forest Land Converted to Grassland*.
- Annual emissions from *Land Converted to Settlements* increased by approximately 82.6 percent from 1990 to 2016 due to losses in aboveground biomass C stocks from *Forest Land Converted to Settlements* and mineral soils C stocks from *Grassland Converted to Settlements*.
- Nitrous oxide emissions from fertilizer application to settlement soils in 2016 totaled to 2.5 MMT CO_2 Eq. (8 kt of N_2O). This represents an increase of 74.6 percent since 1990. Additionally, the application of synthetic fertilizers to forest soils in 2016 resulted in N_2O emissions of 0.5 MMT CO_2 Eq. (2 kt of N_2O). Nitrous oxide emissions from fertilizer application to forest soils have increased by 455 percent since 1990, but still account for a relatively small portion of overall emissions.

Waste

Waste management and treatment activities are sources of greenhouse gas emissions (see Figure 2-13). In 2016, landfills were the third-largest source of U.S. anthropogenic CH_4 emissions, accounting for 16.4 percent of total

U.S. CH_4 emissions.[4] Additionally, wastewater treatment accounts for 15.1 percent of Waste emissions, 2.3 percent of U.S. CH_4 emissions, and 1.3 percent of N_2O emissions. Emissions of CH_4 and N_2O from composting grew from 1990 to 2016, and resulted in emissions of 4.0 MMT CO_2 Eq. in 2016. A summary of greenhouse gas emissions from the Waste chapter is presented in Table 2-9.

Figure 2-13: 2016 Waste Chapter Greenhouse Gas Sources (MMT CO_2 Eq.)



Overall, in 2016, waste activities generated emissions of 131.5 MMT CO_2 Eq., or 2.0 percent of total U.S. greenhouse gas emissions.

Table 2-9: Emissions from Waste (MMT CO_2 Eq.)

Gas/Source	1990	2005	2012	2013	2014	2015	2016
CH_4	**195.6**	**150.4**	**134.0**	**130.2**	**129.8**	**128.9**	**124.6**
Landfills	179.6	132.7	117.0	113.3	112.7	111.7	107.7
Wastewater Treatment	15.7	15.8	15.1	14.9	15.0	15.1	14.8
Composting	0.4	1.9	1.9	2.0	2.1	2.1	2.1
N_2O	**3.7**	**6.1**	**6.4**	**6.5**	**6.7**	**6.7**	**6.8**
Wastewater Treatment	3.4	4.4	4.6	4.7	4.8	4.8	5.0
Composting	0.3	1.7	1.7	1.8	1.9	1.9	1.9
Total	**199.3**	**156.4**	**140.4**	**136.7**	**136.5**	**135.6**	**131.5**

Note: Totals may not sum due to independent rounding.

Some significant trends in U.S. emissions from waste source categories include the following:

- From 1990 to 2016, net CH_4 emissions from landfills decreased by 71.9 MMT CO_2 Eq. (40.0 percent), with small increases occurring in interim years. This downward trend in emissions coincided with increased landfill gas collection and control systems, and a reduction of decomposable materials (i.e., paper and paperboard, food scraps, and yard trimmings) discarded in municipal solid waste (MSW) landfills over the time series.
- Combined CH_4 and N_2O emissions from composting have generally increased since 1990, from 0.7 MMT CO_2 Eq. to 4.0 MMT CO_2 Eq. in 2016, which represents slightly less than a five-fold increase over the time series. The growth in composting since the 1990s is attributable to primarily two factors: (1) steady growth in population and residential housing, and (2) the enactment of legislation by state and local governments that discouraged the disposal of yard trimmings in landfills.

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[4] Landfills also store carbon, due to incomplete degradation of organic materials such as wood products and yard trimmings, as described in the Land Use, Land-Use Change, and Forestry chapter.

- From 1990 to 2016, CH_4 and N_2O emissions from wastewater treatment decreased by 0.9 MMT CO_2 Eq. (5.5 percent) and increased by 1.6 MMT CO_2 Eq. (46.5 percent), respectively. Methane emissions from domestic wastewater treatment have decreased since 1999 due to decreasing percentages of wastewater being treated in anaerobic systems, including reduced use of on-site septic systems and central anaerobic treatment systems. Nitrous oxide emissions from wastewater treatment processes gradually increased across the time series as a result of increasing U.S. population and protein consumption.

2.2 Emissions by Economic Sector

Throughout this report, emission estimates are grouped into five sectors (i.e., chapters) defined by the IPCC and detailed above: Energy; IPPU; Agriculture; LULUCF; and Waste. While it is important to use this characterization for consistency with United Nations Framework Convention on Climate Change (UNFCCC) reporting guidelines and to promote comparability across countries, it is also useful to characterize emissions according to commonly used economic sector categories: residential, commercial, industry, transportation, electric power, and agriculture, as well as U.S. Territories.

Using this categorization, transportation activities, in aggregate, accounted for the largest portion (28.5 percent) of total U.S. greenhouse gas emissions in 2016. Emissions from electric power, in aggregate, accounted for the second largest portion (28.4 percent). Emissions from industry accounted for about 22 percent of total U.S. greenhouse gas emissions in 2016. Emissions from industry have in general declined over the past decade due to a number of factors, including structural changes in the U.S. economy (i.e., shifts from a manufacturing-based to a service-based economy), fuel switching, and efficiency improvements.

The remaining 22 percent of U.S. greenhouse gas emissions were contributed by the residential, agriculture, and commercial sectors, plus emissions from U.S. Territories. The residential sector accounted for 5 percent, and primarily consisted of CO_2 emissions from fossil fuel combustion. Activities related to agriculture accounted for roughly 9 percent of U.S. emissions; unlike other economic sectors, agricultural sector emissions were dominated by N_2O emissions from agricultural soil management and CH_4 emissions from enteric fermentation, rather than CO_2 from fossil fuel combustion. The commercial sector accounted for roughly 6 percent of emissions, while U.S. Territories accounted for less than 1 percent. Carbon dioxide was also emitted and sequestered (in the form of C) by a variety of activities related to forest management practices, tree planting in urban areas, the management of agricultural soils, landfilling of yard trimmings, and changes in C stocks in coastal wetlands.

Table 2-10 presents a detailed breakdown of emissions from each of these economic sectors by source category, as they are defined in this report. Figure 2-14 shows the trend in emissions by sector from 1990 to 2016.

Figure 2-14: U.S. Greenhouse Gas Emissions Allocated to Economic Sectors (MMT CO₂ Eq.)

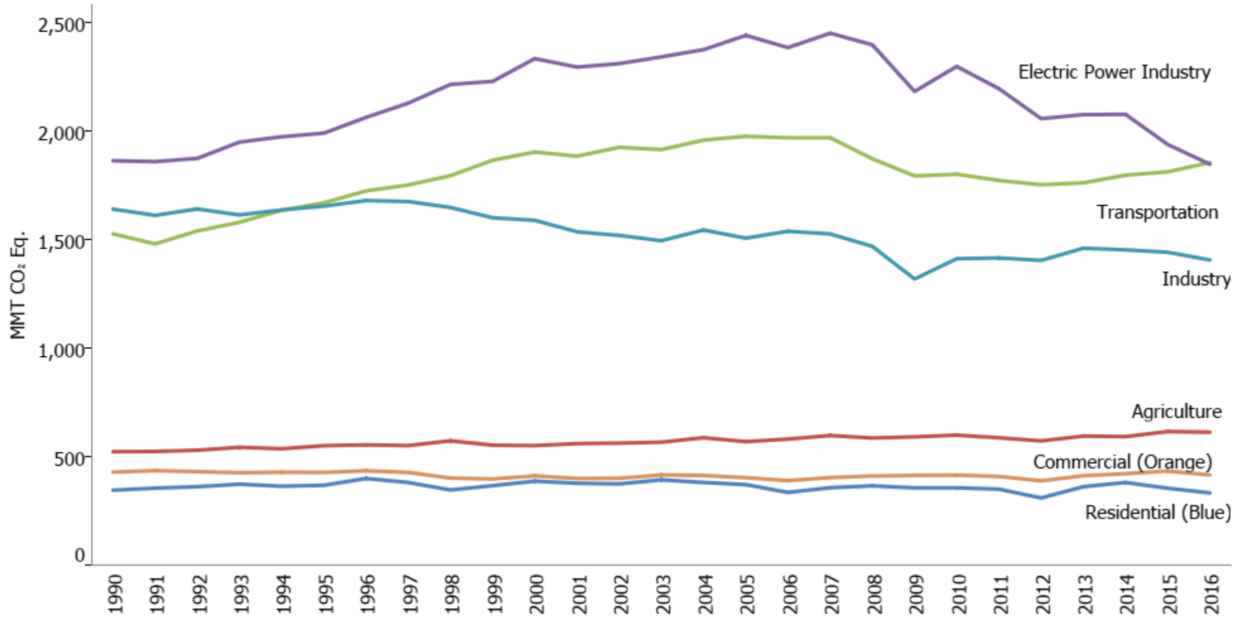

Table 2-10: U.S. Greenhouse Gas Emissions Allocated to Economic Sectors (MMT CO₂ Eq. and Percent of Total in 2016)

Sector/Source	1990	2005	2012	2013	2014	2015	2016[a]	Percent[a]
Transportation	**1,525.5**	**1,974.9**	**1,751.9**	**1,760.6**	**1,795.9**	**1,811.4**	**1,854.0**	**28.5%**
CO_2 from Fossil Fuel Combustion	1,467.6	1,855.8	1,661.9	1,677.6	1,717.1	1,735.5	1,782.6	27.4%
Substitution of Ozone Depleting Substances	+	69.5	58.1	52.7	50.0	47.7	44.8	0.7%
Mobile Combustion	46.1	39.5	23.6	21.6	19.6	18.2	17.2	0.3%
Non-Energy Use of Fuels	11.8	10.2	8.3	8.8	9.1	10.0	9.5	0.1%
Electric Power Industry	**1,862.4**	**2,439.9**	**2,056.3**	**2,074.7**	**2,076.1**	**1,937.5**	**1,846.1**	**28.4%**
CO_2 from Fossil Fuel Combustion	1,820.8	2,400.9	2,022.2	2,038.1	2,038.0	1,900.7	1,809.3	27.8%
Stationary Combustion	6.9	14.0	14.2	15.6	16.0	15.4	16.0	0.2%
Incineration of Waste	8.4	12.9	10.7	10.7	10.9	11.0	11.0	0.2%
Other Process Uses of Carbonates	3.1	3.8	4.6	5.8	6.5	6.2	5.5	0.1%
Electrical Transmission and Distribution	23.1	8.3	4.7	4.5	4.7	4.3	4.3	0.1%
Industry	**1,639.5**	**1,505.8**	**1,403.4**	**1,459.5**	**1,452.1**	**1,440.7**	**1,405.5**	**21.6%**
CO_2 from Fossil Fuel Combustion	827.2	808.3	761.9	793.2	774.2	762.0	760.7	11.7%
Natural Gas Systems	225.0	191.6	182.9	188.6	189.6	191.2	189.0	2.9%
Non-Energy Use of Fuels	102.1	120.6	94.9	109.3	104.6	110.6	97.6	1.5%
Petroleum Systems	47.5	43.8	52.0	59.2	64.9	66.8	61.4	0.9%
Coal Mining	96.5	64.1	66.5	64.6	64.6	61.2	53.8	0.8%
Iron and Steel Production	101.7	68.2	55.6	53.5	58.4	47.8	42.3	0.6%
Cement Production	33.5	46.2	35.3	36.4	39.4	39.9	39.4	0.6%
Petrochemical Production	21.4	26.9	26.6	26.5	26.6	28.2	28.4	0.4%
Substitution of Ozone Depleting Substances	+	7.9	19.7	21.4	23.2	25.7	27.8	0.4%
Lime Production	11.7	14.6	13.8	14.0	14.2	13.3	12.9	0.2%
Ammonia Production	13.0	9.2	9.4	10.0	9.6	10.9	12.2	0.2%
Nitric Acid Production	12.1	11.3	10.5	10.7	10.9	11.6	10.2	0.2%
Abandoned Oil and Gas Wells	6.5	6.9	7.0	7.0	7.1	7.2	7.1	0.1%

Adipic Acid Production	15.2	7.1	5.5	3.9	5.4	4.3	7.0	0.1%
Abandoned Underground Coal Mines	7.2	6.6	6.2	6.2	6.3	6.4	6.7	0.1%
Other Process Uses of Carbonates	3.1	3.8	4.6	5.8	6.5	6.2	5.5	0.1%
Semiconductor Manufacture	3.6	4.7	4.4	4.0	4.9	5.0	5.0	0.1%
Carbon Dioxide Consumption	1.5	1.4	4.0	4.2	4.5	4.5	4.5	0.1%
N_2O from Product Uses	4.2	4.2	4.2	4.2	4.2	4.2	4.2	0.1%
Mobile Combustion	7.2	7.6	4.8	4.7	4.4	4.2	4.1	0.1%
Stationary Combustion	4.9	4.7	4.2	4.3	4.2	4.1	4.0	0.1%
Urea Consumption for Non-Agricultural Purposes	3.8	3.7	4.4	4.1	1.5	4.2	4.0	0.1%
HCFC-22 Production	46.1	20.0	5.5	4.1	5.0	4.3	2.8	+%
Aluminum Production	28.3	7.6	6.4	6.2	5.4	4.8	2.7	+%
Caprolactam, Glyoxal, and Glyoxylic Acid Production	1.7	2.1	2.0	2.0	2.0	2.0	2.0	+%
Ferroalloy Production	2.2	1.4	1.9	1.8	1.9	2.0	1.8	+%
Soda Ash Production	1.4	1.7	1.7	1.7	1.7	1.7	1.7	+%
Titanium Dioxide Production	1.2	1.8	1.5	1.7	1.7	1.6	1.6	+%
Glass Production	1.5	1.9	1.2	1.3	1.3	1.3	1.2	+%
Magnesium Production and Processing	5.2	2.7	1.7	1.5	1.1	1.0	1.1	+%
Phosphoric Acid Production	1.5	1.3	1.1	1.1	1.0	1.0	1.0	+%
Zinc Production	0.6	1.0	1.5	1.4	1.0	0.9	0.9	+%
Lead Production	0.5	0.6	0.5	0.5	0.5	0.5	0.5	+%
Silicon Carbide Production and Consumption	0.4	0.2	0.2	0.2	0.2	0.2	0.2	+%
Agriculture	**522.0**	**568.5**	**571.8**	**594.1**	**591.5**	**615.1**	**611.8**	**9.4%**
N_2O from Agricultural Soil Management	250.5	253.5	247.9	276.6	274.0	295.0	283.6	4.4%
Enteric Fermentation	164.2	168.9	166.7	165.5	164.2	166.5	170.1	2.6%
Manure Management	51.1	72.9	83.2	80.8	80.4	84.0	85.9	1.3%
CO_2 from Fossil Fuel Combustion	31.6	47.4	51.1	50.0	50.8	47.5	48.4	0.7%
Rice Cultivation	16.0	16.7	11.3	11.5	12.7	12.3	13.7	0.2%
Urea Fertilization	2.4	3.5	4.3	4.4	4.5	4.9	5.1	0.1%
Liming	4.7	4.3	6.0	3.9	3.6	3.8	3.9	0.1%
Mobile Combustion	1.2	1.1	0.9	0.8	0.8	0.7	0.7	+%
Field Burning of Agricultural Residues	0.3	0.3	0.4	0.4	0.4	0.4	0.4	+%
Stationary Combustion	0.1	+	0.1	0.1	0.1	0.1	0.1	+%
Commercial	**428.0**	**402.6**	**388.0**	**411.3**	**420.8**	**432.9**	**415.2**	**6.4%**
CO_2 from Fossil Fuel Combustion	227.2	227.0	201.3	225.7	233.6	245.4	231.3	3.6%
Landfills	179.6	132.7	117.0	113.3	112.7	111.7	107.7	1.7%
Substitution of Ozone Depleting Substances	+	17.6	45.1	47.5	49.3	50.3	50.9	0.8%
Wastewater Treatment	15.7	15.8	15.1	14.9	15.0	15.1	14.8	0.2%
Human Sewage	3.4	4.4	4.6	4.7	4.8	4.8	5.0	0.1%
Composting	0.7	3.5	3.7	3.9	4.0	4.0	4.0	0.1%
Stationary Combustion	1.5	1.4	1.2	1.4	1.4	1.6	1.5	+%
Residential	**344.9**	**370.4**	**309.0**	**360.9**	**380.1**	**353.9**	**332.1**	**5.1%**
CO_2 from Fossil Fuel Combustion	338.3	357.8	282.5	329.7	345.3	316.8	292.5	4.5%
Substitution of Ozone Depleting Substances	0.3	7.7	22.1	25.2	28.8	32.3	35.5	0.5%
Stationary Combustion	6.3	4.9	4.5	5.9	6.1	4.7	4.1	0.1%
U.S. Territories	**33.3**	**58.1**	**48.5**	**48.1**	**46.6**	**46.6**	**46.6**	**0.7%**
CO_2 from Fossil Fuel Combustion	27.6	49.7	43.5	42.5	41.4	41.4	41.4	0.6%
Non-Energy Use of Fuels	5.7	8.1	4.8	5.4	5.1	5.1	5.1	0.1%
Stationary Combustion	0.1	0.2	0.2	0.2	0.2	0.2	0.2	+%
Total Emissions	**6,355.6**	**7,320.3**	**6,528.8**	**6,709.1**	**6,763.1**	**6,638.1**	**6,511.3**	**100.0%**

LULUCF Sector Net Total[b]	**(819.6)**	**(731.1)**	**(753.5)**	**(735.8)**	**(740.4)**	**(695.2)**	**(716.8)**	**(11.0%)**
Net Emissions (Sources and Sinks)	**5,536.0**	**6,589.1**	**5,775.3**	**5,973.3**	**6,022.8**	**5,942.9**	**5,794.5**	**89.0%**

Notes: Total emissions presented without LULUCF. Total net emissions presented with LULUCF.

+ Does not exceed 0.05 MMT CO_2 Eq. or 0.05 percent.

[a] Percent of total (gross) emissions excluding emissions from LULUCF for 2016.

[b] The LULUCF Sector Net Total is the net sum of all CH_4 and N_2O emissions to the atmosphere plus net carbon stock changes.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or sequestration.

Emissions with Electricity Distributed to Economic Sectors

It can also be useful to view greenhouse gas emissions from economic sectors with emissions related to electric power distributed into end-use categories (i.e., emissions from electric power are allocated to the economic sectors in which the electricity is used). The generation, transmission, and distribution of electricity, which is the second largest economic sector in the United States, accounted for 28 percent of total U.S. greenhouse gas emissions in 2016. Electric power-related emissions decreased by 1 percent since 1990 and by 4.7 percent from 2015 to 2016, primarily due to decreased CO_2 emissions from fossil fuel combustion due to increased natural gas consumption and decreased coal consumption.

Overall, between 2015 and 2016, the amount of electricity generated (in kWh) increased by less than 0.1 percent. However, total emissions from the electric power sector decreased by 4.7 percent from 2015 to 2016 due to changes in the consumption of coal and natural gas for electric power, which were driven by changes in their relative prices. Coal consumption decreased by 8.1 percent, while natural gas consumption increased by 3.8 percent. The consumption of petroleum for electric power decreased by 11.6 percent in 2016 relative to 2015.

Electricity sales to the residential and commercial end-use sectors each increased by 0.5 percent from 2015 to 2016. The sales trend in the residential sector can largely be attributed to an increase in the number of households in the United States. The sales trend in the commercial sector can largely be attributed to increases in commercial floorspace (EIA 2018a). Electricity sales to the industrial sector from 2015 to 2016 decreased by approximately 1.0 percent.

Table 2-11 provides a detailed summary of emissions from electric power-related activities.

Table 2-11: Electric Power-Related Greenhouse Gas Emissions (MMT CO_2 Eq.)

Gas/Fuel Type or Source	1990	2005	2012	2013	2014	2015	2016
CO_2	**1,831.9**	**2,417.2**	**2,037.1**	**2,054.2**	**2,055.1**	**1,917.5**	**1,825.4**
Fossil Fuel Combustion	1,820.8	2,400.9	2,022.2	2,038.1	2,038.0	1,900.7	1,809.3
Coal	*1,547.6*	*1,983.8*	*1,511.2*	*1,571.3*	*1,569.1*	*1,350.5*	*1,241.4*
Natural Gas	*175.3*	*318.8*	*492.2*	*444.0*	*443.2*	*526.1*	*546.0*
Petroleum	*97.5*	*97.9*	*18.3*	*22.4*	*25.3*	*23.7*	*21.4*
Geothermal	*0.4*	*0.4*	*0.4*	*0.4*	*0.4*	*0.4*	*0.4*
Incineration of Waste	8.0	12.5	10.4	10.4	10.6	10.7	10.7
Other Process Uses of Carbonates	3.1	3.8	4.6	5.8	6.5	6.2	5.5
CH_4	**0.4**	**0.9**	**1.1**	**1.0**	**1.0**	**1.1**	**1.1**
Stationary Sources[a]	0.4	0.9	1.1	1.0	1.0	1.1	1.1
Incineration of Waste	+	+	+	+	+	+	+
N_2O	**6.9**	**13.6**	**13.4**	**14.9**	**15.3**	**14.6**	**15.2**
Stationary Sources[a]	6.5	13.2	13.1	14.6	15.0	14.3	14.9
Incineration of Waste	0.5	0.4	0.3	0.3	0.3	0.3	0.3
SF_6	**23.1**	**8.3**	**4.7**	**4.5**	**4.7**	**4.3**	**4.3**
Electrical Transmission and Distribution	23.1	8.3	4.7	4.5	4.7	4.3	4.3
Total	**1,862.4**	**2,439.9**	**2,056.3**	**2,074.7**	**2,076.1**	**1,937.5**	**1,846.1**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Includes only stationary combustion emissions related to the generation of electricity.
Note: Totals may not sum due to independent rounding.

To distribute electricity emissions among economic end-use sectors, emissions from the source categories assigned to the electric power sector were allocated to the residential, commercial, industry, transportation, and agriculture economic sectors according to each economic sector's share of retail sales of electricity (EIA 2018b; Duffield 2006). These source categories include CO_2 from Fossil Fuel Combustion, CH_4 and N_2O from Stationary Combustion, Incineration of Waste, Other Process Uses of Carbonates, and SF_6 from Electrical Transmission and Distribution Systems. Note that only 50 percent of the Other Process Uses of Carbonates emissions were associated with electric power and distributed as described; the remainder of Other Process Uses of Carbonates emissions were attributed to the industrial processes economic end-use sector.[5]

When emissions from electricity use are distributed among these sectors, industrial activities account for the largest share of total U.S. greenhouse gas emissions (29.1 percent), followed closely by emissions from transportation (28.5 percent). Emissions from the residential and commercial sectors also increase substantially when emissions from electricity are included. In all sectors except agriculture, CO_2 accounts for more than 81 percent of greenhouse gas emissions, primarily from the combustion of fossil fuels.

Table 2-12 presents a detailed breakdown of emissions from each of these economic sectors, with emissions from electric power distributed to them. Figure 2-15 shows the trend in these emissions by sector from 1990 to 2016.

Figure 2-15: U.S. Greenhouse Gas Emissions with Electricity-Related Emissions Distributed to Economic Sectors (MMT CO_2 Eq.)

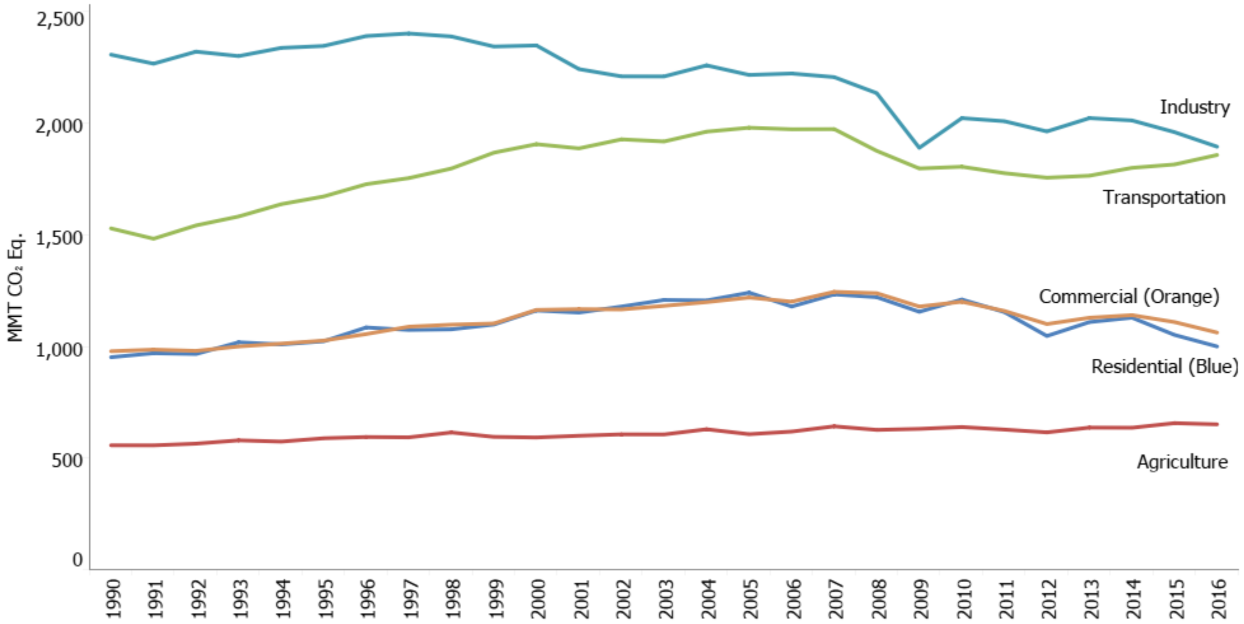

Table 2-12: U.S. Greenhouse Gas Emissions by Economic Sector and Gas with Electricity-Related Emissions Distributed (MMT CO_2 Eq.) and Percent of Total in 2016

Sector/Gas	1990	2005	2012	2013	2014	2015	2016	Percent[a]
Industry	**2,307.1**	**2,216.3**	**1,963.1**	**2,022.8**	**2,012.4**	**1,959.9**	**1,894.8**	**29.1%**
Direct Emissions	**1,639.5**	**1,505.8**	**1,403.4**	**1,459.5**	**1,452.1**	**1,440.7**	**1,405.5**	**21.6%**
CO_2	1,172.5	1,150.9	1,066.0	1,117.3	1,103.1	1,093.0	1,065.8	16.4%
CH_4	353.3	286.5	276.4	282.5	284.9	283.0	273.5	4.2%

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[5] Emissions were not distributed to U.S. Territories, since the electric power sector only includes emissions related to the generation of electricity in the 50 states and the District of Columbia.

N_2O	37.4	29.6	27.1	25.8	27.6	27.0	28.3	0.4%
HFCs, PFCs, SF_6, and NF_3	76.3	38.8	33.9	33.8	36.5	37.7	37.8	0.6%
Electricity-Related	**667.6**	**710.5**	**559.8**	**563.4**	**560.3**	**519.2**	**489.3**	**7.5%**
CO_2	656.7	703.9	554.6	557.8	554.6	513.9	483.9	7.4%
CH_4	0.2	0.3	0.3	0.3	0.3	0.3	0.3	+%
N_2O	2.5	3.9	3.7	4.1	4.1	3.9	4.0	0.1%
SF_6	8.3	2.4	1.3	1.2	1.3	1.1	1.1	+%
Transportation	**1,528.6**	**1,979.7**	**1,755.8**	**1,764.7**	**1,800.0**	**1,815.1**	**1,857.6**	**28.5%**
Direct Emissions	**1,525.5**	**1,974.9**	**1,751.9**	**1,760.6**	**1,795.9**	**1,811.4**	**1,854.0**	**28.5%**
CO_2	1,479.4	1,865.9	1,670.2	1,686.4	1,726.3	1,745.4	1,792.0	27.5%
CH_4	5.8	3.1	2.0	1.9	1.7	1.7	1.6	+%
N_2O	40.2	36.5	21.6	19.7	17.8	16.5	15.5	0.2%
HFCs[b]	+	69.5	58.1	52.7	50.0	47.7	44.8	0.7%
Electricity-Related	**3.1**	**4.8**	**3.9**	**4.1**	**4.1**	**3.8**	**3.5**	**0.1%**
CO_2	3.1	4.8	3.9	4.0	4.1	3.8	3.5	0.1%
CH_4	+	+	+	+	+	+	+	+%
N_2O	+	+	+	+	+	+	+	+%
SF_6	+	+	+	+	+	+	+	+%
Commercial	**978.3**	**1,218.9**	**1,100.1**	**1,128.4**	**1,140.0**	**1,108.9**	**1,061.9**	**16.3%**
Direct Emissions	**428.0**	**402.6**	**388.0**	**411.3**	**420.8**	**432.9**	**415.2**	**6.4%**
CO_2	227.2	227.0	201.3	225.7	233.6	245.4	231.3	3.6%
CH_4	196.7	151.5	135.0	131.3	130.9	130.1	125.8	1.9%
N_2O	4.1	6.4	6.6	6.8	7.0	7.1	7.2	0.1%
HFCs	+	17.6	45.1	47.5	49.3	50.3	50.9	0.8%
Electricity-Related	**550.3**	**816.3**	**712.1**	**717.1**	**719.2**	**676.0**	**646.8**	**9.9%**
CO_2	541.3	808.7	705.4	710.0	711.9	669.0	639.5	9.8%
CH_4	0.1	0.3	0.4	0.4	0.4	0.4	0.4	+%
N_2O	2.0	4.5	4.6	5.2	5.3	5.1	5.3	0.1%
SF_6	6.8	2.8	1.6	1.5	1.6	1.5	1.5	+%
Residential	**951.5**	**1,240.7**	**1,046.5**	**1,109.0**	**1,128.6**	**1,051.4**	**999.6**	**15.4%**
Direct Emissions	**344.9**	**370.4**	**309.0**	**360.9**	**380.1**	**353.9**	**332.1**	**5.1%**
CO_2	338.3	357.8	282.5	329.7	345.3	316.8	292.5	4.5%
CH_4	5.2	4.1	3.7	5.0	5.1	3.9	3.4	0.1%
N_2O	1.0	0.9	0.7	1.0	1.0	0.8	0.7	+%
HFCs	0.3	7.7	22.1	25.2	28.8	32.3	35.5	0.5%
Electricity-Related	**606.6**	**870.2**	**737.5**	**748.1**	**748.5**	**697.5**	**667.5**	**10.3%**
CO_2	596.6	862.1	730.6	740.7	740.9	690.3	660.1	10.1%
CH_4	0.1	0.3	0.4	0.4	0.4	0.4	0.4	+%
N_2O	2.3	4.8	4.8	5.4	5.5	5.2	5.5	0.1%
SF_6	7.5	3.0	1.7	1.6	1.7	1.5	1.6	+%
Agriculture	**556.9**	**606.6**	**614.8**	**636.1**	**635.5**	**656.1**	**650.7**	**10.0%**
Direct Emissions	**522.0**	**568.5**	**571.8**	**594.1**	**591.5**	**615.1**	**611.8**	**9.4%**
CO_2	38.7	55.2	61.3	58.4	58.9	56.1	57.3	0.9%
CH_4	218.4	242.6	244.3	240.8	240.3	245.5	251.9	3.9%
N_2O	264.9	270.7	266.2	294.9	292.3	313.5	302.5	4.6%
Electricity-Related	**34.8**	**38.0**	**43.0**	**42.0**	**44.0**	**41.0**	**38.9**	**0.6%**
CO_2	34.3	37.7	42.6	41.6	43.6	40.6	38.4	0.6%
CH_4	+	+	+	+	+	+	+	+%
N_2O	0.1	0.2	0.3	0.3	0.3	0.3	0.3	+%
SF_6	0.4	0.1	0.1	0.1	0.1	0.1	0.1	+%
U.S. Territories	**33.3**	**58.1**	**48.5**	**48.1**	**46.6**	**46.6**	**46.6**	**0.7%**
Total Emissions	**6,355.6**	**7,320.3**	**6,528.8**	**6,709.1**	**6,763.1**	**6,638.1**	**6,511.3**	**100.0%**
LULUCF Sector Net Total[c]	**(819.6)**	**(731.1)**	**(753.5)**	**(735.8)**	**(740.4)**	**(695.2)**	**(716.8)**	**(11.0%)**
Net Emissions (Sources and Sinks)	**5,536.0**	**6,589.1**	**5,775.3**	**5,973.3**	**6,022.8**	**5,942.9**	**5,794.5**	**89.0%**

Notes: Total emissions presented without LULUCF. Net emissions presented with LULUCF. Emissions from electric power are allocated based on aggregate electricity use in each end-use sector. Totals may not sum due to independent rounding.

+ Does not exceed 0.05 MMT CO_2 Eq. or 0.05 percent.

[a] Percent of total (gross) emissions excluding emissions from LULUCF for year 2016.

[b] Includes primarily HFC-134a.

[c] The LULUCF Sector Net Total is the net sum of all CH_4 and N_2O emissions to the atmosphere plus net carbon stock changes.

Industry

The industry end-use sector includes CO_2 emissions from fossil fuel combustion from all manufacturing facilities, in aggregate. This end-use sector also includes emissions that are produced as a byproduct of the non-energy-related industrial process activities. The variety of activities producing these non-energy-related emissions includes CH_4 emissions from petroleum and natural gas systems, fugitive CH_4 emissions from coal mining, byproduct CO_2 emissions from cement manufacture, and HFC, PFC, SF_6, and NF_3 byproduct emissions from semiconductor manufacture, to name a few.

Since 1990, industrial sector emissions have declined. The decline has occurred both in direct emissions and indirect emissions associated with electricity use. Structural changes within the U.S. economy that led to shifts in industrial output away from energy-intensive manufacturing products to less energy-intensive products (e.g., from steel to computer equipment) have had a significant effect on industrial emissions.

Transportation

When electricity-related emissions are distributed to economic end-use sectors, transportation activities accounted for 28.5 percent of U.S. greenhouse gas emissions in 2016. The largest sources of transportation greenhouse gases in 2016 were passenger cars (41.6 percent), freight trucks (22.9 percent), light-duty trucks, which include sport utility vehicles, pickup trucks, and minivans (18.0 percent), commercial aircraft (6.5 percent), other aircraft (2.6 percent), ships and boats (2.3 percent), rail (2.2 percent), and pipelines (2.1 percent). These figures include direct CO_2, CH_4, and N_2O emissions from fossil fuel combustion used in transportation and emissions from non-energy use (i.e., lubricants) used in transportation, as well as HFC emissions from mobile air conditioners and refrigerated transport allocated to these vehicle types.

In terms of the overall trend, from 1990 to 2016, total transportation emissions increased due, in large part, to increased demand for travel. The number of VMT by light-duty motor vehicles (passenger cars and light-duty trucks) increased 44 percent from 1990 to 2016,[6] as a result of a confluence of factors including population growth, economic growth, urban sprawl, and periods of low fuel prices.

The decline in new light-duty vehicle fuel economy between 1990 and 2004 reflected the increasing market share of light-duty trucks, which grew from about 30 percent of new vehicle sales in 1990 to 48 percent in 2004. Starting in 2005, average new vehicle fuel economy began to increase while light-duty VMT grew only modestly for much of the period. Light-duty VMT grew by less than one percent or declined each year between 2005 and 2014[7] and has since grown at a faster rate (2.6 percent from 2014 to 2015, and 2.5 percent from 2015 to 2016). Average new vehicle fuel economy has increased almost every year since 2005 while the light-duty truck share decreased to about 33 percent in 2009 and has since varied from year to year between 36 percent and 43 percent. Light-duty truck share is about 38 percent of new vehicles in model year 2016 (EPA 2018).

Table 2-13 provides a detailed summary of greenhouse gas emissions from transportation-related activities with electricity-related emissions included in the totals.

Almost all of the energy consumed for transportation was supplied by petroleum-based products, with more than half being related to gasoline consumption in automobiles and other highway vehicles. Other fuel uses, especially

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[6] VMT estimates are based on data from FHWA Highway Statistics Table VM-1 (FHWA 1996 through 2017). In 2011, FHWA changed its methods for estimating VMT by vehicle class, which led to a shift in VMT and emissions among on-road vehicle classes in the 2007 to 2016 time period. In absence of these method changes, light-duty VMT growth between 1990 and 2016 would likely have been even higher.

[7] In 2007 and 2008 light-duty VMT decreased 3 percent and 2.3 percent, respectively. Note that the decline in light-duty VMT from 2006 to 2007 is due at least in part to a change in FHWA's methods for estimating VMT. In absence of these method changes, light-duty VMT growth between 2006 and 2007 would likely have been higher. See previous footnote.

diesel fuel for freight trucks and jet fuel for aircraft, accounted for the remainder. The primary driver of transportation-related emissions was CO_2 from fossil fuel combustion, which increased by 21 percent from 1990 to 2016.[8] This rise in CO_2 emissions, combined with an increase in HFCs from close to zero emissions in 1990 to 44.8 MMT CO_2 Eq. in 2016, led to an increase in overall emissions from transportation activities of 22 percent.[9]

Table 2-13: Transportation-Related Greenhouse Gas Emissions (MMT CO_2 Eq.)

Gas/Vehicle	1990	2005	2012	2013	2014	2015	2016
Passenger Cars	**639.9**	**693.1**	**745.9**	**740.8**	**756.7**	**761.0**	**772.2**
CO_2	612.5	642.6	711.3	710.9	729.6	735.8	749.4
CH_4	3.2	1.3	0.9	0.8	0.7	0.6	0.6
N_2O	24.1	17.6	13.1	11.8	10.5	9.7	8.9
HFCs	0.0	31.7	20.6	17.3	15.9	14.8	13.3
Light-Duty Trucks	**326.9**	**539.7**	**316.2**	**313.2**	**334.2**	**324.8**	**334.2**
CO_2	312.4	490.6	281.3	281.5	304.7	297.4	309.1
CH_4	1.7	0.8	0.3	0.3	0.3	0.2	0.2
N_2O	12.8	15.0	5.3	4.7	4.4	3.8	3.5
HFCs	0.0	33.3	29.3	26.7	24.9	23.3	21.4
Medium- and Heavy-Duty Trucks	**230.3**	**400.3**	**390.5**	**397.4**	**408.7**	**417.1**	**425.9**
CO_2	229.3	395.4	383.6	390.3	401.5	409.7	418.4
CH_4	0.3	0.1	0.1	0.1	0.1	0.1	0.1
N_2O	0.7	1.2	1.0	0.9	0.9	0.8	0.8
HFCs	0.0	3.6	5.8	6.0	6.3	6.5	6.6
Buses	**8.5**	**12.2**	**18.0**	**18.2**	**19.5**	**19.8**	**19.8**
CO_2	8.4	11.6	17.2	17.5	18.8	19.2	19.1
CH_4	+	0.2	0.3	0.2	0.2	0.2	0.2
N_2O	+	+	+	+	+	+	+
HFCs	0.0	0.3	0.4	0.4	0.4	0.4	0.4
Motorcycles	**1.7**	**1.6**	**4.0**	**3.8**	**3.8**	**3.7**	**3.9**
CO_2	1.7	1.6	3.9	3.7	3.7	3.7	3.8
CH_4	+	+	+	+	+	+	+
N_2O	+	+	+	+	+	+	+
Commercial Aircraft[a]	**110.9**	**134.0**	**114.3**	**115.4**	**116.3**	**120.1**	**121.5**
CO_2	109.9	132.7	113.3	114.3	115.2	119.0	120.4
CH_4	0.0	0.0	0.0	0.0	0.0	0.0	0.0
N_2O	1.0	1.2	1.0	1.1	1.1	1.1	1.1
Other Aircraft[b]	**78.3**	**59.7**	**32.1**	**34.7**	**35.0**	**40.4**	**47.5**
CO_2	77.5	59.1	31.8	34.4	34.7	40.0	47.0
CH_4	0.1	0.1	+	+	+	+	+
N_2O	0.7	0.5	0.3	0.3	0.3	0.4	0.4
Ships and Boats[c]	**45.3**	**45.8**	**41.9**	**41.5**	**31.0**	**35.7**	**42.8**
CO_2	44.3	44.3	39.3	38.6	28.0	32.3	39.0
CH_4	0.5	0.5	0.4	0.4	0.3	0.3	0.3
N_2O	0.6	0.6	0.5	0.5	0.3	0.4	0.5
HFCs	0.0	0.5	1.7	2.0	2.3	2.6	2.9
Rail	**38.9**	**50.9**	**43.9**	**44.8**	**46.2**	**44.1**	**40.8**
CO_2	38.5	50.3	43.4	44.2	45.6	43.5	40.2
CH_4	0.1	0.1	0.1	0.1	0.1	0.1	0.1
N_2O	0.3	0.4	0.3	0.3	0.3	0.3	0.3
HFCs	0.0	0.1	0.1	0.1	0.1	0.1	0.1
Other Emissions from Electric Power[d]	0.1	+	+	+	+	+	+

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[8] See previous footnote.

[9] See previous footnote.

Pipelines[e]	**36.0**	**32.4**	**40.5**	**46.2**	**39.4**	**38.5**	**39.6**
CO_2	36.0	32.4	40.5	46.2	39.4	38.5	39.6
Lubricants	**11.8**	**10.2**	**8.3**	**8.8**	**9.1**	**10.0**	**9.5**
CO_2	11.8	10.2	8.3	8.8	9.1	10.0	9.5
Total Transportation	**1,528.6**	**1,979.7**	**1,755.8**	**1,764.7**	**1,800.0**	**1,815.1**	**1,857.6**
International Bunker Fuels[f]	*104.5*	*114.2*	*106.8*	*100.7*	*104.4*	*111.9*	*117.7*
Ethanol CO_2[g]	*4.1*	*22.4*	*71.5*	*73.4*	*74.9*	*76.0*	*78.2*
Biodiesel CO_2[g]	*0.0*	*0.9*	*8.5*	*13.5*	*13.3*	*14.1*	*19.6*

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Consists of emissions from jet fuel consumed by domestic operations of commercial aircraft (no bunkers).

[b] Consists of emissions from jet fuel and aviation gasoline consumption by general aviation and military aircraft.

[c] Fluctuations in emission estimates are associated with fluctuations in reported fuel consumption, and may reflect issues with data sources.

[d] Other emissions from electric power are a result of waste incineration (as the majority of municipal solid waste is combusted in "trash-to-steam" electric power plants), electrical transmission and distribution, and a portion of Other Process Uses of Carbonates (from pollution control equipment installed in electric power plants).

[e] CO_2 estimates reflect natural gas used to power pipelines, but not electricity. While the operation of pipelines produces CH_4 and N_2O, these emissions are not directly attributed to pipelines in the Inventory.

[f] Emissions from International Bunker Fuels include emissions from both civilian and military activities; these emissions are not included in the transportation totals.

[g] Ethanol and biodiesel CO_2 estimates are presented for informational purposes only. See Section 3.11 and the estimates in Land Use, Land-Use Change, and Forestry (see Chapter 6), in line with IPCC methodological guidance and UNFCCC reporting obligations, for more information on ethanol and biodiesel.

Notes: Passenger cars and light-duty trucks include vehicles typically used for personal travel and less than 8,500 lbs; medium- and heavy-duty trucks include vehicles larger than 8,500 lbs. HFC emissions primarily reflect HFC-134a. Totals may not sum due to independent rounding.

Commercial

The commercial sector is heavily reliant on electricity for meeting energy needs, with electricity use for lighting, heating, air conditioning, and operating appliances. The remaining emissions were largely due to the direct consumption of natural gas and petroleum products, primarily for heating and cooking needs. Energy-related emissions from the commercial sector have generally been increasing since 1990, and are often correlated with short-term fluctuations in energy use caused by weather conditions, rather than prevailing economic conditions. Decreases in energy-related emissions in the commercial sector in recent years can be largely attributed to an overall reduction in energy use, a reduction in heating degree days, and increases in energy efficiency.

Landfills and wastewater treatment are included in the commercial sector, with landfill emissions decreasing since 1990 and wastewater treatment emissions decreasing slightly.

Residential

The residential sector is heavily reliant on electricity for meeting energy needs, with electricity consumption for lighting, heating, air conditioning, and operating appliances. The remaining emissions were largely due to the direct consumption of natural gas and petroleum products, primarily for heating and cooking needs. Emissions from the residential sector have generally been increasing since 1990, and are often correlated with short-term fluctuations in energy consumption caused by weather conditions, rather than prevailing economic conditions. In the long term, the residential sector is also affected by population growth, migration trends toward warmer areas, and changes in housing and building attributes (e.g., larger sizes and improved insulation). A shift toward energy efficient products and more stringent energy efficiency standards for household equipment has also contributed to recent trends in energy demand in households (EIA 2017a).

Agriculture

The agriculture end-use sector includes a variety of processes, including enteric fermentation in domestic livestock, livestock manure management, and agricultural soil management. In 2016, agricultural soil management was the largest source of N_2O emissions, and enteric fermentation was the largest source of CH_4 emissions in the United States. This sector also includes small amounts of CO_2 emissions from fossil fuel combustion by motorized farm equipment like tractors.

Box 2-1: Methodology for Aggregating Emissions by Economic Sector

In presenting the Economic Sectors in the annual *Inventory of U.S. Greenhouse Gas Emissions and Sinks*, the Inventory expands upon the standard IPCC sectors common for UNFCCC reporting. Discussing greenhouse gas emissions relevant to U.S.-specific economic sectors improves communication of the report's findings.

The *Electric Power* economic sector includes CO_2 emissions from the combustion of fossil fuels that are included in the EIA electric utility fuel-consuming sector. Stationary combustion emissions of CH_4 and N_2O are also based on the EIA electric power sector. Additional sources include CO_2, CH_4, and N_2O from waste incineration, as the majority of municipal solid waste is combusted in "trash-to-steam" electric power plants. The Electric Power economic sector also includes SF_6 from Electrical Transmission and Distribution, and a portion of CO_2 from Other Process Uses of Carbonates (from pollution control equipment installed in electric power plants).

The *Transportation* economic sector includes CO_2 emissions from the combustion of fossil fuels that are included in the EIA transportation fuel-consuming sector. (Additional analyses and refinement of the EIA data are further explained in the Energy chapter of this report.) Emissions of CH_4 and N_2O from mobile combustion are also apportioned to the Transportation economic sector based on the EIA transportation fuel-consuming sector. Substitution of Ozone Depleting Substances emissions are apportioned to the Transportation economic sector based on emissions from refrigerated transport and motor vehicle air-conditioning systems. Finally, CO_2 emissions from Non-Energy Uses of Fossil Fuels identified as lubricants for transportation vehicles are included in the Transportation economic sector.

The *Industry* economic sector includes CO_2 emissions from the combustion of fossil fuels that are included in the EIA industrial fuel-consuming sector, minus the agricultural use of fuel explained below. The CH_4 and N_2O emissions from stationary and mobile combustion are also apportioned to the Industry economic sector based on the EIA industrial fuel-consuming sector, minus emissions apportioned to the Agriculture economic sector. Substitution of Ozone Depleting Substances emissions are apportioned based on their specific end-uses within the source category, with most emissions falling within the Industry economic sector.

Additionally, all process-related emissions from sources with methods considered within the IPCC IPPU sector are apportioned to the Industry economic sector. This includes the process-related emissions (i.e., emissions from the actual process to make the material, not from fuels to power the plant) from activities such as Cement Production, Iron and Steel Production and Metallurgical Coke Production, and Ammonia Production. Additionally, fugitive emissions from energy production sources, such as Natural Gas Systems, Coal Mining, and Petroleum Systems are included in the Industry economic sector. A portion of CO_2 from Other Process Uses of Carbonates (from pollution control equipment installed in large industrial facilities) is also included in the Industry economic sector. Finally, all remaining CO_2 emissions from Non-Energy Uses of Fossil Fuels are assumed to be industrial in nature (besides the lubricants for transportation vehicles specified above), and are attributed to the Industry economic sector.

The *Agriculture* economic sector includes CO_2 emissions from the combustion of fossil fuels that are included in supplementary sources of agriculture fuel use, because EIA does not include an agriculture fuel-consuming sector. Agriculture equipment is included in the EIA industrial fuel-consuming sector. Agriculture fuel use estimates are obtained from U.S. Department of Agriculture survey data, in combination with separate EIA fuel sales reports (USDA 2018; EIA 2017b). These supplementary data are subtracted from the industrial fuel use reported by EIA to obtain agriculture fuel use. CO_2 emissions from fossil fuel combustion, and CH_4 and N_2O emissions from stationary and mobile combustion, are then apportioned to the Agriculture economic sector based on agricultural fuel use.

The other emission sources included in the Agriculture economic sector are intuitive for the agriculture sectors, such as N_2O emissions from Agricultural Soils, CH_4 from Enteric Fermentation, CH_4 and N_2O from Manure Management, CH_4 from Rice Cultivation, CO_2 emissions from Liming and Urea Application, and CH_4 and N_2O from Field Burning of Agricultural Residues.

The *Residential* economic sector includes CO_2 emissions from the combustion of fossil fuels that are included in the EIA residential fuel-consuming sector. Stationary combustion emissions of CH_4 and N_2O are also based on the EIA residential fuel-consuming sector. Substitution of Ozone Depleting Substances are apportioned to the Residential economic sector based on emissions from residential air-conditioning systems. Nitrous oxide emissions from the application of fertilizers to developed land (termed "settlements" by the IPCC) are also included in the Residential economic sector.

The *Commercial* economic sector includes CO_2 emissions from the combustion of fossil fuels that are included in the EIA commercial fuel-consuming sector. Emissions of CH_4 and N_2O from Mobile Combustion are also apportioned to the Commercial economic sector based on the EIA commercial fuel-consuming sector. Substitution of Ozone Depleting Substances emissions are apportioned to the Commercial economic sector based on emissions from commercial refrigeration/air-conditioning systems. Public works sources including direct CH_4 from Landfills, CH_4 and N_2O from Wastewater Treatment, and Composting are also included in the Commercial economic sector.

Box 2-2: Recent Trends in Various U.S. Greenhouse Gas Emissions-Related Data

Total emissions can be compared to other economic and social indices to highlight changes over time. These comparisons include: (1) emissions per unit of aggregate energy use, because energy-related activities are the largest sources of emissions; (2) emissions per unit of fossil fuel consumption, because almost all energy-related emissions involve the combustion of fossil fuels; (3) emissions per unit of electricity use, because the electric power industry—utilities and non-utilities combined—was the second largest source of U.S. greenhouse gas emissions in 2016; (4) emissions per unit of total gross domestic product as a measure of national economic activity; or (5) emissions per capita.

Table 2-14 provides data on various statistics related to U.S. greenhouse gas emissions normalized to 1990 as a baseline year. These values represent the relative change in each statistic since 1990. Greenhouse gas emissions in the United States have grown at an average annual rate of 0.1 percent since 1990. This rate is slightly slower than that for total energy use and fossil fuel consumption, and much slower than that for electricity use, overall gross domestic product (GDP) and national population (see Table 2-14 and Figure 2-16). These trends vary relative to 2005, when greenhouse gas emissions, total energy use and fossil fuel consumption began to peak. Greenhouse gas emissions in the United States have decreased at an average annual rate of 1.0 percent since 2005. Total energy use and fossil fuel consumption have also decreased at slower rates than emissions since 2005, while electricity use, GDP, and national population continued to increase.

Table 2-14: Recent Trends in Various U.S. Data (Index 1990 = 100)

Variable	1990	2005	2012	2013	2014	2015	2016	Avg. Annual Change since 1990[a]	Avg. Annual Change since 2005[a]
Greenhouse Gas Emissions[b]	100	115	103	106	106	104	102	0.1%	-1.0%
Energy Use[c]	100	118	112	116	117	116	116	0.6%	-0.2%
Fossil Fuel Consumption[c]	100	119	107	110	111	110	109	0.4%	-0.7%
Electricity Use[c]	100	134	135	136	138	137	138	1.2%	0.2%
GDP[d]	100	159	171	174	179	184	187	2.4%	1.5%
Population[e]	100	118	125	126	127	128	129	1.0%	0.8%

[a] Average annual growth rate

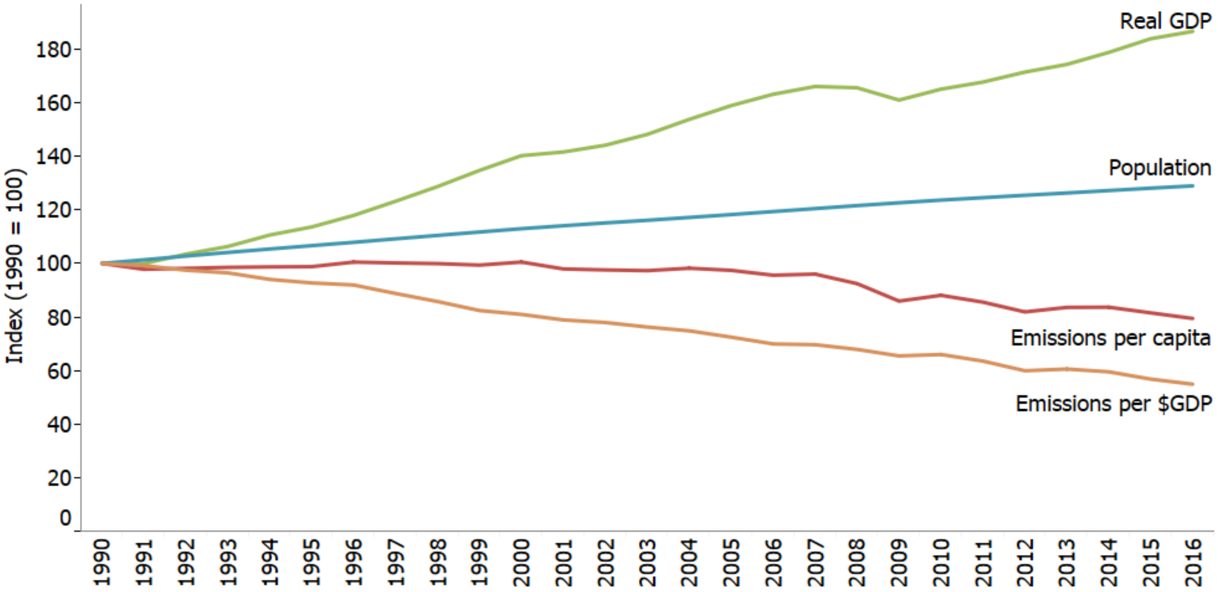
[b] GWP-weighted values

[c] Energy-content-weighted values (EIA 2018b)

[d] GDP in chained 2009 dollars (BEA 2018)

[e] U.S. Census Bureau (2017)

Figure 2-16: U.S. Greenhouse Gas Emissions Per Capita and Per Dollar of Gross Domestic Product



Source: BEA (2017), U.S. Census Bureau (2017), and emission estimates in this report.

2.3 Indirect Greenhouse Gas Emissions (CO, NO_x, NMVOCs, and SO_2)

The reporting requirements of the UNFCCC[10] request that information be provided on indirect greenhouse gases, which include CO, NO_x, NMVOCs, and SO_2. These gases do not have a direct global warming effect, but indirectly affect terrestrial radiation absorption by influencing the formation and destruction of tropospheric and stratospheric ozone, or, in the case of SO_2, by affecting the absorptive characteristics of the atmosphere. Additionally, some of these gases may react with other chemical compounds in the atmosphere to form compounds that are greenhouse gases. Carbon monoxide is produced when carbon-containing fuels are combusted incompletely. Nitrogen oxides (i.e., NO and NO_2) are created by lightning, fires, fossil fuel combustion, and in the stratosphere from N_2O. Non-methane volatile organic compounds—which include hundreds of organic compounds that participate in atmospheric chemical reactions (i.e., propane, butane, xylene, toluene, ethane, and many others)—are emitted primarily from transportation, industrial processes, and non-industrial consumption of organic solvents. In the United States, SO_2 is primarily emitted from coal combustion for electric power generation and the metals industry. Sulfur-containing compounds emitted into the atmosphere tend to exert a negative radiative forcing (i.e., cooling) and therefore are discussed separately.

One important indirect climate change effect of NMVOCs and NO_x is their role as precursors for tropospheric ozone formation. They can also alter the atmospheric lifetimes of other greenhouse gases. Another example of indirect greenhouse gas formation into greenhouse gases is the interaction of CO with the hydroxyl radical—the major

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[10] See <http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf>.

atmospheric sink for CH_4 emissions—to form CO_2. Therefore, increased atmospheric concentrations of CO limit the number of hydroxyl molecules (OH) available to destroy CH_4.

Since 1970, the United States has published estimates of emissions of CO, NO_x, NMVOCs, and SO_2 (EPA 2016),[11] which are regulated under the Clean Air Act. Table 2-15 shows that fuel combustion accounts for the majority of emissions of these indirect greenhouse gases. Industrial processes—such as the manufacture of chemical and allied products, metals processing, and industrial uses of solvents—are also significant sources of CO, NO_x, and NMVOCs.

Table 2-15: Emissions of NO_x, CO, NMVOCs, and SO_2 (kt)

Gas/Activity	1990	2005	2012	2013	2014	2015	2016
NO_x	**21,791**	**17,443**	**12,038**	**11,388**	**10,807**	**10,252**	**9,278**
Mobile Fossil Fuel Combustion	10,862	10,295	6,871	6,448	6,024	5,417	4,814
Stationary Fossil Fuel Combustion	10,023	5,858	3,655	3,504	3,291	3,061	2,692
Oil and Gas Activities	139	321	663	704	745	745	745
Forest Fires	81	239	276	185	185	474	474
Industrial Processes and Product Use	592	572	443	434	424	424	424
Waste Combustion	82	128	82	91	100	100	100
Grassland Fires	5	21	39	13	27	21	19
Agricultural Burning	6	6	7	7	8	8	7
Waste	+	2	2	2	2	2	2
CO	**132,926**	**75,569**	**54,109**	**48,589**	**46,875**	**54,977**	**52,990**
Mobile Fossil Fuel Combustion	119,360	58,615	36,153	34,000	31,848	29,881	27,934
Forest Fires	2,880	8,484	9,804	6,624	6,595	16,752	16,752
Stationary Fossil Fuel Combustion	5,000	4,648	4,027	3,884	3,741	3,741	3,741
Waste Combustion	978	1,403	1,318	1,632	1,947	1,947	1,947
Industrial Processes and Product Use	4,129	1,557	1,246	1,262	1,273	1,273	1,273
Oil and Gas Activities	302	318	666	723	780	780	780
Grassland Fires	84	358	657	217	442	356	324
Agricultural Burning	191	178	232	239	240	239	230
Waste	1	7	6	8	9	9	9
NMVOCs	**20,930**	**13,154**	**11,464**	**11,202**	**10,935**	**10,647**	**10,362**
Industrial Processes and Product Use	7,638	5,849	3,861	3,793	3,723	3,723	3,723
Mobile Fossil Fuel Combustion	10,932	5,724	4,243	3,924	3,605	3,318	3,032
Oil and Gas Activities	554	510	2,651	2,786	2,921	2,921	2,921
Stationary Fossil Fuel Combustion	912	716	569	539	507	507	507
Waste Combustion	222	241	94	108	121	121	121
Waste	673	114	45	51	57	57	57
Agricultural Burning	NA	NA	NA	NA	NA	NA	NA
SO_2	**20,935**	**13,196**	**5,876**	**5,874**	**4,357**	**3,448**	**2,457**
Stationary Fossil Fuel Combustion	18,407	11,541	5,006	5,005	3,640	2,756	1,790
Industrial Processes and Product Use	1,307	831	604	604	496	496	496
Mobile Fossil Fuel Combustion	390	180	108	108	93	93	93
Oil and Gas Activities	793	619	142	142	95	70	44
Waste Combustion	38	25	15	15	32	32	32
Waste	+	1	+	+	1	1	1
Agricultural Burning	NA	NA	NA	NA	NA	NA	NA

\+ Does not exceed 0.5 kt.

NA (Not Available)

Note: Totals may not sum due to independent rounding.

Source: (EPA 2016) except for estimates from Field Burning of Agricultural Residues.

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[11] NO_x and CO emission estimates from Field Burning of Agricultural Residues were estimated separately, and therefore not taken from EPA (2016).

Box 2-3: Sources and Effects of Sulfur Dioxide

Sulfur dioxide (SO_2) emitted into the atmosphere through natural and anthropogenic processes affects the earth's radiative budget through its photochemical transformation into sulfate aerosols that can:

(1) scatter radiation from the sun back to space, thereby reducing the radiation reaching the earth's surface;
(2) affect cloud formation; and
(3) affect atmospheric chemical composition (e.g., by providing surfaces for heterogeneous chemical reactions).

The indirect effect of sulfur-derived aerosols on radiative forcing can be considered in two parts. The first indirect effect is the aerosols' tendency to decrease water droplet size and increase water droplet concentration in the atmosphere. The second indirect effect is the tendency of the reduction in cloud droplet size to affect precipitation by increasing cloud lifetime and thickness. Although still highly uncertain, the radiative forcing estimates from both the first and the second indirect effect are believed to be negative, as is the combined radiative forcing of the two (IPCC 2013).

Sulfur dioxide is also a major contributor to the formation of regional haze, which can cause significant increases in acute and chronic respiratory diseases. Once SO_2 is emitted, it is chemically transformed in the atmosphere and returns to the earth as the primary source of acid rain. Because of these harmful effects, the United States has regulated SO_2 emissions in the Clean Air Act.

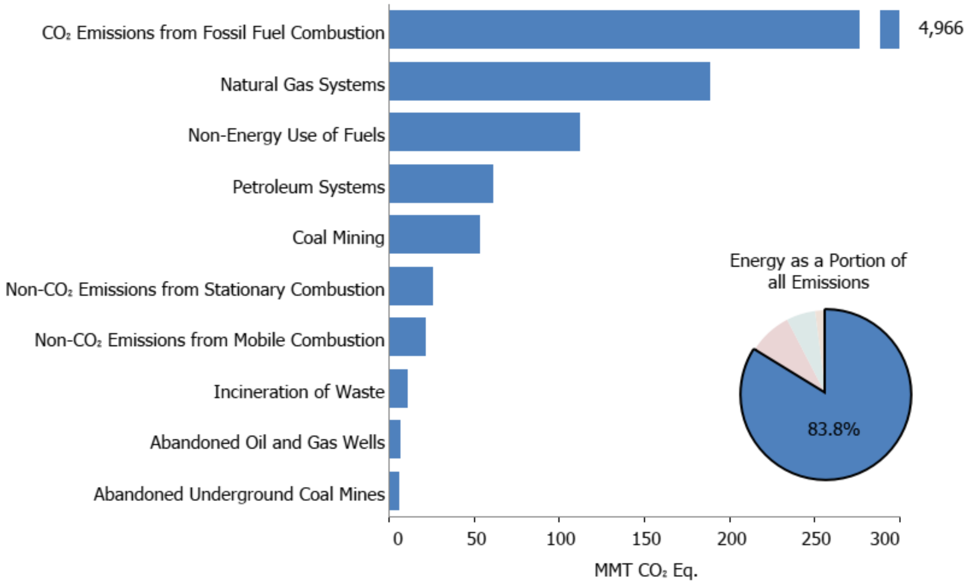
Electric power is the largest anthropogenic source of SO_2 emissions in the United States, accounting for 43.8 percent in 2016. Coal combustion contributes nearly all of those emissions (approximately 92 percent). Sulfur dioxide emissions have decreased in recent years, primarily as a result of electric power generators switching from high-sulfur to low-sulfur coal and installing flue gas desulfurization equipment.

3. Energy

Energy-related activities were the primary sources of U.S. anthropogenic greenhouse gas emissions, accounting for 83.8 percent of total greenhouse gas emissions on a carbon dioxide (CO_2) equivalent basis in 2016.[1] This included 97, 43, and 10 percent of the nation's CO_2, methane (CH_4), and nitrous oxide (N_2O) emissions, respectively. Energy-related CO_2 emissions alone constituted 78.9 percent of national emissions from all sources on a CO_2 equivalent basis, while the non-CO_2 emissions from energy-related activities represented a much smaller portion of total national emissions (4.9 percent collectively).

Emissions from fossil fuel combustion comprise the vast majority of energy-related emissions, with CO_2 being the primary gas emitted (see Figure 3-1). Globally, approximately 32,294 million metric tons (MMT) of CO_2 were added to the atmosphere through the combustion of fossil fuels in 2015, of which the United States accounted for approximately 15 percent.[2] Due to their relative importance, fossil fuel combustion-related CO_2 emissions are considered separately, and in more detail than other energy-related emissions (see Figure 3-2). Fossil fuel combustion also emits CH_4 and N_2O. Stationary combustion of fossil fuels was the second largest source of N_2O emissions in the United States and mobile fossil fuel combustion was the third largest source.

Figure 3-1: 2016 Energy Chapter Greenhouse Gas Sources (MMT CO_2 Eq.)



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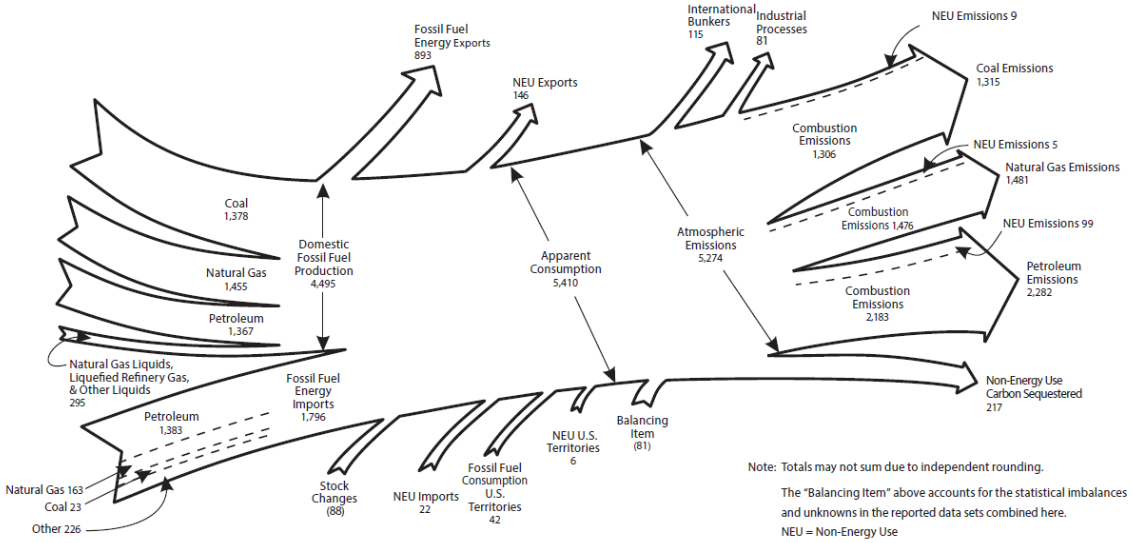
[1] Estimates are presented in units of million metric tons of carbon dioxide equivalent (MMT CO_2 Eq.), which weight each gas by its global warming potential, or GWP, value. See section on global warming potentials in the Executive Summary.

[2] Global CO_2 emissions from fossil fuel combustion were taken from International Energy Agency *CO_2 Emissions from Fossil Fuels Combustion – Highlights* <https://www.iea.org/publications/freepublications/publication/co2-emissions-from-fuel-combustion-highlights-2017.html> IEA (2017).

Figure 3-2: 2016 U.S. Fossil Carbon Flows (MMT CO_2 Eq.)



Note: Totals may not sum due to independent rounding.

The "Balancing Item" above accounts for the statistical imbalances and unknowns in the reported data sets combined here.

NEU = Non-Energy Use

Energy-related activities other than fuel combustion, such as the production, transmission, storage, and distribution of fossil fuels, also emit greenhouse gases. These emissions consist primarily of fugitive CH_4 from natural gas systems, petroleum systems, and coal mining. Table 3-1 summarizes emissions from the Energy sector in units of MMT CO_2 Eq., while unweighted gas emissions in kilotons (kt) are provided in Table 3-2. Overall, emissions due to energy-related activities were 5,455.2 MMT CO_2 Eq. in 2016,[3] an increase of 2.4 percent since 1990 and a decrease of 2.0 percent since 2015.

Each year, some emission and sink estimates in the Inventory are recalculated and revised with improved methods and/or data. In general, recalculations are made to the U.S. greenhouse gas emission estimates either to incorporate new methodologies or, most commonly, to update recent historical data. These improvements are implemented consistently across the previous Inventory's time series (i.e., 1990 to 2015) to ensure that the trend is accurate. Categories in the Energy sector with recalculations resulting in an average change over the time series of greater than 10 MMT CO_2 Eq. include Fossil Fuel Combustion (Transportation emissions shifted to Industrial and Commercial), Petroleum Systems, and Natural Gas Systems. For more information on specific methodological updates, please see the Recalculations Discussion for each category, in this chapter.

Table 3-1: CO_2, CH_4, and N_2O Emissions from Energy (MMT CO_2 Eq.)

Gas/Source	1990	2005	2012	2013	2014	2015	2016
CO_2	**4,905.4**	**5,932.5**	**5,185.3**	**5,338.2**	**5,381.4**	**5,239.2**	**5,137.2**
Fossil Fuel Combustion	4,740.3	5,746.9	5,024.4	5,156.9	5,200.3	5,049.3	4,966.0
Electric Power	*1,820.8*	*2,400.9*	*2,022.2*	*2,038.1*	*2,038.0*	*1,900.7*	*1,809.3*
Transportation	*1,467.6*	*1,855.8*	*1,661.9*	*1,677.6*	*1,717.1*	*1,735.5*	*1,782.6*
Industrial	*858.8*	*855.7*	*812.9*	*843.3*	*824.9*	*809.5*	*809.1*
Residential	*338.3*	*357.8*	*282.5*	*329.7*	*345.3*	*316.8*	*292.5*
Commercial	*227.2*	*227.0*	*201.3*	*225.7*	*233.6*	*245.4*	*231.3*
U.S. Territories	*27.6*	*49.7*	*43.5*	*42.5*	*41.4*	*41.4*	*41.4*
Non-Energy Use of Fuels	119.5	138.9	108.0	123.5	118.9	125.6	112.2
Natural Gas Systems	29.8	22.5	23.3	24.8	25.3	24.9	25.5
Petroleum Systems	7.7	11.7	19.3	22.6	26.3	28.8	22.8
Incineration of Waste	8.0	12.5	10.4	10.4	10.6	10.7	10.7

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[3] Following the current reporting requirements under the UNFCCC, this Inventory report presents CO_2 equivalent values based on the *IPCC Fourth Assessment Report* (AR4) GWP values. See the Introduction chapter for more information.

Abandoned Oil and Gas Wells	+	+	+	+	+	+	+
Biomass-Wood[a]	*215.2*	*206.9*	*206.4*	*228.2*	*234.9*	*217.4*	*208.4*
International Bunker Fuels[b]	*103.5*	*113.1*	*105.8*	*99.8*	*103.4*	*110.9*	*116.6*
Biofuels-Ethanol[a]	*4.2*	*22.9*	*72.8*	*74.7*	*76.1*	*78.9*	*81.2*
Biofuels-Biodiesel[a]	*0.0*	*0.9*	*8.5*	*13.5*	*13.3*	*14.1*	*19.6*
CH_4	**366.5**	**296.0**	**284.4**	**291.7**	**294.0**	**290.9**	**280.7**
Natural Gas Systems	195.2	169.1	159.6	163.8	164.3	166.3	163.5
Coal Mining	96.5	64.1	66.5	64.6	64.6	61.2	53.8
Petroleum Systems	39.8	32.1	32.7	36.6	38.6	38.1	38.6
Stationary Combustion	8.6	7.8	7.4	8.8	8.9	7.9	7.3
Abandoned Oil and Gas Wells	6.5	6.9	7.0	7.0	7.1	7.2	7.1
Abandoned Underground Coal Mines	7.2	6.6	6.2	6.2	6.3	6.4	6.7
Mobile Combustion	12.7	9.4	5.1	4.7	4.2	3.8	3.6
Incineration of Waste	+	+	+	+	+	+	+
International Bunker Fuels[b]	*0.2*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*
N_2O	**53.2**	**56.7**	**41.5**	**41.5**	**40.0**	**37.7**	**37.3**
Stationary Combustion	11.1	17.5	16.9	18.7	19.0	18.1	18.6
Mobile Combustion	41.7	38.8	24.3	22.5	20.6	19.3	18.4
Incineration of Waste	0.5	0.4	0.3	0.3	0.3	0.3	0.3
International Bunker Fuels[b]	*0.9*	*1.0*	*0.9*	*0.9*	*0.9*	*0.9*	*1.0*
Total	**5,325.1**	**6,285.2**	**5,511.2**	**5,671.4**	**5,715.4**	**5,567.8**	**5,455.2**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Emissions from Wood Biomass, Ethanol, and Biodiesel Consumption are not included specifically in summing Energy sector totals. Net carbon fluxes from changes in biogenic carbon reservoirs are accounted for in the estimates for LULUCF.

[b] Emissions from International Bunker Fuels are not included in totals. These values are presented for informational purposes only, in line with the *2006 IPCC Guidelines* and UNFCCC reporting obligations.

Note: Totals may not sum due to independent rounding.

Table 3-2: CO_2, CH_4, and N_2O Emissions from Energy (kt)

Gas/Source	1990	2005	2012	2013	2014	2015	2016
CO_2	**4,905,366**	**5,932,514**	**5,185,335**	**5,338,189**	**5,381,444**	**5,239,206**	**5,137,215**
Fossil Fuel Combustion	4,740,344	5,746,942	5,024,373	5,156,898	5,200,297	5,049,254	4,966,049
Non-Energy Use of Fuels	119,546	138,885	107,987	123,485	118,877	125,634	112,199
Natural Gas Systems	29,831	22,512	23,276	24,827	25,336	24,888	25,516
Petroleum Systems	7,689	11,700	19,300	22,611	26,324	28,752	22,767
Incineration of Waste	7,950	12,469	10,392	10,361	10,604	10,670	10,676
Abandoned Oil and Gas Wells	6	7	7	7	7	7	7
Biomass-Wood[a]	*215,186*	*206,901*	*206,434*	*228,200*	*234,884*	*217,418*	*208,354*
International Bunker Fuels[b]	*103,463*	*113,139*	*105,805*	*99,763*	*103,400*	*110,887*	*116,594*
Biofuels-Ethanol[a]	*4,227*	*22,943*	*72,827*	*74,743*	*76,075*	*78,934*	*81,250*
Biofuels-Biodiesel[a]	*0*	*856*	*8,470*	*13,462*	*13,349*	*14,077*	*19,648*
CH_4	**14,659**	**11,841**	**11,375**	**11,667**	**11,760**	**11,635**	**11,229**
Natural Gas Systems	7,806	6,765	6,384	6,553	6,572	6,651	6,541
Coal Mining	3,860	2,565	2,658	2,584	2,583	2,449	2,153
Petroleum Systems	1,592	1,284	1,307	1,463	1,543	1,523	1,544
Stationary Combustion	345	313	295	351	356	317	293
Abandoned Oil and Gas Wells	260	275	279	280	282	286	284

Abandoned Underground Coal Mines	288	264	249	249	253	256	268
Mobile Combustion	508	374	204	188	170	152	146
Incineration of Waste	+	+	+	+	+	+	+
International Bunker Fuels[b]	*7*	*5*	*4*	*3*	*3*	*3*	*4*
N_2O	**179**	**190**	**139**	**139**	**134**	**127**	**125**
Stationary Combustion	37	59	57	63	64	61	62
Mobile Combustion	140	130	81	75	69	65	62
Incineration of Waste	2	1	1	1	1	1	1
International Bunker Fuels[b]	*3*	*3*	*3*	*3*	*3*	*3*	*3*

+ Does not exceed 0.5 kt.

[a] Emissions from Wood Biomass, Ethanol, and Biodiesel Consumption are not included specifically in summing Energy sector totals. Net carbon fluxes from changes in biogenic carbon reservoirs are accounted for in the estimates for LULUCF.

[b] Emissions from International Bunker Fuels are not included in totals. These values are presented for informational purposes only, in line with the *2006 IPCC Guidelines* and UNFCCC reporting obligations.

Note: Totals may not sum due to independent rounding.

Box 3-1: Methodological Approach for Estimating and Reporting U.S. Emissions and Removals

In following the United Nations Framework Convention on Climate Change (UNFCCC) requirement under Article 4.1 to develop and submit national greenhouse gas emission inventories, the emissions and removals presented in this report and this chapter, are organized by source and sink categories and calculated using internationally-accepted methods provided by the Intergovernmental Panel on Climate Change (IPCC) in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories (2006 IPCC Guidelines)*. Additionally, the calculated emissions and removals in a given year for the United States are presented in a common manner in line with the UNFCCC reporting guidelines for the reporting of inventories under this international agreement. The use of consistent methods to calculate emissions and removals by all nations providing their inventories to the UNFCCC ensures that these reports are comparable. The presentation of emissions and removals provided in this Inventory do not preclude alternative examinations, but rather, this Inventory presents emissions and removals in a common format consistent with how countries are to report Inventories under the UNFCCC. The report itself, and this chapter, follows this standardized format, and provides an explanation of the application of methods used to calculate emissions and removals.

Box 3-2: Energy Data from EPA's Greenhouse Gas Reporting Program

On October 30, 2009, the U.S. Environmental Protection Agency (EPA) published a rule requiring annual reporting of greenhouse gas data from large greenhouse gas emission sources in the United States. Implementation of the rule, codified at 40 CFR Part 98, is referred to as EPA's Greenhouse Gas Reporting Program (GHGRP). The rule applies to direct greenhouse gas emitters, fossil fuel suppliers, industrial gas suppliers, and facilities that inject CO_2 underground for sequestration or other reasons and requires reporting by sources or suppliers in 41 industrial categories. Annual reporting is at the facility level, except for certain suppliers of fossil fuels and industrial greenhouse gases. Data reporting by affected facilities includes the reporting of emissions from fuel combustion at that affected facility. In general, the threshold for reporting is 25,000 metric tons or more of CO_2 Eq. per year.

EPA's GHGRP dataset and the data presented in this Inventory are complementary. The GHGRP dataset continues to be an important resource for the Inventory, providing not only annual emissions information, but also other annual information, such as activity data and emission factors that can improve and refine national emission estimates and trends over time. GHGRP data also allow EPA to disaggregate national inventory estimates in new ways that can highlight differences across regions and sub-categories of emissions, along with enhancing application of QA/QC procedures and assessment of uncertainties.

EPA uses annual GHGRP data in a number of categories to improve the national estimates presented in this Inventory consistent with IPCC guidelines (see also Box 3-4).[4] As indicated in the respective Planned Improvements sections for source categories in this chapter, EPA continues to examine the uses of facility-level GHGRP data to improve the national estimates presented in this Inventory. Most methodologies used in EPA's GHGRP are consistent with IPCC, though for EPA's GHGRP, facilities collect detailed information specific to their operations according to detailed measurement standards, which may differ with the more aggregated data collected for the Inventory to estimate total national U.S. emissions. It should be noted that the definitions and provisions for reporting fuel types in EPA's GHGRP may differ from those used in the Inventory in meeting the UNFCCC reporting guidelines. In line with the UNFCCC reporting guidelines, the Inventory report is a comprehensive accounting of all emissions from fuel types identified in the IPCC guidelines and provides a separate reporting of emissions from biomass. Further information on the reporting categorizations in EPA's GHGRP and specific data caveats associated with monitoring methods in EPA's GHGRP has been provided on the GHGRP website.[5]

EPA presents the data collected by its GHGRP through a data publication tool that allows data to be viewed in several formats including maps, tables, charts and graphs for individual facilities or groups of facilities.[6]

In addition to using GHGRP data to estimate emissions, EPA also uses the GHGRP fuel consumption activity data in the Energy sector to disaggregate industrial end-use sector emissions in the category of CO_2 Emissions from Fossil Fuel Combustion, for use in reporting emissions in Common Reporting Format (CRF) tables. The industrial end-use sector activity data collected for the Inventory (EIA 2018) represent aggregated data for the industrial end-use sector. EPA's GHGRP collects industrial fuel consumption activity data by individual categories within the industrial end-use sector. Therefore, the GHGRP data are used to provide a more detailed breakout of total emissions in the industrial end-use sector within that source category.

3.1 Fossil Fuel Combustion (CRF Source Category 1A)

Emissions from the combustion of fossil fuels for energy include the gases CO_2, CH_4, and N_2O. Given that CO_2 is the primary gas emitted from fossil fuel combustion and represents the largest share of U.S. total emissions, CO_2 emissions from fossil fuel combustion are discussed at the beginning of this section. Following that is a discussion of emissions of all three gases from fossil fuel combustion presented by sectoral breakdowns. Methodologies for estimating CO_2 from fossil fuel combustion also differ from the estimation of CH_4 and N_2O emissions from stationary combustion and mobile combustion. Thus, three separate descriptions of methodologies, uncertainties, recalculations, and planned improvements are provided at the end of this section. Total CO_2, CH_4, and N_2O emissions from fossil fuel combustion are presented in Table 3-3 and Table 3-4.

Table 3-3: CO_2, CH_4, and N_2O Emissions from Fossil Fuel Combustion (MMT CO_2 Eq.)

Gas	1990	2005	2012	2013	2014	2015	2016
CO_2	4,740.3	5,746.9	5,024.4	5,156.9	5,200.3	5,049.3	4,966.0
CH_4	21.3	17.2	12.5	13.5	13.2	11.7	11.0
N_2O	52.8	56.3	41.2	41.2	39.7	37.4	36.9
Total	**4,814.4**	**5,820.4**	**5,078.0**	**5,211.5**	**5,253.1**	**5,098.4**	**5,014.0**

Note: Totals may not sum due to independent rounding

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[4] See <http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf>.

[5] See <http://www.ccdsupport.com/confluence/display/ghgp/Detailed+Description+of+Data+for+Certain+Sources+and+Processes>.

[6] See <http://ghgdata.epa.gov>.

Table 3-4: CO_2, CH_4, and N_2O Emissions from Fossil Fuel Combustion (kt)

Gas	1990	2005	2012	2013	2014	2015	2016
CO_2	4,740,344	5,746,942	5,024,373	5,156,898	5,200,297	5,049,254	4,966,049
CH_4	853	688	499	538	526	470	439
N_2O	177	189	138	138	133	126	124

CO_2 from Fossil Fuel Combustion

Carbon dioxide is the primary gas emitted from fossil fuel combustion and represents the largest share of U.S. total greenhouse gas emissions. Carbon dioxide emissions from fossil fuel combustion are presented in Table 3-5. In 2016, CO_2 emissions from fossil fuel combustion decreased by 1.6 percent relative to the previous year. The decrease in CO_2 emissions from fossil fuel combustion was a result of multiple factors, including: (1) substitution from coal to natural gas and other non-fossil energy sources in the electric power sector; and (2) warmer winter conditions in 2016 resulting in a decreased demand for heating fuel in the residential and commercial sectors. In 2016, CO_2 emissions from fossil fuel combustion were 4,966.0 MMT CO_2 Eq., or 4.8 percent above emissions in 1990 (see Table 3-5).[7]

Table 3-5: CO_2 Emissions from Fossil Fuel Combustion by Fuel Type and Sector (MMT CO_2 Eq.)

Fuel/Sector	1990	2005	2012	2013	2014	2015	2016
Coal	**1,718.4**	**2,112.3**	**1,592.8**	**1,653.8**	**1,652.6**	**1,423.3**	**1,306.4**
Residential	3.0	0.8	NO	NO	NO	NO	NO
Commercial	12.0	9.3	4.1	3.9	3.8	2.9	2.2
Industrial	155.3	115.3	74.1	75.7	75.6	65.9	58.7
Transportation	NE	NE	NE	NE	NE	NE	NE
Electric Power	1,547.6	1,983.8	1,511.2	1,571.3	1,569.1	1,350.5	1,241.4
U.S. Territories	0.6	3.0	3.4	2.8	4.0	4.0	4.0
Natural Gas	**1,000.3**	**1,166.7**	**1,352.6**	**1,391.2**	**1,422.0**	**1,463.9**	**1,476.1**
Residential	238.0	262.2	224.8	266.2	277.9	253.2	238.3
Commercial	142.1	162.9	156.9	179.1	189.3	175.7	170.3
Industrial	408.9	388.5	434.8	451.9	468.4	466.4	477.9
Transportation	36.0	33.1	41.3	47.0	40.3	39.5	40.6
Electric Power	175.3	318.8	492.2	444.0	443.2	526.1	546.0
U.S. Territories	NO	1.3	2.6	3.0	3.0	3.0	3.0
Petroleum	**2,021.2**	**2,467.6**	**2,078.5**	**2,111.5**	**2,125.3**	**2,161.6**	**2,183.1**
Residential	97.4	94.9	57.7	63.5	67.4	63.6	54.2
Commercial	73.1	54.9	40.4	42.7	40.4	66.7	58.7
Industrial	294.7	351.9	304.1	315.7	280.9	277.3	272.5
Transportation	1,431.5	1,822.7	1,620.6	1,630.6	1,676.9	1,696.0	1,741.9
Electric Power	97.5	97.9	18.3	22.4	25.3	23.7	21.4
U.S. Territories	26.9	45.4	37.5	36.6	34.3	34.3	34.3
Geothermal[a]	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**
Total	**4,740.3**	**5,746.9**	**5,024.4**	**5,156.9**	**5,200.3**	**5,049.3**	**4,966.0**

NE (Not Estimated)

NO (Not Occurring)

[a] Although not technically a fossil fuel, geothermal energy-related CO_2 emissions are included for reporting purposes.

Note: Totals may not sum due to independent rounding.

Trends in CO_2 emissions from fossil fuel combustion are influenced by many long-term and short-term factors. On a year-to-year basis, the overall demand for fossil fuels in the United States and other countries generally fluctuates in

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[7] An additional discussion of fossil fuel emission trends is presented in the Trends in U.S. Greenhouse Gas Emissions chapter.

response to changes in general economic conditions, energy prices, weather, and the availability of non-fossil alternatives. For example, in a year with increased consumption of goods and services, low fuel prices, severe summer and winter weather conditions, nuclear plant closures, and lower precipitation feeding hydroelectric dams, there would likely be proportionally greater fossil fuel consumption than a year with poor economic performance, high fuel prices, mild temperatures, and increased output from nuclear and hydroelectric plants.

Longer-term changes in energy usage patterns, however, tend to be more a function of aggregate societal trends that affect the scale of energy use (e.g., population, number of cars, size of houses, and number of houses), the efficiency with which energy is used in equipment (e.g., cars, power plants, steel mills, and light bulbs), and social planning and consumer behavior (e.g., walking, bicycling, or telecommuting to work instead of driving).

Carbon dioxide emissions also depend on the source of energy and its carbon (C) intensity. The amount of C in fuels varies significantly by fuel type. For example, coal contains the highest amount of C per unit of useful energy. Petroleum has roughly 75 percent of the C per unit of energy as coal, and natural gas has only about 55 percent.[8] Table 3-6 shows annual changes in emissions during the last five years for coal, petroleum, and natural gas in selected sectors.

Table 3-6: Annual Change in CO_2 Emissions and Total 2016 Emissions from Fossil Fuel Combustion for Selected Fuels and Sectors (MMT CO_2 Eq. and Percent)

Sector	Fuel Type	2012 to 2013		2013 to 2014		2014 to 2015		2015 to 2016		Total 2016
Electric Power	Coal	60.1	4.0%	-2.2	-0.1%	-218.7	-13.9%	-109.1	-8.1%	1,241.4
Electric Power	Natural Gas	-48.3	-9.8%	-0.8	-0.2%	82.9	18.7%	19.9	3.8%	546.0
Electric Power	Petroleum	4.1	22.3%	2.9	12.8%	-1.6	-6.4%	-2.2	-9.3%	21.4
Transportation	Petroleum	10.0	0.6%	46.3	2.8%	19.1	1.1%	46.0	2.7%	1,741.9
Residential	Natural Gas	41.4	18.4%	11.6	4.4%	-24.7	-8.9%	-14.9	-5.9%	238.3
Commercial	Natural Gas	22.3	14.2%	10.2	5.7%	-13.6	-7.2%	-5.4	-3.1%	170.3
Industrial	Coal	1.7	2.3%	-0.1	-0.1%	-9.8	-12.9%	-7.1	-10.8%	58.7
Industrial	Natural Gas	17.1	3.9%	16.5	3.7%	-2.0	-0.4%	11.5	2.5%	477.9
All Sectors[a]	**All Fuels[a]**	**132.5**	**2.6%**	**43.4**	**0.8%**	**-151.0**	**-2.9%**	**-83.2**	**-1.6%**	**4,966.0**

[a] Includes sector and fuel combinations not shown in this table.

Note: Totals may not sum due to independent rounding.

As shown in Table 3-6, recent trends in CO_2 emissions from fossil fuel combustion show a 2.6 percent increase from 2012 to 2013, then a 0.8 percent increase from 2013 to 2014, then a 2.9 percent decrease from 2014 to 2015, and a 1.6 percent decrease from 2015 to 2016. Total electric power generation remained relatively flat over that time period but emission trends generally mirror the trends in the amount of coal used to generate electricity. The consumption of coal used to generate electricity increased by roughly 4 percent from 2012 to 2013, stayed relatively flat from 2013 to 2014, decreased by 14 percent from 2014 to 2015, and decreased by 8 percent from 2015 to 2016. The overall CO_2 emission trends from fossil fuel combustion also follow closely changes in heating degree days over that time period. Heating degree days increased by 18 percent from 2012 to 2013, increased by 2 percent from 2013 to 2014, decreased by 10 percent from 2014 to 2015, and decreased by 5 percent from 2015 to 2016. A decrease in heating degree days leads to decreased demand for heating fuel and electricity for heat in the residential and commercial sector, primarily in winter months. The overall CO_2 emission trends from fossil fuel combustion also generally follow changes in overall petroleum use and emissions. Carbon dioxide emissions from petroleum increased by 1.6 percent from 2012 to 2013, increased by 0.7 percent from 2013 to 2014, increased by 1.7 percent from 2014 to 2015, and increased by 1.0 percent from 2015 to 2016. The increase in petroleum CO_2 emissions from 2015 to 2016 somewhat offsets emission reductions from other sources like decreased coal use in the electricity sector.

In the United States, 81 percent of the energy used in 2016 was produced through the combustion of fossil fuels such as coal, natural gas, and petroleum (see Figure 3-3 and Figure 3-4). The remaining portion was supplied by nuclear electric power (9 percent) and by a variety of renewable energy sources (11 percent), primarily hydroelectric power,

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[8] Based on national aggregate carbon content of all coal, natural gas, and petroleum fuels combusted in the United States.

wind energy and biofuels (EIA 2018).[9] Specifically, petroleum supplied the largest share of domestic energy demands, accounting for 37 percent of total U.S. energy used in 2016. Natural gas and coal followed in order of energy demand importance, accounting for approximately 29 percent and 15 percent of total U.S. energy used, respectively. Petroleum was consumed primarily in the transportation end-use sector and the vast majority of coal was used in the electric power end-use sector. Natural gas was broadly consumed in all end-use sectors except transportation (see Figure 3-5) (EIA 2018).

Figure 3-3: 2016 U.S. Energy Consumption by Energy Source (Percent)

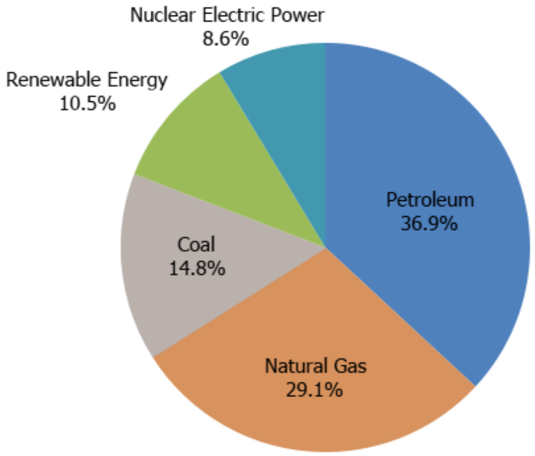
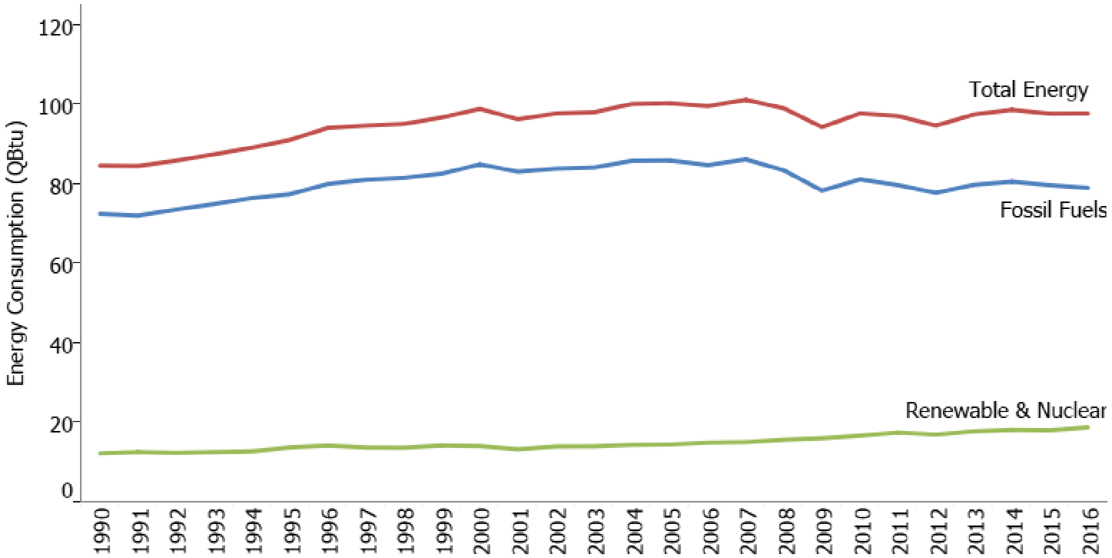


Figure 3-4: U.S. Energy Consumption (Quadrillion Btu)



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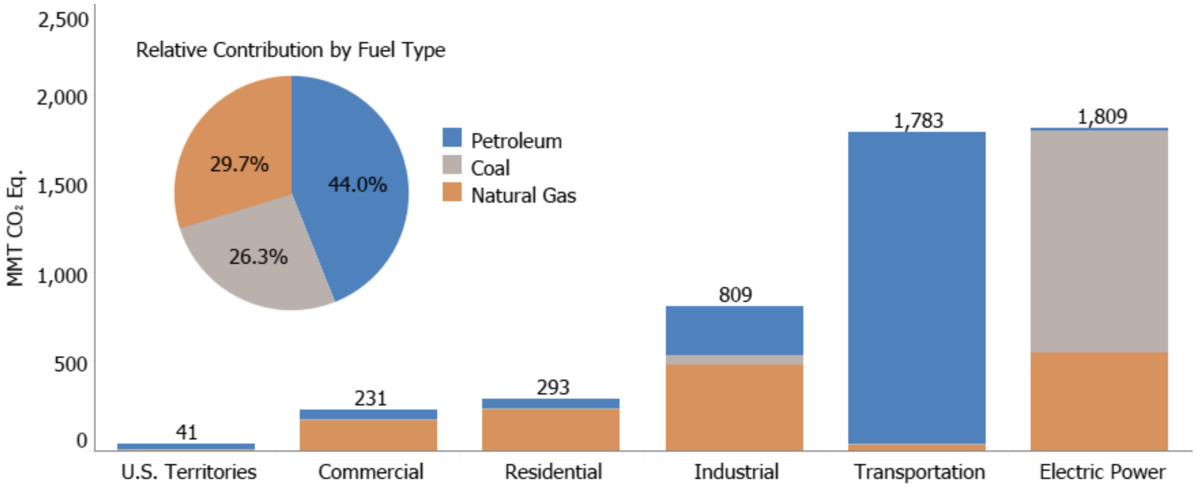
[9] Renewable energy, as defined in EIA's energy statistics, includes the following energy sources: hydroelectric power, geothermal energy, biofuels, solar energy, and wind energy.

Figure 3-5: 2016 CO_2 Emissions from Fossil Fuel Combustion by Sector and Fuel Type (MMT CO_2 Eq.)



Note: Fossil Fuel Combustion from electric power also includes emissions of less than 0.5 MMT CO_2 Eq. from geothermal-based generation.

Fossil fuels are generally combusted for the purpose of producing energy for useful heat and work. During the combustion process, the C stored in the fuels is oxidized and emitted as CO_2 and smaller amounts of other gases, including CH_4, CO, and NMVOCs.[10] These other C-containing non-CO_2 gases are emitted as a byproduct of incomplete fuel combustion, but are, for the most part, eventually oxidized to CO_2 in the atmosphere. Therefore, it is assumed all of the C in fossil fuels used to produce energy is eventually converted to atmospheric CO_2.

Box 3-3: Weather and Non-Fossil Energy Effects on CO_2 from Fossil Fuel Combustion Trends

In 2016, weather conditions, and a warm first and fourth quarter of the year in particular, caused a significant decrease in demand for heating fuels and is reflected in the decreased residential emissions from 2015 to 2016. The United States in 2016 also experienced a warmer winter overall compared to 2015, as heating degree days decreased (5.1 percent). Warmer winter conditions compared to 2015 resulted in a decrease in the amount of energy required for heating, and heating degree days in the United States were 14.3 percent below normal (see Figure 3-6). Cooling degree days increased by 4.7 percent, which increased demand for air conditioning in the residential and commercial sector. This led in part to an overall residential electricity demand increase of 0.5 percent. Summer conditions were significantly warmer in 2016 compared to 2015, with cooling degree days 28.1 percent above normal (see Figure 3-7) (EIA 2018).[11]

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[10] See the sections entitled Stationary Combustion and Mobile Combustion in this chapter for information on non-CO_2 gas emissions from fossil fuel combustion.

[11] Degree days are relative measurements of outdoor air temperature. Heating degree days are deviations of the mean daily temperature below 65 degrees Fahrenheit, while cooling degree days are deviations of the mean daily temperature above 65 degrees Fahrenheit. Heating degree days have a considerably greater effect on energy demand and related emissions than do cooling degree days. Excludes Alaska and Hawaii. Normals are based on data from 1981 through 2010. The variation in these normals during this time period was ±12 percent and ±19 percent for heating and cooling degree days, respectively (99 percent confidence interval).

Figure 3-6: Annual Deviations from Normal Heating Degree Days for the United States (1950–2016, Index Normal = 100)

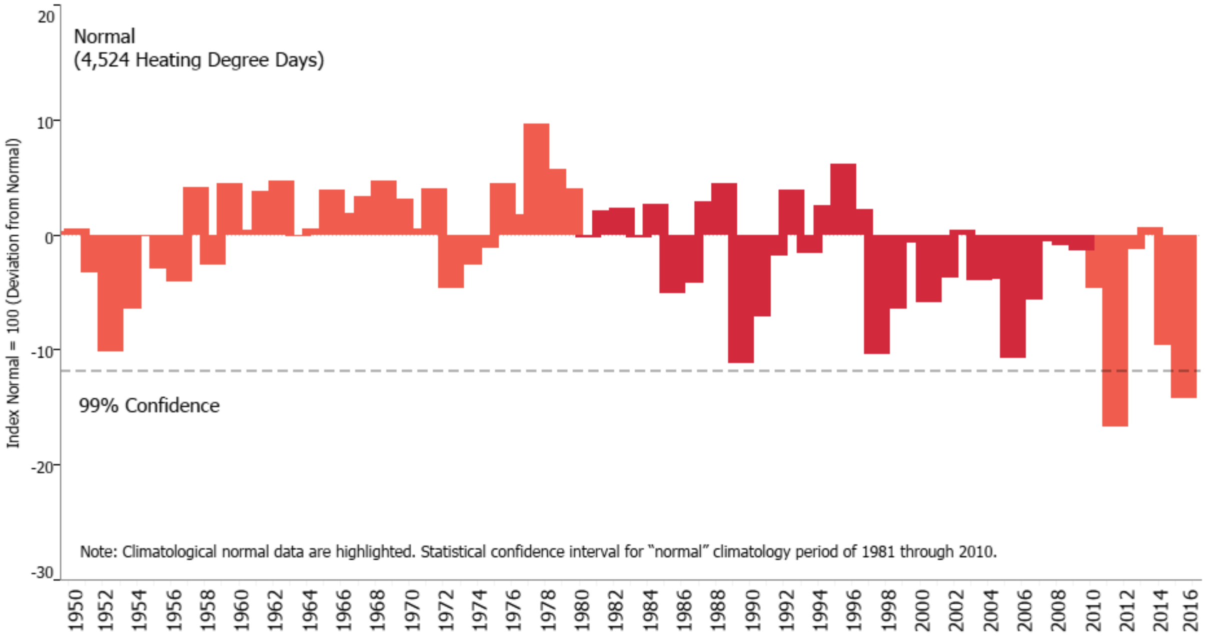
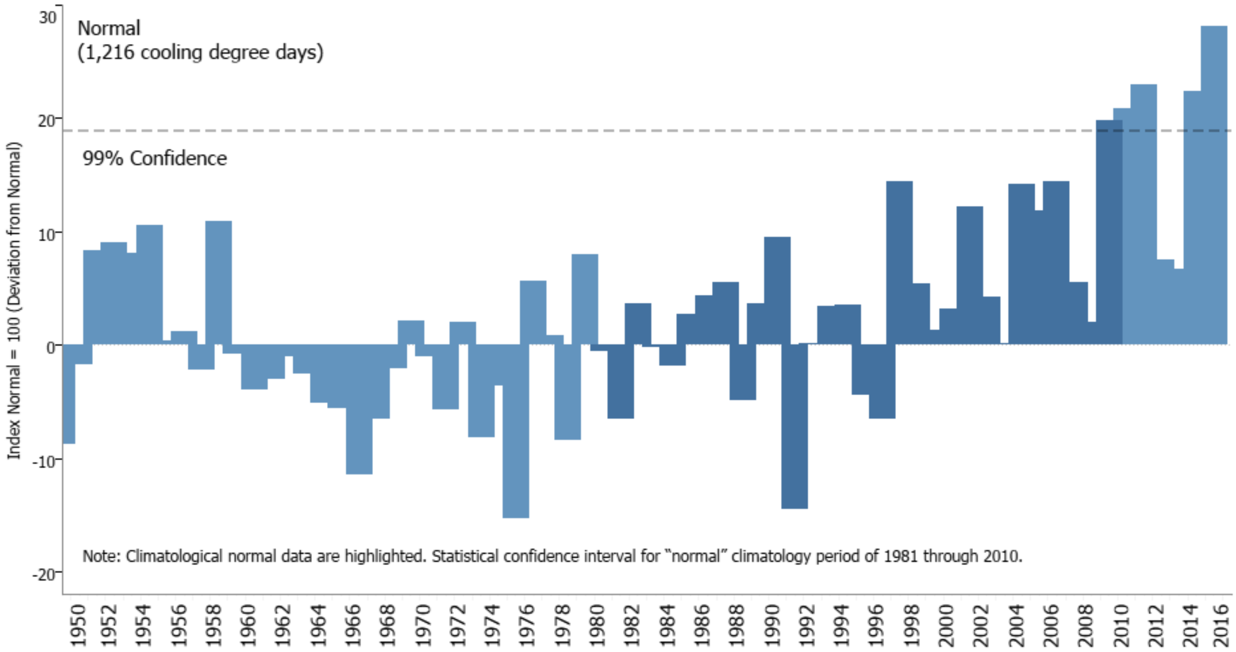


Figure 3-7: Annual Deviations from Normal Cooling Degree Days for the United States (1950–2016, Index Normal = 100)



The carbon intensity of the electric power sector is impacted by the amount of non-fossil energy sources of electricity. The utilization (i.e., capacity factors)[12] of nuclear power plants in 2016 remained high at 92 percent. In

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[12] The capacity factor equals generation divided by net summer capacity. Summer capacity is defined as "The maximum output that generating equipment can supply to system load, as demonstrated by a multi-hour test, at the time of summer peak demand (period of June 1 through September 30)." Data for both the generation and net summer capacity are from EIA (2017c).

2016, nuclear power represented 21 percent of total electricity production. In recent years, the wind and solar power sectors have been showing strong growth, such that, on the margin, they are becoming relatively important electricity sources. Between 1990 and 2016, renewable energy generation (in kWh) from solar and wind energy have increased from 0.1 percent in 1990 to 7 percent in 2016, which helped drive the decrease in the carbon intensity of the electricity supply in the United States.

Fossil Fuel Combustion Emissions by Sector

In addition to the CO_2 emitted from fossil fuel combustion, CH_4 and N_2O are emitted from stationary and mobile combustion as well. Table 3-7 provides an overview of the CO_2, CH_4, and N_2O emissions from fossil fuel combustion by sector.

Table 3-7: CO_2, CH_4, and N_2O Emissions from Fossil Fuel Combustion by Sector (MMT CO_2 Eq.)

End-Use Sector	1990	2005	2012	2013	2014	2015	2016
Electric Power	**1,827.7**	**2,414.9**	**2,036.3**	**2,053.8**	**2,054.0**	**1,916.1**	**1,825.3**
CO_2	1,820.8	2,400.9	2,022.2	2,038.1	2,038.0	1,900.7	1,809.3
CH_4	0.4	0.9	1.1	1.0	1.0	1.1	1.1
N_2O	6.5	13.2	13.1	14.6	15.0	14.3	14.9
Transportation	**1,522.0**	**1,903.9**	**1,691.3**	**1,704.8**	**1,742.0**	**1,758.6**	**1,804.6**
CO_2	1,467.6	1,855.8	1,661.9	1,677.6	1,717.1	1,735.5	1,782.6
CH_4	12.7	9.4	5.1	4.7	4.2	3.8	3.6
N_2O	41.7	38.8	24.3	22.5	20.6	19.3	18.4
Industrial	**863.8**	**860.4**	**817.2**	**847.6**	**829.2**	**813.7**	**813.2**
CO_2	858.8	855.7	812.9	843.3	824.9	809.5	809.1
CH_4	1.8	1.8	1.6	1.6	1.6	1.6	1.6
N_2O	3.1	3.0	2.7	2.7	2.7	2.6	2.5
Residential	**344.6**	**362.8**	**287.0**	**335.7**	**351.4**	**321.6**	**296.6**
CO_2	338.3	357.8	282.5	329.7	345.3	316.8	292.5
CH_4	5.2	4.1	3.7	5.0	5.1	3.9	3.4
N_2O	1.0	0.9	0.7	1.0	1.0	0.8	0.7
Commercial	**228.7**	**228.5**	**202.5**	**227.1**	**235.0**	**247.0**	**232.8**
CO_2	227.2	227.0	201.3	225.7	233.6	245.4	231.3
CH_4	1.1	1.1	0.9	1.1	1.1	1.2	1.2
N_2O	0.4	0.3	0.3	0.3	0.3	0.4	0.3
U.S. Territories[a]	**27.7**	**49.9**	**43.7**	**42.6**	**41.5**	**41.5**	**41.5**
Total	**4,814.4**	**5,820.4**	**5,078.0**	**5,211.5**	**5,253.1**	**5,098.4**	**5,014.0**

[a] U.S. Territories are not apportioned by sector, and emissions are total greenhouse gas emissions from all fuel combustion sources.

Notes: Totals may not sum due to independent rounding. Emissions from fossil fuel combustion by electric power are allocated based on aggregate national electricity consumption by each end-use sector.

Other than CO_2, gases emitted from stationary combustion include the greenhouse gases CH_4 and N_2O and the indirect greenhouse gases NO_x, CO, and NMVOCs.[13] Methane and N_2O emissions from stationary combustion sources depend upon fuel characteristics, size and vintage, along with combustion technology, pollution control equipment, ambient environmental conditions, and operation and maintenance practices. Nitrous oxide emissions from stationary combustion are closely related to air-fuel mixes and combustion temperatures, as well as the characteristics of any pollution control equipment that is employed. Methane emissions from stationary combustion are primarily a function of the CH_4 content of the fuel and combustion efficiency.

Mobile combustion produces greenhouse gases other than CO_2, including CH_4, N_2O, and indirect greenhouse gases including NO_x, CO, and NMVOCs. As with stationary combustion, N_2O and NO_x emissions from mobile

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[13] Sulfur dioxide (SO_2) emissions from stationary combustion are addressed in Annex 6.3.

combustion are closely related to fuel characteristics, air-fuel mixes, combustion temperatures, and the use of pollution control equipment. Nitrous oxide from mobile sources, in particular, can be formed by the catalytic processes used to control NO_x, CO, and hydrocarbon emissions. Carbon monoxide emissions from mobile combustion are significantly affected by combustion efficiency and the presence of post-combustion emission controls. Carbon monoxide emissions are highest when air-fuel mixtures have less oxygen than required for complete combustion. These emissions occur especially in idle, low speed, and cold start conditions. Methane and NMVOC emissions from motor vehicles are a function of the CH_4 content of the motor fuel, the amount of hydrocarbons passing uncombusted through the engine, and any post-combustion control of hydrocarbon emissions (such as catalytic converters).

An alternative method of presenting combustion emissions is to allocate emissions associated with electric power to the sectors in which it is used. Four end-use sectors were defined: industrial, transportation, residential, and commercial. In the table below, electric power emissions have been distributed to each end-use sector based upon the sector's share of national electricity use, with the exception of CH_4 and N_2O from transportation.[14] Emissions from U.S. Territories are also calculated separately due to a lack of end-use-specific consumption data.[15] This method assumes that emissions from combustion sources are distributed across the four end-use sectors based on the ratio of electricity use in that sector. The results of this alternative method are presented in Table 3-8.

Table 3-8: CO_2, CH_4, and N_2O Emissions from Fossil Fuel Combustion by End-Use Sector (MMT CO_2 Eq.)

End-Use Sector	1990	2005	2012	2013	2014	2015	2016
Transportation	**1,525.0**	**1,908.7**	**1,695.1**	**1,708.8**	**1,746.0**	**1,762.3**	**1,808.1**
CO_2	1,470.6	1,860.5	1,665.8	1,681.6	1,721.2	1,739.2	1,786.1
CH_4	12.7	9.4	5.1	4.7	4.2	3.8	3.6
N_2O	41.7	38.8	24.3	22.5	20.6	19.3	18.4
Industrial	**1,553.2**	**1,601.3**	**1,414.1**	**1,446.9**	**1,427.1**	**1,367.7**	**1,335.4**
CO_2	1,545.6	1,592.3	1,405.7	1,438.0	1,418.1	1,359.0	1,326.7
CH_4	2.0	2.0	1.9	1.9	1.9	1.9	1.9
N_2O	5.6	7.0	6.5	7.0	7.0	6.7	6.8
Residential	**939.9**	**1,224.1**	**1,017.3**	**1,076.2**	**1,091.9**	**1,011.4**	**956.6**
CO_2	931.4	1,214.1	1,007.8	1,064.6	1,080.0	1,001.1	946.7
CH_4	5.4	4.4	4.1	5.3	5.4	4.3	3.8
N_2O	3.2	5.6	5.5	6.2	6.4	5.9	6.1
Commercial	**768.7**	**1,036.5**	**907.7**	**937.0**	**946.5**	**915.5**	**872.3**
CO_2	765.2	1,030.3	901.6	930.2	939.6	908.6	865.2
CH_4	1.2	1.4	1.3	1.4	1.5	1.6	1.6
N_2O	2.3	4.8	4.8	5.4	5.5	5.4	5.6
U.S. Territories[a]	**27.7**	**49.9**	**43.7**	**42.6**	**41.5**	**41.5**	**41.5**
Total	**4,814.4**	**5,820.4**	**5,078.0**	**5,211.5**	**5,253.1**	**5,098.4**	**5,014.0**

[a] U.S. Territories are not apportioned by sector, and emissions are total greenhouse gas emissions from all fuel combustion sources.

Notes: Totals may not sum due to independent rounding. Emissions from fossil fuel combustion by electric power are allocated based on aggregate national electricity use by each end-use sector.

Stationary Combustion

The direct combustion of fuels by stationary sources in the electric power, industrial, commercial, and residential sectors represent the greatest share of U.S. greenhouse gas emissions. Table 3-9 presents CO_2 emissions from fossil fuel combustion by stationary sources. The CO_2 emitted is closely linked to the type of fuel being combusted in each sector (see Methodology section of CO_2 from Fossil Fuel Combustion). Other than CO_2, gases emitted from

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[14] Separate calculations were performed for transportation-related CH_4 and N_2O. The methodology used to calculate these emissions are discussed in the mobile combustion section.

[15] U.S. Territories consumption data that are obtained from EIA are only available at the aggregate level and cannot be broken out by end-use sector. The distribution of emissions to each end-use sector for the 50 states does not apply to territories data.

stationary combustion include the greenhouse gases CH_4 and N_2O. Table 3-10 and Table 3-11 present CH_4 and N_2O emissions from the combustion of fuels in stationary sources. The CH_4 and N_2O emission estimation methodology utilizes facility-specific technology and fuel use data reported to EPA's Acid Rain Program (EPA 2017a) (see Methodology section for CH_4 and N_2O from Stationary Combustion). Table 3-7 presents the corresponding direct CO_2, CH_4, and N_2O emissions from all sources of fuel combustion, without allocating emissions from electricity use to the end-use sectors.

Table 3-9: CO_2 Emissions from Stationary Fossil Fuel Combustion (MMT CO_2 Eq.)

Sector/Fuel Type	1990	2005	2012	2013	2014	2015	2016
Electric Power	**1,820.8**	**2,400.9**	**2,022.2**	**2,038.1**	**2,038.0**	**1,900.7**	**1,809.3**
Coal	1,547.6	1,983.8	1,511.2	1,571.3	1,569.1	1,350.5	1,241.4
Natural Gas	175.3	318.8	492.2	444.0	443.2	526.1	546.0
Fuel Oil	97.5	97.9	18.3	22.4	25.3	23.7	21.4
Geothermal	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Industrial	**858.8**	**855.7**	**812.9**	**843.3**	**824.9**	**809.5**	**809.1**
Coal	155.3	115.3	74.1	75.7	75.6	65.9	58.7
Natural Gas	408.9	388.5	434.8	451.9	468.4	466.4	477.9
Fuel Oil	294.7	351.9	304.1	315.7	280.9	277.3	272.5
Commercial	**227.2**	**227.0**	**201.3**	**225.7**	**233.6**	**245.4**	**231.3**
Coal	12.0	9.3	4.1	3.9	3.8	2.9	2.2
Natural Gas	142.1	162.9	156.9	179.1	189.3	175.7	170.3
Fuel Oil	73.1	54.9	40.4	42.7	40.4	66.7	58.7
Residential	**338.3**	**357.8**	**282.5**	**329.7**	**345.3**	**316.8**	**292.5**
Coal	3.0	0.8	NO	NO	NO	NO	NO
Natural Gas	238.0	262.2	224.8	266.2	277.9	253.2	238.3
Fuel Oil	97.4	94.9	57.7	63.5	67.4	63.6	54.2
U.S. Territories	**27.6**	**49.7**	**43.5**	**42.5**	**41.4**	**41.4**	**41.4**
Coal	0.6	3.0	3.4	2.8	4.0	4.0	4.0
Natural Gas	NO	1.3	2.6	3.0	3.0	3.0	3.0
Fuel Oil	26.9	45.4	37.5	36.6	34.3	34.3	34.3
Total	**3,272.8**	**3,891.2**	**3,362.5**	**3,479.3**	**3,483.2**	**3,313.8**	**3,183.5**

NO (Not Occurring)

Note: Totals may not sum due to independent rounding.

Table 3-10: CH_4 Emissions from Stationary Combustion (MMT CO_2 Eq.)

Sector/Fuel Type	1990	2005	2012	2013	2014	2015	2016
Electric Power	**0.4**	**0.9**	**1.1**	**1.0**	**1.0**	**1.1**	**1.1**
Coal	0.3	0.4	0.3	0.3	0.3	0.3	0.2
Fuel Oil	+	+	+	+	+	+	+
Natural gas	0.1	0.5	0.8	0.7	0.7	0.9	0.9
Wood	+	+	+	+	+	+	+
Industrial	**1.8**	**1.8**	**1.6**	**1.6**	**1.6**	**1.6**	**1.6**
Coal	0.4	0.3	0.2	0.2	0.2	0.2	0.2
Fuel Oil	0.2	0.2	0.2	0.2	0.1	0.2	0.1
Natural gas	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Wood	1.0	1.0	1.0	1.1	1.1	1.1	1.0
Commercial	**1.1**	**1.1**	**0.9**	**1.1**	**1.1**	**1.2**	**1.2**
Coal	+	+	+	+	+	+	+
Fuel Oil	0.3	0.2	0.1	0.2	0.1	0.2	0.2
Natural gas	0.3	0.4	0.4	0.4	0.4	0.4	0.4
Wood	0.5	0.5	0.4	0.5	0.5	0.6	0.6
Residential	**5.2**	**4.1**	**3.7**	**5.0**	**5.1**	**3.9**	**3.4**
Coal	0.2	0.1	NO	NO	NO	NO	NO
Fuel Oil	0.3	0.3	0.2	0.2	0.2	0.2	0.2

Natural Gas	0.5	0.6	0.5	0.6	0.6	0.6	0.5
Wood	4.1	3.1	3.0	4.1	4.2	3.1	2.7
U.S. Territories	**+**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Coal	+	+	+	+	+	+	+
Fuel Oil	+	0.1	0.1	0.1	0.1	0.1	0.1
Natural Gas	NO	+	+	+	+	+	+
Wood	NO	NO	NO	NO	NO	NO	NO
Total	**8.6**	**7.8**	**7.4**	**8.8**	**8.9**	**7.9**	**7.3**

+ Does not exceed 0.05 MMT CO_2 Eq.
NO (Not Occurring)
Note: Totals may not sum due to independent rounding.

Table 3-11: N_2O Emissions from Stationary Combustion (MMT CO_2 Eq.)

Sector/Fuel Type	1990	2005	2012	2013	2014	2015	2016
Electric Power	**6.5**	**13.2**	**13.1**	**14.6**	**15.0**	**14.3**	**14.9**
Coal	6.1	11.1	9.8	11.6	11.9	10.6	11.1
Fuel Oil	0.1	0.1	+	+	+	+	+
Natural Gas	0.3	1.9	3.2	3.0	3.1	3.6	3.7
Wood	+	+	+	+	+	+	+
Industrial	**3.1**	**3.0**	**2.7**	**2.7**	**2.7**	**2.6**	**2.5**
Coal	0.7	0.5	0.4	0.4	0.4	0.3	0.3
Fuel Oil	0.5	0.6	0.4	0.4	0.4	0.4	0.3
Natural Gas	0.2	0.2	0.2	0.2	0.3	0.2	0.3
Wood	1.6	1.6	1.7	1.7	1.7	1.7	1.7
Commercial	**0.4**	**0.3**	**0.3**	**0.3**	**0.3**	**0.4**	**0.3**
Coal	0.1	+	+	+	+	+	+
Fuel Oil	0.2	0.1	0.1	0.1	0.1	0.2	0.1
Natural Gas	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Wood	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Residential	**1.0**	**0.9**	**0.7**	**1.0**	**1.0**	**0.8**	**0.7**
Coal	+	+	NO	NO	NO	NO	NO
Fuel Oil	0.2	0.2	0.2	0.2	0.2	0.2	0.1
Natural Gas	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Wood	0.7	0.5	0.5	0.7	0.7	0.5	0.4
U.S. Territories	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Coal	+	+	+	+	+	+	+
Fuel Oil	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Natural Gas	NO	+	+	+	+	+	+
Wood	NO	NO	NO	NO	NO	NO	NO
Total	**11.1**	**17.5**	**16.9**	**18.7**	**19.0**	**18.1**	**18.6**

+ Does not exceed 0.05 MMT CO_2 Eq.
NO (Not Occurring)
Note: Totals may not sum due to independent rounding.

Electric Power Sector

The process of generating electricity is the single largest source of CO_2 emissions in the United States, representing 34 percent of total CO_2 emissions from all CO_2 emissions sources across the United States. Methane and N_2O accounted for a small portion of total greenhouse gas emissions from electric power, representing 0.1 percent and 0.8 percent, respectively. Electric power also accounted for the largest share of CO_2 emissions from fossil fuel combustion, approximately 36.4 percent in 2016. Methane and N_2O from electric power represented 10.4 and 40.3 percent of total CH_4 and N_2O emissions from fossil fuel combustion in 2016, respectively.

For the underlying energy data used in this chapter, the Energy Information Administration (EIA) places electric power generation into three functional categories: the electric power sector, the commercial sector, and the industrial sector. The electric power sector consists of electric utilities and independent power producers whose primary business is the production of electricity. This includes both regulated utilities and non-utilities (e.g., independent power producers, qualifying co-generators, and other small power producers). Electric generation is reported as occurring in other sectors where the producer of the power indicates that its primary business is something other than the production of electricity.[16]

Emissions from the electric power sector have decreased by 0.1 percent since 1990. The carbon intensity of the electric power sector, in terms of CO_2 Eq. per QBtu, has decreased by 12 percent during that same timeframe with the majority of the emissions and carbon intensity decreases occurring in the past decade as shown below in Figure 3-8. This recent decarbonization of the electric power sector is a result of several key drivers. Coal-fired electric power (in kilowatt-hours [kWh]) decreased from almost 54 percent of generation in 1990 to 32 percent in 2016.[17] This generation corresponded with an increase in natural gas and renewable energy generation, largely from wind and solar energy. Natural gas generation (in kWh) represented 11 percent of electric power generation in 1990, and increased over the 27-year period to represent 33 percent of electric power sector generation in 2016.

In 2016, CO_2 emissions from the electric power sector decreased by 4.8 percent relative to 2015. This decrease in CO_2 emissions was a result of changes in the types of fuel consumed to produce electricity in the electric power sector in recent years. The shift from coal to less-CO_2-intensive natural gas to supply electricity has accelerated in recent years. Consumption of coal for electric power decreased by 8.1 percent from 2015 to 2016, while consumption of natural gas increased by 3.8 percent. There has also been a rapid increase in renewable energy capacity additions in the electric power sector in recent years. In 2016, renewable energy sources accounted for 63 percent of capacity additions, with natural gas accounting for the remaining additions. The share of renewable energy capacity additions has grown significantly since 2010, when renewable energy sources accounted for only 28 percent of total capacity additions (EIA 2017d). Electricity generation from renewable sources increased by 14 percent from 2015 to 2016. The decrease in coal-powered electricity generation and increase in renewable energy electricity generation contributed to a decrease in emissions from electric power generation over the time series (see Figure 3-8).

Decreases in natural gas costs and the associated increase in natural gas generation, particularly between 2005 and 2016, was one of the main drivers of the recent fuel switching and decrease in electric power sector carbon intensity. During this time period, the cost of natural gas (in \$/MMBtu) decreased by 57 percent while the cost of coal (in \$/MMBtu) increased by 82 percent (EIA 2018). Also, between 1990 and 2016, renewable energy generation (in kWh) from wind and solar energy have increased from 0.1 percent in 1990 to 7 percent in 2016, which also helped drive the decrease in electric power sector carbon intensity. This decrease in carbon intensity occurred even as total electricity retail sales increased 39 percent, from 2,713 billion kWh in 1990 to 3,762 billion kWh in 2016.

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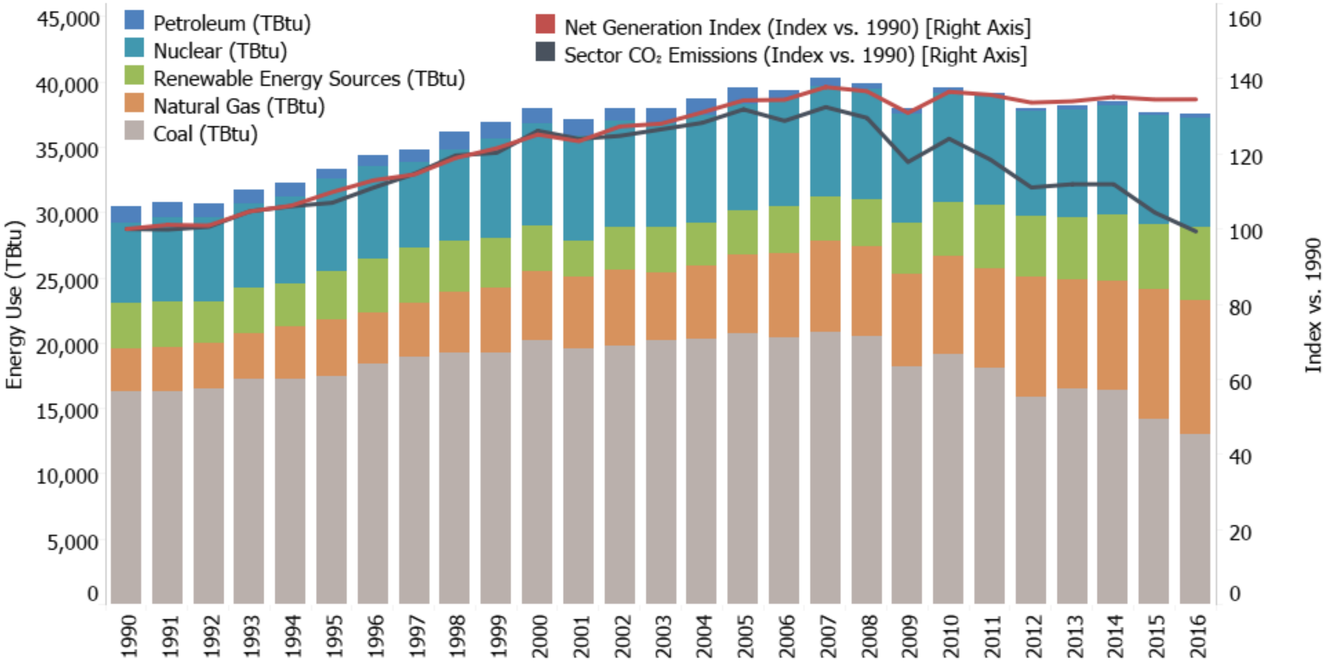
[16] Utilities primarily generate power for the U.S. electric grid for sale to retail customers. Non-utilities produce electricity for their own use, to sell to large consumers, or to sell on the wholesale electricity market (e.g., to utilities for distribution and resale to customers).

[17] Values represent electricity *net* generation from the electric power sector (EIA 2018).

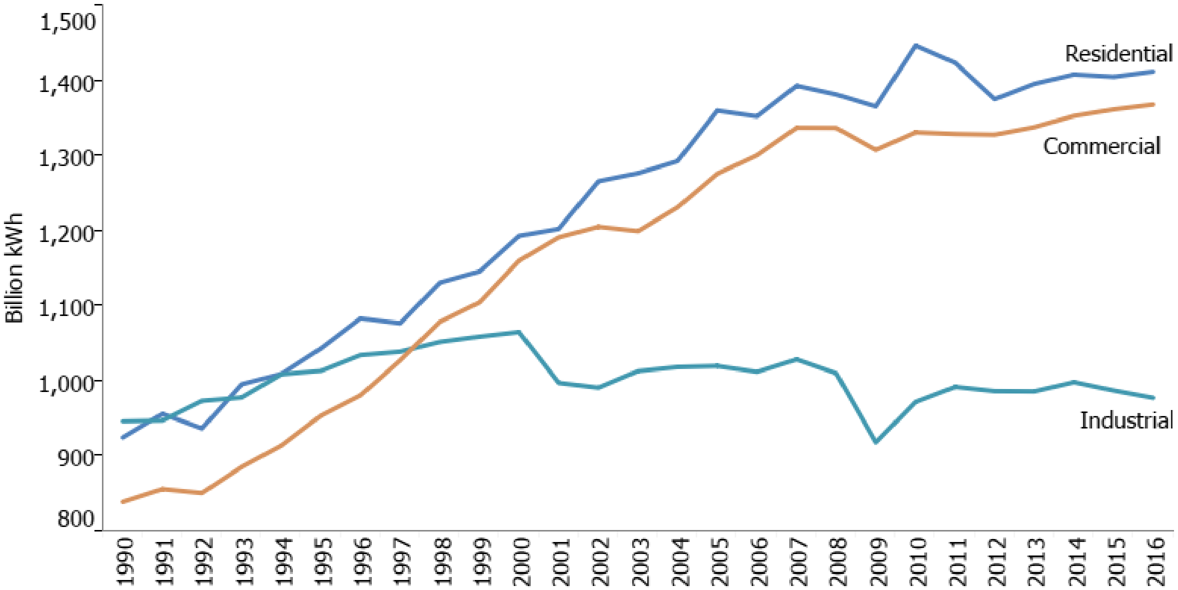
Figure 3-8: Fuels Used in Electric Power Generation (TBtu) and Total Electric Power Sector CO_2 Emissions



Source: Information on fuel consumption and net electricity generation was obtained from EIA (2018).

Electricity was consumed primarily in the residential, commercial, and industrial end-use sectors for lighting, heating, electric motors, appliances, electronics, and air conditioning (see Figure 3-9).

Figure 3-9: Electric Power Retail Sales by End-Use Sector (Billion kWh)



The industrial, residential, and commercial end-use sectors, as presented in Table 3-8, were reliant on electricity for meeting energy needs. The residential and commercial end-use sectors are especially reliant on electricity use for lighting, heating, air conditioning, and operating appliances. In 2016, electricity sales to the residential and commercial end-use sectors each increased by 0.5 percent. Electricity sales to the industrial sector in 2016 decreased approximately 1.0 percent. Overall, in 2016, the amount of electricity retail sales (in kWh) increased by 0.1 percent.

Industrial Sector

Industrial sector CO_2, CH_4, and N_2O, emissions accounted for 16, 14, and 7 percent of CO_2, CH_4, and N_2O, emissions from fossil fuel combustion, respectively. Carbon dioxide, CH_4, and N_2O emissions resulted from the direct consumption of fossil fuels for steam and process heat production.

The industrial end-use sector, per the underlying energy use data from EIA, includes activities such as manufacturing, construction, mining, and agriculture. The largest of these activities in terms of energy use is manufacturing, of which six industries—Petroleum Refineries, Chemicals, Paper, Primary Metals, Food, and Nonmetallic Mineral Products—represent the vast majority of the energy use (EIA 2018; EIA 2009b).

There are many dynamics that impact emissions from the industrial sector including economic activity, changes in the make-up of the industrial sector, changes in the emissions intensity of industrial processes, and weather impacts on heating of industrial buildings.[18] Structural changes within the U.S. economy that lead to shifts in industrial output away from energy-intensive manufacturing products to less energy-intensive products (e.g., from steel to computer equipment) have had a significant effect on industrial emissions.

From 2015 to 2016, total industrial production and manufacturing output increased by 1.2 percent (FRB 2017). Over this period, output increased across production indices for Food, Petroleum Refineries, Chemicals, and Nonmetallic Mineral Products, and decreased slightly for Primary Metals and Paper (see Figure 3-10). Through EPA's Greenhouse Gas Reporting Program (GHGRP), specific industrial sector trends can be discerned from the overall total EIA industrial fuel consumption data used for these calculations.

For example, from 2015 to 2016, the underlying EIA data showed decreased consumption of coal, and relatively flat use of natural gas in the industrial sector. The GHGRP data highlights that several industries contributed to these trends, including chemical manufacturing; pulp, paper and print; and food processing, beverages and tobacco.[19]

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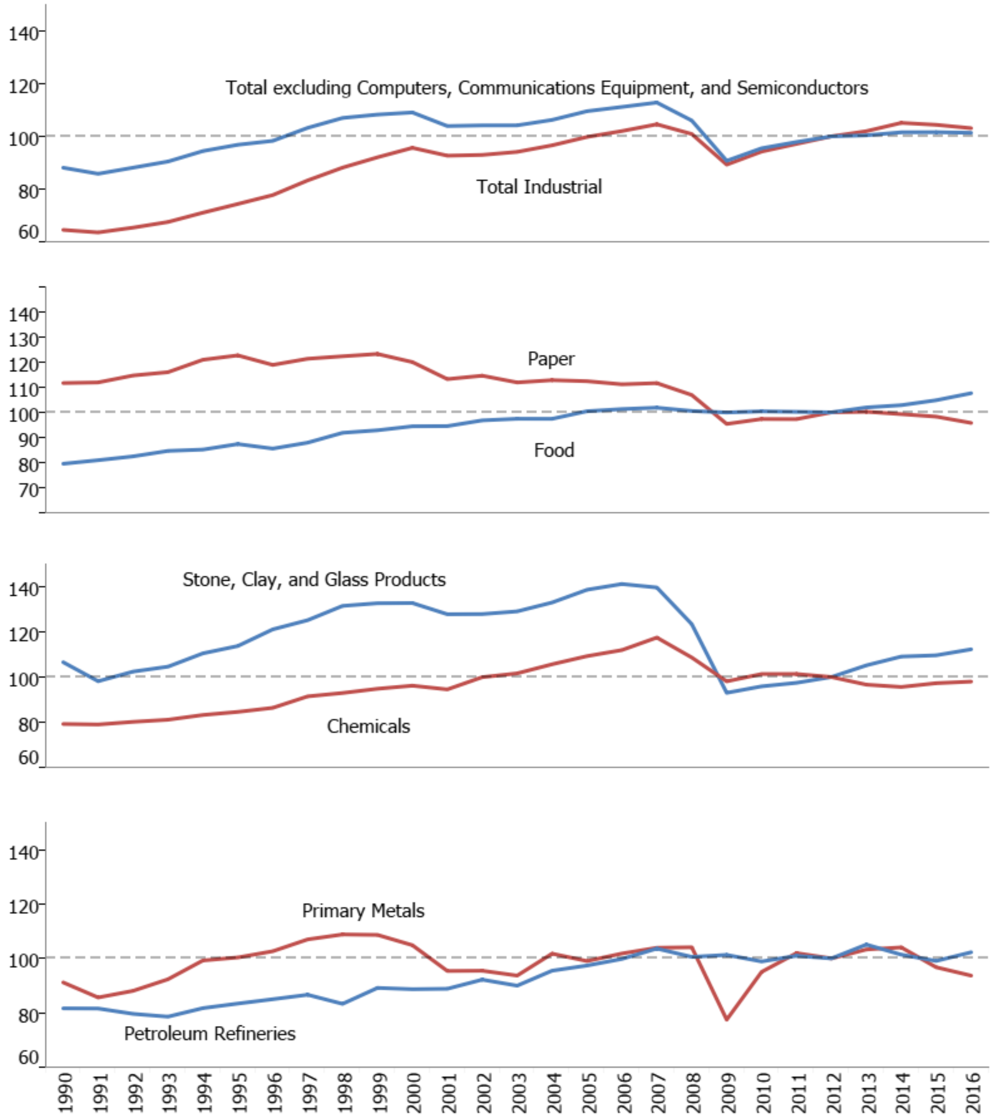
[18] Some commercial customers are large enough to obtain an industrial price for natural gas and/or electricity and are consequently grouped with the industrial end-use sector in U.S. energy statistics. These misclassifications of large commercial customers likely cause the industrial end-use sector to appear to be more sensitive to weather conditions.

[19] Further details on industrial sector combustion emissions are provided by EPA's GHGRP. See <http://ghgdata.epa.gov/ghgp/main.do>.

Figure 3-10: Industrial Production Indices (Index 2012=100)



Despite the growth in industrial output (60 percent) and the overall U.S. economy (87 percent) from 1990 to 2016, CO_2 emissions from fossil fuel combustion in the industrial sector decreased by 5.8 percent over the same time series. A number of factors are believed to have caused this disparity between growth in industrial output and decrease in industrial emissions, including: (1) more rapid growth in output from less energy-intensive industries relative to traditional manufacturing industries, and (2) energy-intensive industries such as steel are employing new methods, such as electric arc furnaces, that are less carbon intensive than the older methods. In 2016, CO_2, CH_4, and N_2O emissions from fossil fuel combustion and electricity use within the industrial end-use sector totaled 1,335.4 MMT CO_2 Eq., a 2.4 percent decrease from 2015 emissions.

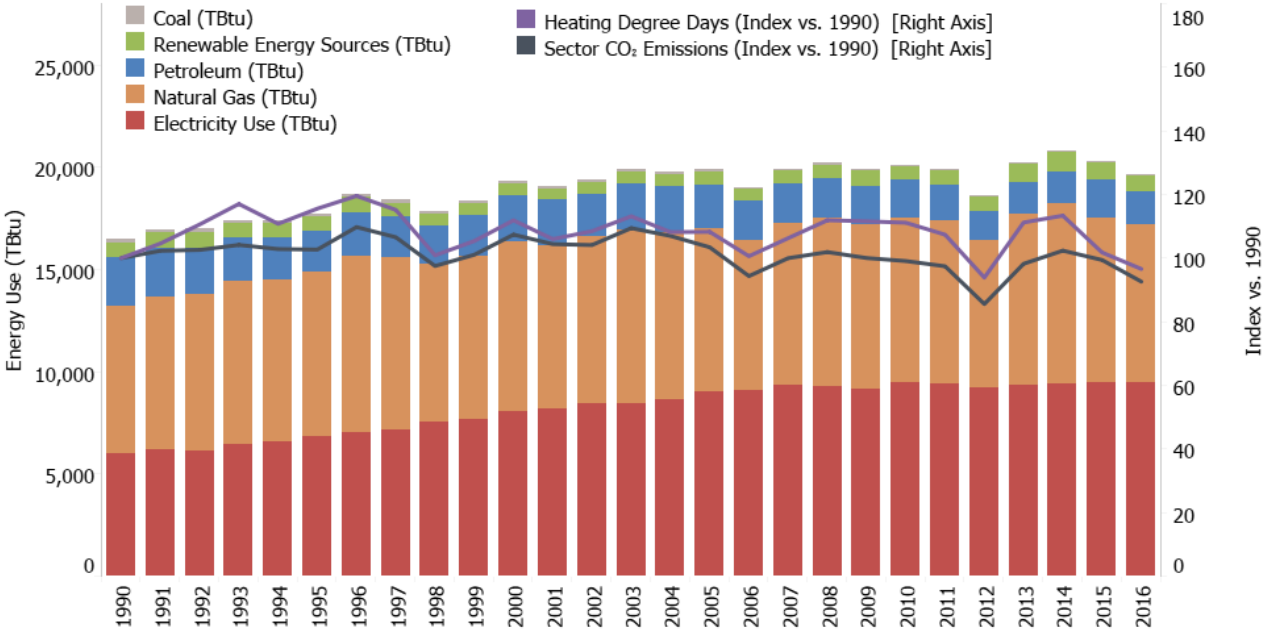
Residential and Commercial Sectors

Emissions from the residential and commercial sectors have increased since 1990, and are often correlated with short-term fluctuations in energy use caused by weather conditions, rather than prevailing economic conditions. More significant changes in emissions from the residential and commercial sectors in recent years can be largely attributed to an overall reduction in energy use, a reduction in heating degree days, and increases in energy efficiency (see Figure 3-11).

In 2016 the residential and commercial sectors accounted for 6 and 5 percent of CO_2 emissions from fossil fuel combustion, 31 and 11 percent of CH_4 emissions from fossil fuel combustion, and 2 and 1 percent of N_2O emissions from fossil fuel combustion, respectively. Emissions from these sectors were largely due to the direct consumption of natural gas and petroleum products, primarily for heating and cooking needs. Coal consumption was a minor component of energy use in both of these end-use sectors. In 2016, total emissions (CO_2, CH_4, and N_2O) from fossil fuel combustion and electricity use within the residential and commercial end-use sectors were 956.6 MMT CO_2 Eq. and 872.3 MMT CO_2 Eq., respectively. Total CO_2, CH_4, and N_2O emissions from fossil fuel combustion and electricity use within the residential and commercial end-use sectors decreased by 5.4 and 4.7 percent from 2015 to 2016, respectively, and heating degree days decreased by 5 percent over the same time period. A decrease in heating degree days led to a decreased demand for heating fuel and electricity for heat in the residential and commercial sectors. In addition, a shift toward energy efficient products and more stringent energy efficiency standards for household equipment has also contributed to a decrease in energy demand in households (EIA 2017e), resulting in a decrease in energy-related emissions. In the long term, the residential sector is also affected by population growth, migration trends toward warmer areas, and changes in housing and building attributes (e.g., larger sizes and improved insulation).

In 2016, combustion emissions from natural gas consumption represented 81 and 74 percent of the direct fossil fuel CO_2 emissions from the residential and commercial sectors, respectively. Natural gas combustion CO_2 emissions from the residential and commercial sectors in 2016 decreased by 5.9 percent and 3.1 percent from 2015 levels, respectively.

Figure 3-11: Fuels Used in Residential and Commercial Sectors (TBtu), Heating Degree Days, and Total Sector CO_2 Emissions



Note: Petroleum use in the residential and commercial sectors include adjustments for the sectoral allocation of distillate fuel oil and motor gasoline.

Source: Information on fuel consumption and electricity use were obtained from EIA (2018).

U.S. Territories

Emissions from U.S. Territories are based on the fuel consumption in American Samoa, Guam, Puerto Rico, U.S. Virgin Islands, Wake Island, and other U.S. Pacific Islands. As described in the Methodology section of CO_2 from Fossil Fuel Combustion, this data is collected separately from the sectoral-level data available for the general calculations. As sectoral information is not available for U.S. Territories, CO_2, CH_4, and N_2O emissions are not presented for U.S. Territories in the tables above by sector, though the emissions will include some transportation and mobile combustion sources.

Transportation Sector and Mobile Combustion

This discussion of transportation emissions follows the alternative method of presenting combustion emissions by allocating emissions associated with electricity generation to the transportation end-use sector, as presented in Table 3-8. Table 3-7 presents direct CO_2, CH_4, and N_2O emissions from all transportation sources (i.e., excluding emissions allocated to electricity consumption in the transportation end-use sector).

The transportation end-use sector and other mobile combustion accounted for 1,808.1 MMT CO_2 Eq. in 2016, which represented 36 percent of CO_2 emissions, 33 percent of CH_4 emissions, and 50 percent of N_2O emissions from fossil fuel combustion, respectively.[20] Fuel purchased in the United States for international aircraft and marine travel accounted for an additional 117.7 MMT CO_2 Eq. in 2016; these emissions are recorded as international bunkers and are not included in U.S. totals according to UNFCCC reporting protocols.

Transportation End-Use Sector

From 1990 to 2016, transportation emissions from fossil fuel combustion rose by 19 percent due, in large part, to increased demand for travel (see Figure 3-12). The number of vehicle miles traveled (VMT) by light-duty motor vehicles (passenger cars and light-duty trucks) increased 44 percent from 1990 to 2016,[21] as a result of a confluence of factors including population growth, economic growth, urban sprawl, and periods of low fuel prices.

From 2015 to 2016, CO_2 emissions from the transportation end-use sector increased by 2.7 percent. The increase in emissions can largely be attributed to increased VMT and motor gasoline consumption by light-duty vehicles, as well as diesel consumption by medium-and heavy-duty vehicles. From 2015 to 2016, there were also increases in residual fuel oil consumption by ships and boats and jet fuel use in general aviation aircraft.

Commercial aircraft emissions were similar between 2015 and 2016, but have decreased 14 percent since 2007 (FAA 2018).[22] Decreases in jet fuel emissions (excluding bunkers) since 2007 are due in part to improved operational efficiency that results in more direct flight routing, improvements in aircraft and engine technologies to reduce fuel burn and emissions, and the accelerated retirement of older, less fuel-efficient aircraft.

Almost all of the energy consumed for transportation was supplied by petroleum-based products, with more than half being related to gasoline consumption in automobiles and other highway vehicles. Other fuel uses, especially diesel fuel for freight trucks and jet fuel for aircraft, accounted for the remainder. The primary driver of transportation-related emissions was CO_2 from fossil fuel combustion. Annex 3.2 presents the total emissions from all transportation and mobile sources, including CO_2, N_2O, CH_4, and HFCs.

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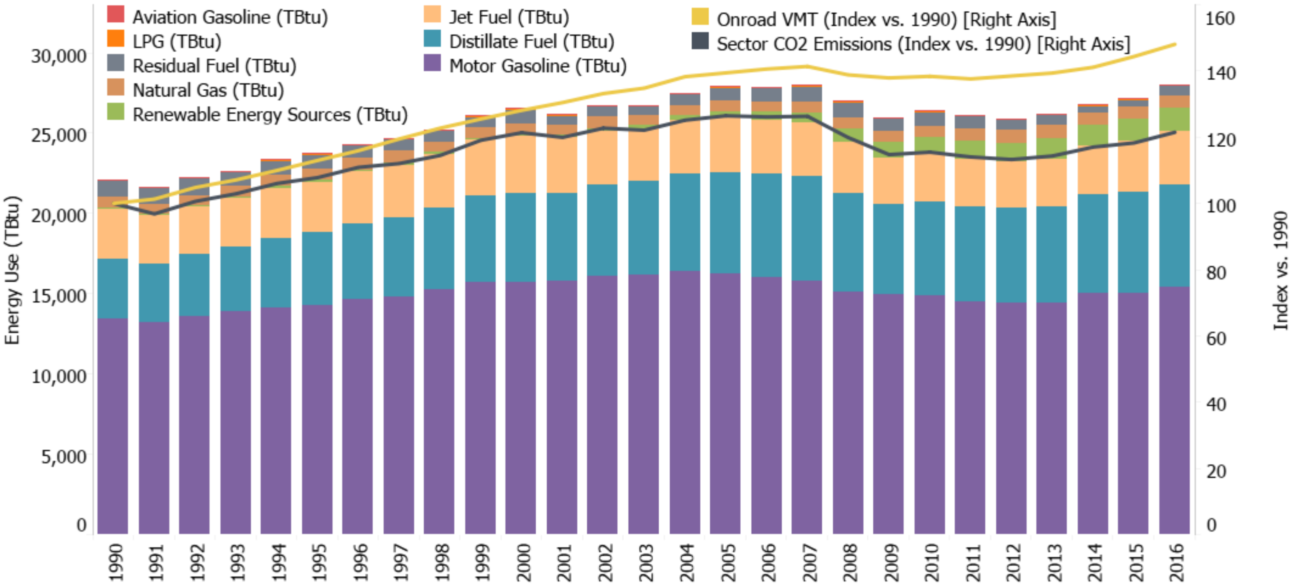
[20] Note that these totals include CO_2, CH_4 and N_2O emissions from some sources in the U.S. Territories (ships and boats, recreational boats, non-transportation mobile sources) and CH_4 and N_2O emissions from transportation rail electricity.

[21] VMT estimates are based on data from FHWA Highway Statistics Table VM-1 (FHWA 1996 through 2017). In 2011, FHWA changed its methods for estimating VMT by vehicle class, which led to a shift in VMT and emissions among on-road vehicle classes in the 2007 to 2016 time period. In absence of these method changes, light-duty VMT growth between 1990 and 2016 would likely have been even higher.

[22] Commercial aircraft, as modeled in FAA's AEDT (FAA 2018), consists of passenger aircraft, cargo, and other chartered flights.

Figure 3-12: Fuels Used in Transportation Sector (TBtu), Onroad VMT, and Total Sector CO_2 Emissions



Notes: Distillate fuel, residual fuel, and jet fuel include adjustments for international bunker fuels. Distillate fuel and motor gasoline include adjustments for the sectoral allocation of these fuels.
Source: Information on fuel consumption was obtained from EIA (2018).

Transportation Fossil Fuel Combustion CO_2 Emissions

Domestic transportation CO_2 emissions increased by 21 percent (315.4 MMT CO_2) between 1990 and 2016, an annualized increase of 0.8 percent. Among domestic transportation sources in 2016, light-duty vehicles (including passenger cars and light-duty trucks) represented 59 percent of CO_2 emissions from fossil fuel combustion, medium- and heavy-duty trucks and buses 24 percent, commercial aircraft 7 percent, and other sources 9 percent. See Table 3-12 for a detailed breakdown of transportation CO_2 emissions by mode and fuel type.

Almost all of the energy consumed by the transportation sector is petroleum-based, including motor gasoline, diesel fuel, jet fuel, and residual oil. Carbon dioxide emissions from the combustion of ethanol and biodiesel for transportation purposes, along with the emissions associated with the agricultural and industrial processes involved in the production of biofuel, are captured in other Inventory sectors.[23] Ethanol consumption from the transportation sector has increased from 0.7 billion gallons in 1990 to 13.5 billion gallons in 2016, while biodiesel consumption has increased from 0.01 billion gallons in 2001 to 2.1 billion gallons in 2016. For further information, see Section 3.11 on biofuel consumption at the end of this chapter and Table A-96 in Annex 3.2.

Carbon dioxide emissions from passenger cars and light-duty trucks totaled 1,058.5 MMT CO_2 in 2016. This is an increase of 14 percent (133.6 MMT CO_2) from 1990 due, in large part, to increased demand for travel as fleet-wide light-duty vehicle fuel economy was relatively stable (average new vehicle fuel economy declined slowly from 1990 through 2004 and then increased more rapidly from 2005 through 2016). Carbon dioxide emissions from passenger cars and light-duty trucks peaked at 1,150.6 MMT CO_2 in 2004, and since then have declined about 8 percent. The decline in new light-duty vehicle fuel economy between 1990 and 2004 (Figure 3-13) reflected the increasing market share of light-duty trucks, which grew from about 30 percent of new vehicle sales in 1990 to 48 percent in

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[23] Biofuel estimates are presented in the Energy chapter for informational purposes only, in line with IPCC methodological guidance and UNFCCC reporting obligations. Net carbon fluxes from changes in biogenic carbon reservoirs in croplands are accounted for in the estimates for Land Use, Land-Use Change, and Forestry (see Chapter 6). More information and additional analyses on biofuels are available at EPA's Renewable Fuels Standards website. See <https://www.epa.gov/renewable-fuel-standard-program>.

2004. Starting in 2005, average new vehicle fuel economy began to increase while light-duty VMT grew only modestly for much of the period. Light-duty VMT grew by less than one percent or declined each year between 2005 and 2013[24] and has since grown at a faster rate (2.6 percent from 2014 to 2015, and 2.5 percent from 2015 to 2016). Average new vehicle fuel economy has increased almost every year since 2005, while the light-duty truck share decreased to about 33 percent in 2009 and has since varied from year to year between 36 and 43 percent. Light-duty truck share is about 38 percent of new vehicles in model year 2016 (EPA 2016a). See also Annex 3.2 for data by vehicle mode and information on VMT and the share of new vehicles (in VMT).

Medium- and heavy-duty truck CO_2 emissions increased by 82 percent from 1990 to 2016. This increase was largely due to a substantial growth in medium- and heavy-duty truck VMT, which increased by 100 percent between 1990 and 2016.[25] Carbon dioxide from the domestic operation of commercial aircraft increased by 10 percent (10.5 MMT CO_2) from 1990 to 2016.[26] Across all categories of aviation, excluding international bunkers, CO_2 emissions decreased by 11 percent (19.9 MMT CO_2) between 1990 and 2016.[27] This includes a 66 percent (22.7 MMT CO_2) decrease in CO_2 emissions from domestic military operations.

Transportation sources also produce CH_4 and N_2O; these emissions are included in Table 3-13 and Table 3-14 and in the CH_4 and N_2O from Mobile Combustion section. Annex 3.2 presents total emissions from all transportation and mobile sources, including CO_2, CH_4, N_2O, and HFCs.

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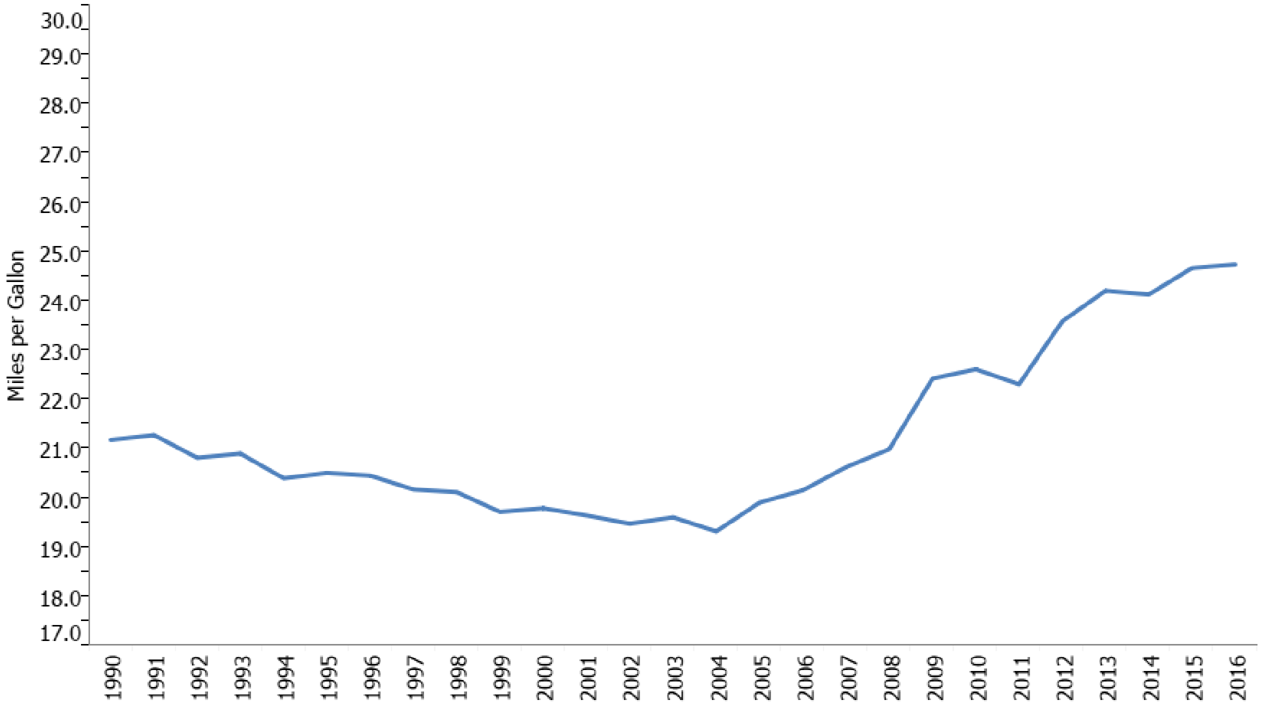
[24] VMT estimates are based on data from FHWA Highway Statistics Table VM-1 (FHWA 1996 through 2017). In 2007 and 2008 light-duty VMT decreased 3.0 percent and 2.3 percent, respectively. Note that the decline in light-duty VMT from 2006 to 2007 is due at least in part to a change in FHWA's methods for estimating VMT. In 2011, FHWA changed its methods for estimating VMT by vehicle class, which led to a shift in VMT and emissions among on-road vehicle classes in the 2007 to 2016 time period. In absence of these method changes, light-duty VMT growth between 2006 and 2007 would likely have been higher.

[25] While FHWA data shows consistent growth in medium- and heavy-duty truck VMT over the 1990 to 2016 time period, part of the growth reflects a method change for estimating VMT starting in 2007. This change in methodology in FHWA's VM-1 table resulted in large changes in VMT by vehicle class, thus leading to a shift in VMT and emissions among on-road vehicle classes in the 2007 to 2016 time period. During the time period prior to the method change (1990 to 2006), VMT for medium- and heavy-duty trucks increased by 51 percent.

[26] Commercial aircraft, as modeled in FAA's AEDT, consists of passenger aircraft, cargo, and other chartered flights.

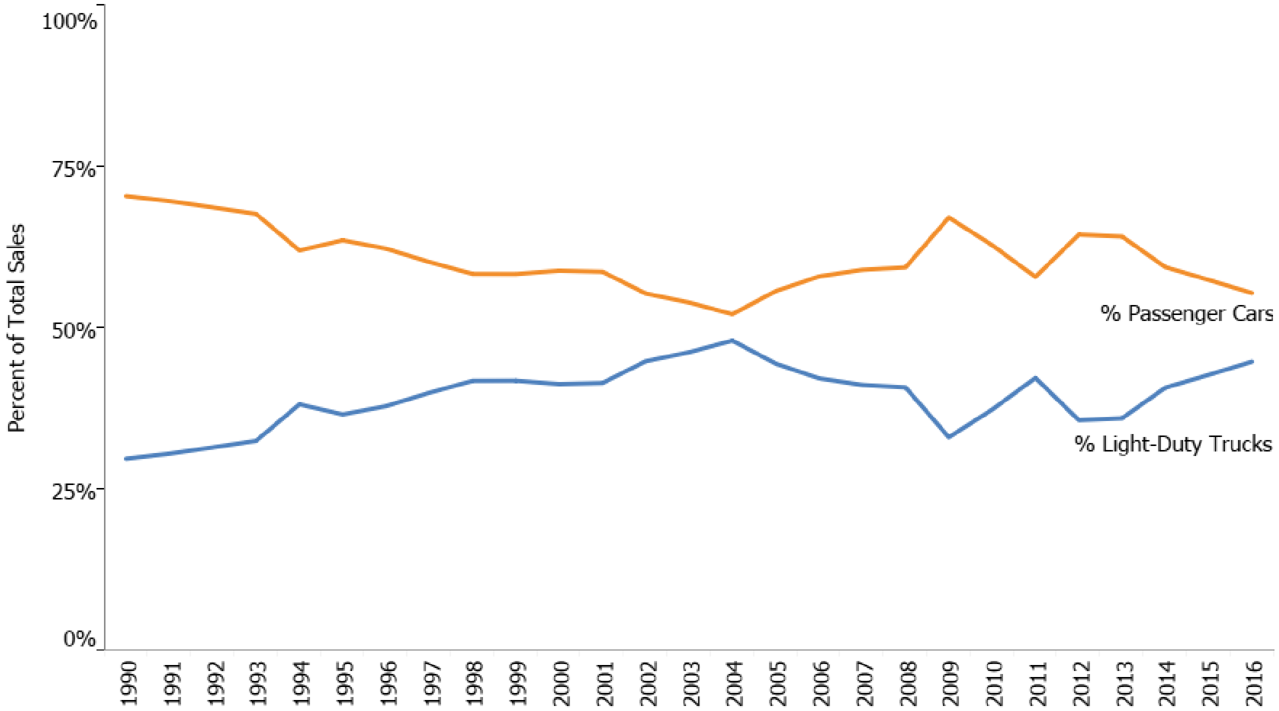
[27] Includes consumption of jet fuel and aviation gasoline. Does not include aircraft bunkers, which are not included in national emission totals, in line with IPCC methodological guidance and UNFCCC reporting obligations.

Figure 3-13: Sales-Weighted Fuel Economy of New Passenger Cars and Light-Duty Trucks, 1990–2016 (miles/gallon)



Source: EPA (2016a)

Figure 3-14: Sales of New Passenger Cars and Light-Duty Trucks, 1990–2016 (Percent)



Source: EPA (2016a)

Table 3-12: CO_2 Emissions from Fossil Fuel Combustion in Transportation End-Use Sector (MMT CO_2 Eq.)

Fuel/Vehicle Type	1990	2005	2012[a]	2013[a]	2014[a]	2015[a]	2016[a]
Gasoline[b]	**957.3**	**1,152.4**	**1,029.8**	**1,030.2**	**1,072.0**	**1,070.5**	**1,096.3**
Passenger Cars	604.6	638.3	707.2	706.9	725.4	731.3	744.6
Light-Duty Trucks	300.7	464.4	268.2	268.3	290.2	283.2	294.5
Medium- and Heavy-Duty Trucks[c]	37.7	33.9	37.4	38.2	39.5	39.3	40.4
Buses	0.3	0.4	0.8	0.8	0.9	0.9	0.9
Motorcycles	1.7	1.6	3.9	3.7	3.7	3.7	3.8
Recreational Boats[d]	12.3	13.8	12.3	12.2	12.2	12.2	12.1
Distillate Fuel Oil (Diesel)[b]	**262.9**	**457.5**	**427.5**	**433.9**	**446.3**	**459.8**	**462.8**
Passenger Cars	7.9	4.2	4.1	4.1	4.1	4.3	4.3
Light-Duty Trucks	11.5	25.8	12.9	12.9	13.8	13.9	14.3
Medium- and Heavy-Duty Trucks[c]	190.5	360.2	344.4	350.0	360.0	368.8	376.4
Buses	8.0	10.6	15.4	15.5	16.8	17.1	17.0
Rail	35.5	45.5	39.5	40.1	41.5	39.8	36.7
Recreational Boats	2.0	3.2	3.7	3.7	3.8	3.9	4.0
Ships and Non-Recreational Boats[e]	7.5	8.0	7.5	7.5	6.1	12.0	9.9
International Bunker Fuels[f]	*11.7*	*9.4*	*6.8*	*5.6*	*6.1*	*8.4*	*8.7*
Jet Fuel	**184.2**	**189.3**	**143.4**	**147.1**	**148.4**	**157.6**	**166.0**
Commercial Aircraft[g]	109.9	132.7	113.3	114.3	115.2	119.0	120.4
Military Aircraft	35.0	19.4	12.1	11.0	14.0	13.5	12.3
General Aviation Aircraft	39.4	37.3	18.0	21.8	19.2	25.1	33.4
International Bunker Fuels[f]	*38.0*	*60.1*	*64.5*	*65.7*	*69.6*	*71.9*	*74.1*
International Bunker Fuels from Commercial Aviation	*30.0*	*55.6*	*61.4*	*62.8*	*66.3*	*68.6*	*70.8*
Aviation Gasoline General	**3.1**	**2.4**	**1.7**	**1.5**	**1.5**	**1.5**	**1.4**
Aviation Aircraft **Residual**	3.1	2.4	1.7	1.5	1.5	1.5	1.4
Fuel Oil	**22.6**	**19.3**	**15.8**	**15.1**	**5.8**	**4.2**	**12.9**
Ships and Boats[e]	22.6	19.3	15.8	15.1	5.8	4.2	12.9
International Bunker Fuels[f]	*53.7*	*43.6*	*34.5*	*28.5*	*27.7*	*30.6*	*33.8*
Natural Gas [j]	**36.0**	**33.1**	**41.3**	**47.0**	**40.3**	**39.5**	**40.6**
Passenger Cars	+	+	+	+	+	+	+
Light-Duty Trucks	+	+	+	+	+	+	+
Medium- and Heavy-Duty Trucks	+	+	+	+	+	+	+
Buses	+	0.6	0.8	0.8	0.8	0.9	1.0
Pipeline[h]	36.0	32.4	40.5	46.2	39.4	38.5	39.6
LPG [j]	**1.4**	**1.7**	**2.3**	**2.7**	**2.9**	**2.5**	**2.5**
Passenger Cars	+	+	+	+	+	0.2	0.4
Light-Duty Trucks	0.2	0.3	0.2	0.3	0.6	0.4	0.2
Medium- and Heavy-Duty Trucks[c]	1.1	1.3	1.8	2.1	1.9	1.6	1.6
Buses	0.1	0.1	0.3	0.4	0.3	0.3	0.2
Electricity	**3.0**	**4.7**	**3.9**	**4.0**	**4.1**	**3.7**	**3.5**
Rail	3.0	4.7	3.9	4.0	4.1	3.7	3.5
Total[k]	**1,470.6**	**1,860.5**	**1,665.8**	**1,681.6**	**1,721.2**	**1,739.2**	**1,786.1**
Total (Including Bunkers)[f]	**1,574.1**	**1,973.6**	**1,771.6**	**1,781.4**	**1,824.6**	**1,850.1**	**1,902.7**
Biofuels-Ethanol[i]	4.1	*22.4*	*71.5*	*73.4*	*74.9*	*75.9*	*78.2*
Biofuels-Biodiesel[i]	+	*0.9*	*8.5*	*13.5*	*13.3*	*14.1*	*19.6*

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] In 2011 FHWA changed its methods for estimating vehicle miles traveled (VMT) and related data. These methodological changes included how vehicles are classified, moving from a system based on body-type to one that is based on wheelbase. These changes were first incorporated for the 1990 through 2010 Inventory and apply to the 2007 through 2016 time period. This resulted in large changes in VMT and fuel consumption data by vehicle class, thus leading to a shift in emissions among on-road vehicle classes.

[b] Gasoline and diesel highway vehicle fuel consumption estimates are based on data from FHWA Highway Statistics Table MF-21, MF-27, and VM-1 (FHWA 1996 through 2017). Data from Table VM-1 is used to estimate the share of consumption between each on-road vehicle class. These fuel consumption estimates are combined with estimates of fuel shares by vehicle type from DOE's TEDB Annex Tables A.1 through A.6 (DOE 1993 through 2016). TEDB data for 2016 has not been published yet, therefore 2015 data are used as a proxy.

[c] Includes medium- and heavy-duty trucks over 8,500 lbs.

[d] In 2014, EPA incorporated the NONROAD2008 model into MOVES2014. The current Inventory uses the NONROAD component of MOVES2014a for years 1999 through 2016.

[e] Note that large year over year fluctuations in emission estimates partially reflect nature of data collection for these sources.

[f] Official estimates exclude emissions from the combustion of both aviation and marine international bunker fuels; however, estimates including international bunker fuel-related emissions are presented for informational purposes.

[g] Commercial aircraft, as modeled in FAA's Aviation Environmental Design Tool (AEDT), consists of passenger aircraft, cargo, and other chartered flights.

[h] Pipelines reflect CO_2 emissions from natural gas-powered pipelines transporting natural gas.

[i] Ethanol and biodiesel estimates are presented for informational purposes only. See Section 3.11 of this chapter and the estimates in Land Use, Land-Use Change, and Forestry (see Chapter 6), in line with IPCC methodological guidance and UNFCCC reporting obligations, for more information on ethanol and biodiesel.

[j] Transportation sector natural gas and LPG consumption are based on data from EIA (2017). Prior to the previous (i.e., 1990 through 2015) Inventory, data from DOE TEDB were used to estimate each vehicle class's share of the total natural gas and LPG consumption. Since TEDB does not include estimates for natural gas use by medium and heavy-duty trucks or LPG use by passenger cars, EIA Alternative Fuel Vehicle Data (Browning 2017) is now used to determine each vehicle class's share of the total natural gas and LPG consumption. These changes were first incorporated in the previous Inventory and apply to the 1990 to 2016 time period.

[k] Includes emissions from rail electricity.

Notes: This table does not include emissions from non-transportation mobile sources, such as agricultural equipment and construction/mining equipment; it also does not include emissions associated with electricity consumption by pipelines or lubricants used in transportation. In addition, this table does not include CO_2 emissions from U.S. Territories, since these are covered in a separate chapter of the Inventory. Totals may not sum due to independent rounding.

Mobile Fossil Fuel Combustion CH_4 and N_2O Emissions

Mobile combustion includes emissions of CH_4 and N_2O from all transportation sources identified in the U.S. Inventory with the exception of pipelines and electric locomotives;[28] mobile sources also include non-transportation sources such as construction/mining equipment, agricultural equipment, vehicles used off-road, and other sources (e.g., snowmobiles, lawnmowers, etc.). [29] Annex 3.2 includes a summary of all emissions from both transportation and mobile sources. Table 3-13 and Table 3-14 provide mobile fossil fuel CH_4 and N_2O emission estimates in MMT CO_2 Eq.[30]

Mobile combustion was responsible for a small portion of national CH_4 emissions (0.6 percent) but was the third largest source of U.S. N_2O emissions (5.0 percent). From 1990 to 2016, mobile source CH_4 emissions declined by

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[28] Emissions of CH_4 from natural gas systems are reported separately. More information on the methodology used to calculate these emissions are included in this chapter and Annex 3.4.

[29] See the methodology sub-sections of the CO_2 from Fossil Fuel Combustion and CH_4 and N_2O from Mobile Combustion sections of this chapter. Note that N_2O and CH_4 emissions are reported using different categories than CO_2. CO_2 emissions are reported by end-use sector (Transportation, Industrial, Commercial, Residential, U.S. Territories), and generally adhere to a top-down approach to estimating emissions. CO_2 emissions from non-transportation sources (e.g., lawn and garden equipment, farm equipment, construction equipment) are allocated to their respective end-use sector (i.e., construction equipment CO_2 emissions are included in the Industrial end-use sector instead of the Transportation end-use sector). CH_4 and N_2O emissions are reported using the "Mobile Combustion" category, which includes non-transportation mobile sources. CH_4 and N_2O emission estimates are bottom-up estimates, based on total activity (fuel use, VMT) and emissions factors by source and technology type. These reporting schemes are in accordance with IPCC guidance. For informational purposes only, CO_2 emissions from non-transportation mobile sources are presented separately from their overall end-use sector in Annex 3.2.

[30] See Annex 3.2 for a complete time series of emission estimates for 1990 through 2016.

71 percent, to 3.6 MMT CO_2 Eq. (146 kt CH_4), due largely to control technologies employed in on-road vehicles since the mid-1990s to reduce CO, NO_x, NMVOC, and CH_4 emissions. Mobile source emissions of N_2O decreased by 56 percent, to 18.4 MMT CO_2 Eq. (62 kt N_2O). Earlier generation control technologies initially resulted in higher N_2O emissions, causing a 30 percent increase in N_2O emissions from mobile sources between 1990 and 1997. Improvements in later-generation emission control technologies have reduced N_2O output, resulting in a 66 percent decrease in mobile source N_2O emissions from 1997 to 2016 (Figure 3-15). Overall, CH_4 and N_2O emissions were predominantly from gasoline-fueled passenger cars and light-duty trucks. See also Annex 3.2 for data by vehicle mode and information on VMT and the share of new vehicles (in VMT).

Figure 3-15: Mobile Source CH_4 and N_2O Emissions (MMT CO_2 Eq.)

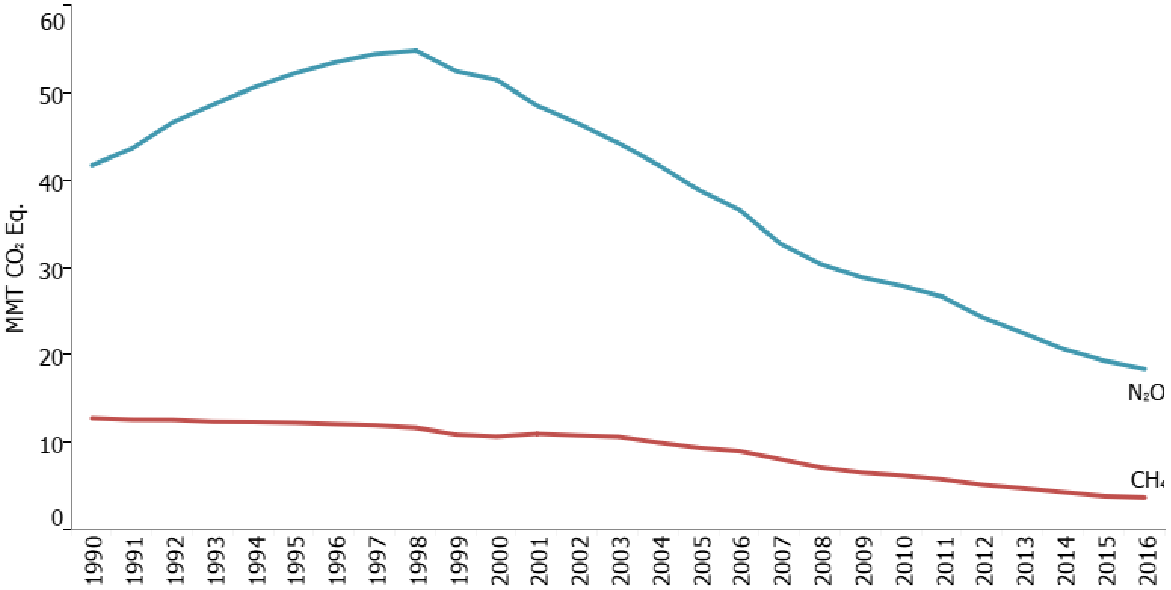

Table 3-13: CH_4 Emissions from Mobile Combustion (MMT CO_2 Eq.)

Fuel Type/Vehicle Type[a]	1990	2005	2012	2013	2014	2015	2016
Gasoline On-Road[b]	**5.2**	**2.2**	**1.3**	**1.1**	**1.0**	**0.9**	**0.9**
Passenger Cars	3.2	1.3	0.9	0.8	0.7	0.6	0.6
Light-Duty Trucks	1.7	0.8	0.3	0.3	0.2	0.2	0.2
Medium- and Heavy-Duty Trucks and Buses	0.3	0.1	0.1	0.1	+	+	+
Motorcycles	+	+	+	+	+	+	+
Diesel On-Road[b]	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Passenger Cars	+	+	+	+	+	+	+
Light-Duty Trucks	+	+	+	+	+	+	+
Medium- and Heavy-Duty Trucks and Buses	+	+	+	+	+	+	+
Alternative Fuel On-Road	**+**	**0.2**	**0.3**	**0.3**	**0.2**	**0.3**	**0.3**
Non-Road[c]	**7.5**	**6.9**	**3.5**	**3.3**	**3.0**	**2.6**	**2.5**
Ships and Boats	0.5	0.5	0.4	0.4	0.3	0.3	0.3
Rail	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Aircraft	0.1	0.1	+	+	+	+	+
Agricultural Equipment[d]	0.8	0.5	0.2	0.2	0.2	0.1	0.1
Construction/Mining Equipment[e]	0.9	0.9	0.6	0.6	0.5	0.4	0.4
Other[f]	5.2	4.9	2.2	2.0	1.8	1.6	1.6
Total	**12.7**	**9.4**	**5.1**	**4.7**	**4.2**	**3.8**	**3.6**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] See Annex 3.2 for definitions of on-road vehicle types.

[b] Gasoline and diesel highway vehicle mileage estimates are based on data from FHWA Highway Statistics Table VM-1 (FHWA 1996 through 2017). These mileage estimates are combined with estimates of fuel shares by vehicle type from DOE's TEDB Annex Tables A.1 through A.6 (DOE 1993 through 2016). TEDB data for 2016 has not been published yet, therefore 2015 data are used as a proxy.

[c] Rail emissions do not include emissions from electric powered locomotives. Class II and Class III rail diesel consumption for 2014-2016 are not available, therefore 2013 data is used as a proxy. Commuter and intercity rail diesel consumption data for 2016 is not available yet, therefore 2015 data are used as a proxy.

[d] Includes equipment, such as tractors and combines, as well as fuel consumption from trucks that are used off-road in agriculture.

[e] Includes equipment, such as cranes, dumpers, and excavators, as well as fuel consumption from trucks that are used off-road in construction.

[f] "Other" includes snowmobiles and other recreational equipment, logging equipment, lawn and garden equipment, railroad equipment, airport equipment, commercial equipment, and industrial equipment, as well as fuel consumption from trucks that are used off-road for commercial/industrial purposes.

Notes: In 2011, FHWA changed its methods for estimating vehicle miles traveled (VMT) and related data. These methodological changes included how vehicles are classified, moving from a system based on body-type to one that is based on wheelbase. These changes were first incorporated for the 1990 through 2010 Inventory and apply to the 2007 through 2016 time period. This resulted in large changes in VMT and fuel consumption data by vehicle class, thus leading to a shift in emissions among on-road vehicle classes. Totals may not sum due to independent rounding.

Table 3-14: N$_2$O Emissions from Mobile Combustion (MMT CO$_2$ Eq.)

Fuel Type/Vehicle Type[a]	**1990**	**2005**	**2012**	**2013**	**2014**	**2015**	**2016**
Gasoline On-Road[b]	**37.5**	**33.5**	**19.1**	**17.2**	**15.4**	**14.0**	**12.8**
Passenger Cars	24.1	17.5	13.1	11.8	10.5	9.7	8.9
Light-Duty Trucks	12.8	15.0	5.3	4.7	4.4	3.8	3.5
Medium- and Heavy-Duty Trucks and Buses	0.5	0.9	0.7	0.6	0.5	0.5	0.4
Motorcycles	+	+	+	+	+	+	+
Diesel On-Road[b]	**0.2**	**0.3**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**
Passenger Cars	+	+	+	+	+	+	+
Light-Duty Trucks	+	+	+	+	+	+	+
Medium- and Heavy-Duty Trucks and Buses	0.2	0.3	0.4	0.4	0.4	0.4	0.4
Alternative Fuel On-Road	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Non-Road	**4.0**	**5.0**	**4.8**	**4.9**	**4.8**	**5.0**	**5.2**
Ships and Boats	0.6	0.6	0.5	0.5	0.3	0.4	0.5
Rail[c]	0.3	0.4	0.3	0.3	0.3	0.3	0.3
Aircraft	1.7	1.8	1.3	1.4	1.4	1.5	1.5
Agricultural Equipment[d]	0.4	0.6	0.7	0.7	0.7	0.7	0.7
Construction/Mining Equipment[e]	0.6	0.9	1.0	1.1	1.1	1.1	1.1
Other[f]	0.5	0.9	1.0	1.0	1.0	1.1	1.1
Total	**41.7**	**38.8**	**24.3**	**22.5**	**20.7**	**19.3**	**18.4**

+ Does not exceed 0.05 MMT CO$_2$ Eq.

[a] See Annex 3.2 for definitions of on-road vehicle types.

[b] Gasoline and diesel highway vehicle mileage estimates are based on data from FHWA Highway Statistics Table VM-1 (FHWA 1996 through 2017). These mileage estimates are combined with estimates of fuel shares by vehicle type from DOE's TEDB Annex Tables A.1 through A.6 (DOE 1993 through 2016). TEDB data for 2016 has not been published yet, therefore 2015 data are used as a proxy.

[c] Rail emissions do not include emissions from electric powered locomotives. Class II and Class III rail diesel consumption for 2014-2016 are not available, therefore 2013 data is used as a proxy. Commuter and intercity rail diesel consumption data for 2016 is not available yet, therefore 2015 data are used as a proxy.

[d] Includes equipment, such as tractors and combines, as well as fuel consumption from trucks that are used off-road in agriculture.

[e] Includes equipment, such as cranes, dumpers, and excavators, as well as fuel consumption from trucks that are used off-road in construction.

[f] "Other" includes snowmobiles and other recreational equipment, logging equipment, lawn and garden equipment, railroad equipment, airport equipment, commercial equipment, and industrial equipment, as well as fuel consumption from trucks that are used off-road for commercial/industrial purposes.

Note: In 2011, FHWA changed its methods for estimating vehicle miles traveled (VMT) and related data. These methodological changes included how vehicles are classified, moving from a system based on body type to one that is based on wheelbase. These changes were first incorporated for the 1990 through 2010 Inventory and apply to the 2007 through 2016 time period. This resulted in large changes in VMT and fuel consumption data by vehicle class, thus leading to a shift in emissions among on-road vehicle classes. Totals may not sum due to independent rounding.

CO_2 from Fossil Fuel Combustion

Methodology

CO_2 emissions from fossil fuel combustion are estimated in line with a Tier 2 method described by the IPCC in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006) with some exceptions as discussed below.[31] A detailed description of the U.S. methodology is presented in Annex 2.1, and is characterized by the following steps:

1. *Determine total fuel consumption by fuel type and sector*. Total fossil fuel consumption for each year is estimated by aggregating consumption data by end-use sector (e.g., commercial, industrial, etc.), primary fuel type (e.g., coal, petroleum, gas), and secondary fuel category (e.g., motor gasoline, distillate fuel oil, etc.). Fuel consumption data for the United States were obtained directly from the EIA of the U.S. Department of Energy (DOE), primarily from the Monthly Energy Review (EIA 2018). The EIA does not include territories in its national energy statistics, so fuel consumption data for territories were collected separately from EIA's International Energy Statistics (EIA 2017a).[32]

   For consistency of reporting, the IPCC has recommended that countries report energy data using the International Energy Agency (IEA) reporting convention and/or IEA data. Data in the IEA format are presented "top down"—that is, energy consumption for fuel types and categories are estimated from energy production data (accounting for imports, exports, stock changes, and losses). The resulting quantities are referred to as "apparent consumption." The data collected in the United States by EIA on an annual basis and used in this Inventory are predominantly from mid-stream or conversion energy consumers such as refiners and electric power generators. These annual surveys are supplemented with end-use energy consumption surveys, such as the Manufacturing Energy Consumption Survey, that are conducted on a periodic basis (every four years). These consumption data sets help inform the annual surveys to arrive at the national total and sectoral breakdowns for that total.[33]

   Also, note that U.S. fossil fuel energy statistics are generally presented using gross calorific values (GCV) (i.e., higher heating values). Fuel consumption activity data presented here have not been adjusted to correspond to international standards, which are to report energy statistics in terms of net calorific values (NCV) (i.e., lower heating values).[34]

2. *Subtract uses accounted for in the Industrial Processes and Product Use chapter*. Portions of the fuel consumption data for seven fuel categories—coking coal, distillate fuel, industrial other coal, petroleum coke, natural gas, residual fuel oil, and other oil—were reallocated to the Industrial Processes and Product

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[31] The IPCC Tier 3B methodology is used for estimating emissions from commercial aircraft.

[32] Fuel consumption by U.S. Territories (i.e., American Samoa, Guam, Puerto Rico, U.S. Virgin Islands, Wake Island, and other U.S. Pacific Islands) is included in this report and contributed total emissions of 41.4 MMT CO_2 Eq. in 2016.

[33] See IPCC Reference Approach for Estimating CO_2 Emissions from Fossil Fuel Combustion in Annex 4 for a comparison of U.S. estimates using top-down and bottom-up approaches.

[34] A crude convention to convert between gross and net calorific values is to multiply the heat content of solid and liquid fossil fuels by 0.95 and gaseous fuels by 0.9 to account for the water content of the fuels. Biomass-based fuels in U.S. energy statistics, however, are generally presented using net calorific values.

Use chapter, as they were consumed during non-energy-related industrial activity. To make these adjustments, additional data were collected from AISI (2004 through 2016), Coffeyville (2012), U.S. Census Bureau (2001 through 2011), EIA (2018, 2017b, 2017c), USAA (2008 through 2017), USGS (1991 through 2015a), (USGS 2016a), USGS (2014 through 2016a), USGS (2014 through 2016b), USGS (1995 through 2013), USGS (1995, 1998, 2000, 2001), USGS (2017), USGS (1991 through 2013), USGS (2016d), USGS (2015b), USGS (2014), USGS (1996 through 2013), USGS (1991 through 2015b), USGS (2015 and 2016), USGS (1991 through 2015c).[35]

3. *Adjust for conversion of fuels and exports of CO_2.* Fossil fuel consumption estimates are adjusted downward to exclude fuels created from other fossil fuels and exports of CO_2.[36] Synthetic natural gas is created from industrial coal, and is currently included in EIA statistics for both coal and natural gas. Therefore, synthetic natural gas is subtracted from energy consumption statistics.[37] Since October 2000, the Dakota Gasification Plant has been exporting CO_2 to Canada by pipeline. Since this CO_2 is not emitted to the atmosphere in the United States, the associated fossil fuel burned to create the exported CO_2 is subtracted from fossil fuel consumption statistics. The associated fossil fuel is the total fossil fuel burned at the plant with the CO_2 capture system multiplied by the fraction of the plant's total site-generated CO_2 that is recovered by the capture system. To make these adjustments, additional data for ethanol and biodiesel were collected from EIA (2018), data for synthetic natural gas were collected from EIA (2017c), and data for CO_2 exports were collected from the Eastman Gasification Services Company (2011), Dakota Gasification Company (2006), Fitzpatrick (2002), Erickson (2003), EIA (2008) and DOE (2012).
4. *Adjust Sectoral Allocation of Distillate Fuel Oil and Motor Gasoline.* EPA had conducted a separate bottom-up analysis of transportation fuel consumption based on data from the Federal Highway Administration that indicated that the amount of distillate and motor gasoline consumption allocated to the transportation sector in the EIA statistics should be adjusted. Therefore, for these estimates, the transportation sector's distillate fuel and motor gasoline consumption was adjusted to match the value obtained from the bottom-up analysis. As the total distillate and motor gasoline consumption estimate from EIA are considered to be accurate at the national level, the distillate and motor gasoline consumption totals for the residential, commercial, and industrial sectors were adjusted proportionately. The data sources used in the bottom-up analysis of transportation fuel consumption include AAR (2008 through 2017), Benson (2002 through 2004), DOE (1993 through 2016), EIA (2007), EIA (1991 through 2017), EPA (2017b), and FHWA (1996 through 2017).[38]
5. *Adjust for fuels consumed for non-energy uses*. U.S. aggregate energy statistics include consumption of fossil fuels for non-energy purposes. These are fossil fuels that are manufactured into plastics, asphalt, lubricants, or other products. Depending on the end-use, this can result in storage of some or all of the C contained in the fuel for a period of time. As the emission pathways of C used for non-energy purposes are vastly different than fuel combustion (since the C in these fuels ends up in products instead of being combusted), these emissions are estimated separately in Section 3.2 – Carbon Emitted and Stored in Products from Non-Energy Uses of Fossil Fuels. Therefore, the amount of fuels used for non-energy purposes was subtracted from total fuel consumption. Data on non-fuel consumption was provided by EIA (2018).
6. *Subtract consumption of international bunker fuels.* According to the UNFCCC reporting guidelines emissions from international transport activities, or bunker fuels, should not be included in national totals. U.S. energy consumption statistics include these bunker fuels (e.g., distillate fuel oil, residual fuel oil, and

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[35] See sections on Iron and Steel Production and Metallurgical Coke Production, Ammonia Production and Urea Consumption, Petrochemical Production, Titanium Dioxide Production, Ferroalloy Production, Aluminum Production, and Silicon Carbide Production and Consumption in the Industrial Processes and Product Use chapter.

[36] Energy statistics from EIA (2018) are already adjusted downward to account for ethanol added to motor gasoline, biodiesel added to diesel fuel, and biogas in natural gas.

[37] These adjustments are explained in greater detail in Annex 2.1.

[38] Bottom-up gasoline and diesel highway vehicle fuel consumption estimates are based on data from FHWA Highway Statistics Table MF-21, MF-27, and VM-1 (FHWA 1996 through 2017).

jet fuel) as part of consumption by the transportation end-use sector, however, so emissions from international transport activities were calculated separately following the same procedures used for emissions from consumption of all fossil fuels (i.e., estimation of consumption, and determination of C content).[39] The Office of the Under Secretary of Defense (Installations and Environment) and the Defense Logistics Agency Energy (DLA Energy) of the U.S. Department of Defense (DoD) (DLA Energy 2017) supplied data on military jet fuel and marine fuel use. Commercial jet fuel use was obtained from FAA (2017); residual and distillate fuel use for civilian marine bunkers was obtained from DOC (1991 through 2017) for 1990 through 2001 and 2007 through 2016, and DHS (2008) for 2003 through 2006.[40] Consumption of these fuels was subtracted from the corresponding fuels in the transportation end-use sector. Estimates of international bunker fuel emissions for the United States are discussed in detail in Section 3.10 – International Bunker Fuels.

7. *Determine the total C content of fuels consumed.* Total C was estimated by multiplying the amount of fuel consumed by the amount of C in each fuel. This total C estimate defines the maximum amount of C that could potentially be released to the atmosphere if all of the C in each fuel was converted to CO_2. The C content coefficients used by the United States were obtained from EIA's *Emissions of Greenhouse Gases in the United States 2008* (EIA 2009a), and an EPA analysis of C content coefficients developed for the GHGRP (EPA 2010). A discussion of the methodology used to develop the C content coefficients are presented in Annexes 2.1 and 2.2.
8. *Estimate CO_2 Emissions.* Total CO_2 emissions are the product of the adjusted energy consumption (from the previous methodology steps 1 through 6), the C content of the fuels consumed, and the fraction of C that is oxidized. The fraction oxidized was assumed to be 100 percent for petroleum, coal, and natural gas based on guidance in IPCC (2006) (see Annex 2.1).
9. *Allocate transportation emissions by vehicle type.* This report provides a more detailed accounting of emissions from transportation because it is such a large consumer of fossil fuels in the United States. For fuel types other than jet fuel, fuel consumption data by vehicle type and transportation mode were used to allocate emissions by fuel type calculated for the transportation end-use sector. Heat contents and densities were obtained from EIA (2018) and USAF (1998).[41]
    - For on-road vehicles, annual estimates of combined motor gasoline and diesel fuel consumption by vehicle category were obtained from FHWA (1996 through 2017); for each vehicle category, the percent gasoline, diesel, and other (e.g., CNG, LPG) fuel consumption are estimated using data from DOE (1993 through 2016). [42,43]
    - For non-road vehicles, activity data were obtained from AAR (2008 through 2017), APTA (2007 through 2016), APTA (2006), BEA (2016), Benson (2002 through 2004), DOE (1993 through 2016),

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[39] See International Bunker Fuels section in this chapter for a more detailed discussion.

[40] Data for 2002 were interpolated due to inconsistencies in reported fuel consumption data.

[41] For a more detailed description of the data sources used for the analysis of the transportation end use sector see the Mobile Combustion (excluding CO_2) and International Bunker Fuels sections of the Energy chapter, Annex 3.2, and Annex 3.8, respectively.

[42] Data from FHWA's Table VM-1 is used to estimate the share of fuel consumption between each on-road vehicle class. These fuel consumption estimates are combined with estimates of fuel shares by vehicle type from DOE's TEDB Annex Tables A.1 through A.6 (DOE 1993 through 2016). TEDB data for 2016 has not been published yet, therefore 2015 data is used as a proxy. In 2011, FHWA changed its methods for estimating data in the VM-1 table. These methodological changes included how vehicles are classified, moving from a system based on body-type to one that is based on wheelbase. These changes were first incorporated for the 1990 through 2010 Inventory and apply to the 2007 through 2015 time period. This resulted in large changes in VMT and fuel consumption data by vehicle class, thus leading to a shift in emissions among on-road vehicle classes.

[43] Transportation sector natural gas and LPG consumption are based on data from EIA (2018). In previous Inventory years, data from DOE TEDB was used to estimate each vehicle class's share of the total natural gas and LPG consumption. Since TEDB does not include estimates for natural gas use by medium- and heavy-duty trucks or LPG use by passenger cars, EIA Alternative Fuel Vehicle Data (Browning 2017) is now used to determine each vehicle class's share of the total natural gas and LPG consumption. These changes were first incorporated in the current Inventory and apply to the 1990 to 2015 time period.

DLA Energy (2017), DOC (1991 through 2017), DOT (1991 through 2016), EIA (2009a), EIA (2018), EIA (2017), EIA (1991 through 2017), EPA (2017b),[44] and Gaffney (2007).

- For jet fuel used by aircraft, CO_2 emissions from commercial aircraft were developed by the U.S. Federal Aviation Administration (FAA) using a Tier 3B methodology, consistent IPCC (2006) (see Annex 3.3). Carbon dioxide emissions from other aircraft were calculated directly based on reported consumption of fuel as reported by EIA. Allocation to domestic military uses was made using DoD data (see Annex 3.8). General aviation jet fuel consumption is calculated as the remainder of total jet fuel use (as determined by EIA) nets all other jet fuel use as determined by FAA and DoD. For more information, see Annex 3.2.

Box 3-4: Uses of Greenhouse Gas Reporting Program Data and Improvements in Reporting Emissions from Industrial Sector Fossil Fuel Combustion

As described in the calculation methodology, total fossil fuel consumption for each year is based on aggregated end-use sector consumption published by the EIA. The availability of facility-level combustion emissions through EPA's GHGRP has provided an opportunity to better characterize the industrial sector's energy consumption and emissions in the United States, through a disaggregation of EIA's industrial sector fuel consumption data from select industries.

For GHGRP 2010 through 2016 reporting years, facility-level fossil fuel combustion emissions reported through EPA's GHGRP were categorized and distributed to specific industry types by utilizing facility-reported NAICS codes (as published by the U.S. Census Bureau). As noted previously in this report, the definitions and provisions for reporting fuel types in EPA's GHGRP include some differences from the Inventory's use of EIA national fuel statistics to meet the UNFCCC reporting guidelines. The IPCC has provided guidance on aligning facility-level reported fuels and fuel types published in national energy statistics, which guided this exercise.[45]

As with previous Inventory reports, the current effort represents an attempt to align, reconcile, and coordinate the facility-level reporting of fossil fuel combustion emissions under EPA's GHGRP with the national-level approach presented in this report. Consistent with recommendations for reporting the Inventory to the UNFCCC, progress was made on certain fuel types for specific industries and has been included in the CRF tables that are submitted to the UNFCCC along with this report.[46] The efforts in reconciling fuels focus on standard, common fuel types (e.g., natural gas, distillate fuel oil, etc.) where the fuels in EIA's national statistics aligned well with facility-level GHGRP data. For these reasons, the current information presented in the CRF tables should be viewed as an initial attempt at this exercise. Additional efforts will be made for future Inventory reports to improve the mapping of fuel types, and examine ways to reconcile and coordinate any differences between facility-level data and national statistics. The current analysis includes the full time series presented in the CRF tables. Analyses were conducted linking GHGRP facility-level reporting with the information published by EIA in its MECS data in order to disaggregate the full 1990 through 2016 time period in the CRF tables. It is believed that the current analysis has led to improvements in the presentation of data in the Inventory, but further work will be conducted, and future improvements will be realized in subsequent Inventory reports. This includes incorporating the latest MECS data as it becomes available.

Box 3-5: Carbon Intensity of U.S. Energy Consumption

The amount of C emitted from the combustion of fossil fuels is dependent upon the C content of the fuel and the fraction of that C that is oxidized. Fossil fuels vary in their average C content, ranging from about 53 MMT CO_2

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[44] In 2014, EPA incorporated the NONROAD2008 model into MOVES2014. The current Inventory uses the NONROAD component of MOVES2014a for years 1999 through 2016.

[45] See Section 4 "Use of Facility-Level Data in Good Practice National Greenhouse Gas Inventories" of the IPCC meeting report, and specifically the section on using facility-level data in conjunction with energy data, at <http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf>.

[46] See <http://www.epa.gov/climatechange/ghgemissions/usinventoryreport.html>.

Eq./QBtu for natural gas to upwards of 95 MMT CO_2 Eq./QBtu for coal and petroleum coke.[47] In general, the C content per unit of energy of fossil fuels is the highest for coal products, followed by petroleum, and then natural gas. The overall C intensity of the U.S. economy is thus dependent upon the quantity and combination of fuels and other energy sources employed to meet demand.

Table 3-15 provides a time series of the C intensity of direct emissions for each sector of the U.S. economy. The time series incorporates only the energy from the direct combustion of fossil fuels in each sector. For example, the C intensity for the residential sector does not include the energy from or emissions related to the use of electricity for lighting, as it is instead allocated to the electric power sector. For the purposes of maintaining the focus of this section, renewable energy and nuclear energy are not included in the energy totals used in Table 3-15 in order to focus attention on fossil fuel combustion as detailed in this chapter. Looking only at this direct consumption of fossil fuels, the residential sector exhibited the lowest C intensity, which is related to the large percentage of its energy derived from natural gas for heating. The C intensity of the commercial sector has predominantly declined since 1990 as commercial businesses shift away from petroleum to natural gas. The industrial sector was more dependent on petroleum and coal than either the residential or commercial sectors, and thus had higher C intensities over this period. The C intensity of the transportation sector was closely related to the C content of petroleum products (e.g., motor gasoline and jet fuel, both around 70 MMT CO_2 Eq./EJ), which were the primary sources of energy. Lastly, the electric power sector had the highest C intensity due to its heavy reliance on coal for generating electricity.

Table 3-15: Carbon Intensity from Direct Fossil Fuel Combustion by Sector (MMT CO_2 Eq./QBtu)

Sector	1990	2005	2012	2013	2014	2015	2016
Residential[a]	57.4	56.6	55.5	55.3	55.4	55.5	55.2
Commercial[a]	59.6	57.7	56.3	56.1	55.8	57.2	56.8
Industrial[a]	64.4	64.5	62.3	62.1	61.6	61.2	60.8
Transportation[a]	71.1	71.4	71.5	71.4	71.5	71.5	71.5
Electric Power[b]	87.3	85.8	79.9	81.3	81.2	78.1	76.9
U.S. Territories[c]	73.0	73.5	72.2	71.9	72.3	72.3	72.3
All Sectors[c]	**73.0**	**73.5**	**70.9**	**70.9**	**70.8**	**69.7**	**69.3**

[a] Does not include electricity or renewable energy consumption.

[b] Does not include electricity produced using nuclear or renewable energy.

[c] Does not include nuclear or renewable energy consumption.

Note: Excludes non-energy fuel use emissions and consumption.

For the time period of 1990 through about 2008, the C intensity of U.S. energy consumption was fairly constant, as the proportion of fossil fuels used by the individual sectors did not change significantly over that time. Starting in 2008 the C intensity has decreased, reflecting the shift from coal to natural gas in the electric power sector during that time period. Per capita energy consumption fluctuated little from 1990 to 2007, but then started decreasing after 2007 and, in 2016, was approximately 10.4 percent below levels in 1990 (see Figure 3-16). To differentiate these estimates from those of Table 3-15, the C intensity trend shown in Figure 3-16 and described below includes nuclear and renewable energy EIA data to provide a comprehensive economy-wide picture of energy consumption. Due to a general shift from a manufacturing-based economy to a service-based economy, as well as overall increases in efficiency, energy consumption and energy-related CO_2 emissions per dollar of gross domestic product (GDP) have both declined since 1990 (BEA 2017).

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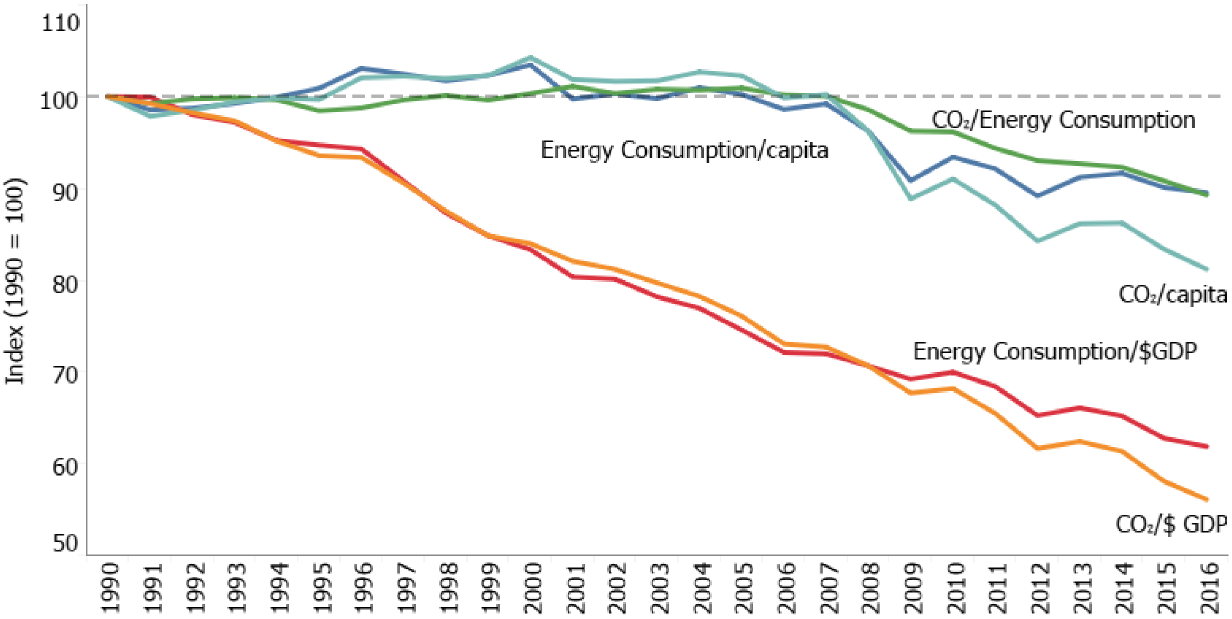
[47] One exajoule (EJ) is equal to 10^{18} joules or 0.9478 QBtu.

Figure 3-16: U.S. Energy Consumption and Energy-Related CO_2 Emissions Per Capita and Per Dollar GDP



C intensity estimates were developed using nuclear and renewable energy data from EIA (2018), EPA (2010), and fossil fuel consumption data as discussed above and presented in Annex 2.1.

Uncertainty and Time-Series Consistency

For estimates of CO_2 from fossil fuel combustion, the amount of CO_2 emitted is directly related to the amount of fuel consumed, the fraction of the fuel that is oxidized, and the carbon content of the fuel. Therefore, a careful accounting of fossil fuel consumption by fuel type, average carbon contents of fossil fuels consumed, and production of fossil fuel-based products with long-term carbon storage should yield an accurate estimate of CO_2 emissions.

Nevertheless, there are uncertainties in the consumption data, carbon content of fuels and products, and carbon oxidation efficiencies. For example, given the same primary fuel type (e.g., coal, petroleum, or natural gas), the amount of carbon contained in the fuel per unit of useful energy can vary. For the United States, however, the impact of these uncertainties on overall CO_2 emission estimates is believed to be relatively small. See, for example, Marland and Pippin (1990).

Although statistics of total fossil fuel and other energy consumption are relatively accurate, the allocation of this consumption to individual end-use sectors (i.e., residential, commercial, industrial, and transportation) is less certain. For example, for some fuels the sectoral allocations are based on price rates (i.e., tariffs), but a commercial establishment may be able to negotiate an industrial rate or a small industrial establishment may end up paying an industrial rate, leading to a misallocation of emissions. Also, the deregulation of the natural gas industry and the more recent deregulation of the electric power industry have likely led to some minor problems in collecting accurate energy statistics as firms in these industries have undergone significant restructuring.

To calculate the total CO_2 emission estimate from energy-related fossil fuel combustion, the amount of fuel used in non-energy production processes were subtracted from the total fossil fuel consumption. The amount of CO_2 emissions resulting from non-energy related fossil fuel use has been calculated separately and reported in the Carbon Emitted from Non-Energy Uses of Fossil Fuels section of this report (Section 3.2). These factors all contribute to the uncertainty in the CO_2 estimates. Detailed discussions on the uncertainties associated with C emitted from Non-Energy Uses of Fossil Fuels can be found within that section of this chapter.

Various sources of uncertainty surround the estimation of emissions from international bunker fuels, which are subtracted from the U.S. totals (see the detailed discussions on these uncertainties provided in Section 3.10 – International Bunker Fuels). Another source of uncertainty is fuel consumption by U.S. Territories. The United States does not collect energy statistics for its territories at the same level of detail as for the fifty states and the District of Columbia. Therefore, estimating both emissions and bunker fuel consumption by these territories is difficult.

Uncertainties in the emission estimates presented above also result from the data used to allocate CO_2 emissions from the transportation end-use sector to individual vehicle types and transport modes. In many cases, bottom-up estimates of fuel consumption by vehicle type do not match aggregate fuel-type estimates from EIA. Further research is planned to improve the allocation into detailed transportation end-use sector emissions.

The uncertainty analysis was performed by primary fuel type for each end-use sector, using the IPCC-recommended Approach 2 uncertainty estimation methodology, Monte Carlo Stochastic Simulation technique, with @RISK software. For this uncertainty estimation, the inventory estimation model for CO_2 from fossil fuel combustion was integrated with the relevant variables from the inventory estimation model for International Bunker Fuels, to realistically characterize the interaction (or endogenous correlation) between the variables of these two models. About 120 input variables were modeled for CO_2 from energy-related Fossil Fuel Combustion (including about 10 for non-energy fuel consumption and about 20 for International Bunker Fuels).

In developing the uncertainty estimation model, uniform distributions were assumed for all activity-related input variables and emission factors, based on the SAIC/EIA (2001) report.[48] Triangular distributions were assigned for the oxidization factors (or combustion efficiencies). The uncertainty ranges were assigned to the input variables based on the data reported in SAIC/EIA (2001) and on conversations with various agency personnel.[49]

The uncertainty ranges for the activity-related input variables were typically asymmetric around their inventory estimates; the uncertainty ranges for the emissions factors were symmetric. Bias (or systematic uncertainties) associated with these variables accounted for much of the uncertainties associated with these variables (SAIC/EIA 2001).[50] For purposes of this uncertainty analysis, each input variable was simulated 10,000 times through Monte Carlo sampling.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 3-16. Fossil fuel combustion CO_2 emissions in 2016 were estimated to be between 4,859.3 and 5,195.4 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 2 percent below to 5 percent above the 2016 emission estimate of 4,966.0 MMT CO_2 Eq.

Table 3-16: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Energy-Related Fossil Fuel Combustion by Fuel Type and Sector (MMT CO_2 Eq. and Percent)

Fuel/Sector	2016 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound

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[48] SAIC/EIA (2001) characterizes the underlying probability density function for the input variables as a combination of uniform and normal distributions (the former to represent the bias component and the latter to represent the random component). However, for purposes of the current uncertainty analysis, it was determined that uniform distribution was more appropriate to characterize the probability density function underlying each of these variables.

[49] In the SAIC/EIA (2001) report, the quantitative uncertainty estimates were developed for each of the three major fossil fuels used within each end-use sector; the variations within the sub-fuel types within each end-use sector were not modeled. However, for purposes of assigning uncertainty estimates to the sub-fuel type categories within each end-use sector in the current uncertainty analysis, SAIC/EIA (2001)-reported uncertainty estimates were extrapolated.

[50] Although, in general, random uncertainties are the main focus of statistical uncertainty analysis, when the uncertainty estimates are elicited from experts, their estimates include both random and systematic uncertainties. Hence, both these types of uncertainties are represented in this uncertainty analysis.

Coal[b]	**1,306.4**	**1,261.7**	**1,429.7**	**-3%**	**9%**
Residential	NE	NE	NE	NE	NE
Commercial	2.2	2.1	2.6	-5%	15%
Industrial	58.7	55.9	68.0	-5%	16%
Transportation	NE	NE	NE	NE	NE
Electric Power	1,241.4	1,193.8	1,361.0	-4%	10%
U.S. Territories	4.0	3.5	4.8	-12%	19%
Natural Gas[b]	**1,476.1**	**1,459.1**	**1,544.1**	**-1%**	**5%**
Residential	238.3	231.5	255.1	-3%	7%
Commercial	170.3	165.6	182.3	-3%	7%
Industrial	477.9	463.7	512.2	-3%	7%
Transportation	40.6	39.5	43.5	-3%	7%
Electric Power	546.0	530.2	573.7	-3%	5%
U.S. Territories	3.0	2.6	3.5	-12%	17%
Petroleum[b]	**2,183.1**	**2,047.5**	**2,311.3**	**-6%**	**6%**
Residential	54.2	51.2	57.1	-6%	5%
Commercial	58.7	55.4	61.9	-6%	5%
Industrial	272.5	216.4	324.3	-21%	19%
Transportation	1,741.9	1,630.0	1,853.8	-6%	6%
Electric Power	21.4	20.3	23.4	-5%	9%
U.S. Territories	34.3	31.7	38.2	-8%	11%
Total (excluding Geothermal)[b]	**4,965.6**	**4,858.9**	**5,195.0**	**-2%**	**5%**
Geothermal	0.4	NE	NE	NE	NE
Total (including Geothermal)[b,c]	**4,966.0**	**4,859.3**	**5,195.4**	**-2%**	**5%**

NE (Not Estimated)

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

[b] The low and high estimates for total emissions were calculated separately through simulations and, hence, the low and high emission estimates for the sub-source categories do not sum to total emissions.

[c] Geothermal emissions added for reporting purposes, but an uncertainty analysis was not performed for CO_2 emissions from geothermal production.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2016. Details on the emission trends through time are described in more detail in the Methodology section, above. As discussed in Annex 5, data are unavailable to include estimates of CO_2 emissions from any liquid fuel used in pipeline transport or non-hazardous industrial waste incineration, but those emissions are assumed to insignificant.

QA/QC and Verification

A source-specific QA/QC plan for CO_2 from fossil fuel combustion was developed and implemented consistent with the *2006 IPCC Guidelines* and the *Quality Assurance/Quality Control and Uncertainty Management Plan* (QA/QC Management Plan) referenced in this report and described further in Annex 8. This effort included a general (Tier 1) analysis, as well as portions of a category-specific (Tier 2) analysis. The Tier 2 procedures that were implemented involved checks specifically focusing on the activity data and methodology used for estimating CO_2 emissions from fossil fuel combustion in the United States. Emission totals for the different sectors and fuels were compared and trends were investigated to determine whether any corrective actions were needed. Minor corrective actions were taken.

Recalculations Discussion

The Energy Information Administration (EIA 2018) updated energy consumption statistics across the time series relative to the previous Inventory. EIA revised LPG consumption in the residential and industrial sectors for the years 2010 through 2015, and in the commercial and transportation sectors for the years 2011 through 2015.[51] EIA also revised 2014 and 2015 distillate fuel consumption in the transportation sector, 2015 natural gas consumption in all sectors, and 2015 motor gasoline consumption in the commercial, industrial, and transportation sectors. Revisions to LPG, distillate fuel, and motor gasoline consumption resulted in an average annual decrease of 0.1 MMT CO_2 Eq. (less than 0.05 percent) in CO_2 emissions from petroleum. Revisions to natural gas consumption resulted in an average annual increase of less than 0.5 MMT CO_2 Eq. (less than 0.05 percent) in CO_2 emissions from natural gas. Overall, these changes resulted in an average annual decrease of 0.1 MMT CO_2 Eq. (less than 0.05 percent) in CO_2 emissions from fossil fuel combustion for the period 1990 through 2015, relative to the previous Inventory.

In addition, changes were made to the historic allocation of gasoline to on-road and non-road applications. In 2016, the Federal Highway Administration (FHWA) changed its methods for estimating the share of gasoline used in on-road and non-road applications. Among other updates, FHWA included lawn and garden equipment as well as off-road recreational equipment in its estimates of non-road gasoline consumption for the first time. This change created a time-series inconsistency between the data reported for years 2015 and 2016 and previous years. To create a more consistent time series of motor gasoline consumption and emissions data for the current Inventory, the historical time series was modified. Specifically, the lawn, garden, and recreational vehicle gasoline consumption from EPA's NONROAD model is subtracted from the highway motor gasoline consumption from FHWA Table MF-21 when determining the total highway motor gasoline consumption for years 1990 through 2014.

Planned Improvements

To reduce uncertainty of CO_2 from fossil fuel combustion estimates for U.S. Territories, efforts will be made to improve the quality of the U.S. Territories data, including through work with EIA and other agencies. This improvement is part of an ongoing analysis and efforts to continually improve the CO_2 from fossil fuel combustion estimates. In addition, further expert elicitation may be conducted to better quantify the total uncertainty associated with emissions from this source.

The availability of facility-level combustion emissions through EPA's GHGRP will continue to be examined to help better characterize the industrial sector's energy consumption in the United States, and further classify total industrial sector fossil fuel combustion emissions by business establishments according to industrial economic activity type. Most methodologies used in EPA's GHGRP are consistent with IPCC, though for EPA's GHGRP, facilities collect detailed information specific to their operations according to detailed measurement standards, which may differ with the more aggregated data collected for the Inventory to estimate total, national U.S. emissions. In addition, and unlike the reporting requirements for this chapter under the UNFCCC reporting guidelines, some facility-level fuel combustion emissions reported under the GHGRP may also include industrial process emissions.[52] In line with UNFCCC reporting guidelines, fuel combustion emissions are included in this chapter, while process emissions are included in the Industrial Processes and Product Use chapter of this report. In examining data from EPA's GHGRP that would be useful to improve the emission estimates for the CO_2 from fossil fuel combustion category, particular attention will also be made to ensure time-series consistency, as the facility-level reporting data from EPA's GHGRP are not available for all inventory years as reported in this Inventory. Additional analyses will be conducted to align reported facility-level fuel types and IPCC fuel types per the national energy statistics. For example, efforts will be taken to incorporate updated industrial fuel consumption data from EIA's Manufacturing Energy Consumption Survey (MECS), with updated data for 2014. Additional work will look at CO_2 emissions from biomass to ensure they are separated in the facility-level reported data, and maintaining consistency with national energy statistics provided by EIA. In implementing improvements and integration of data from EPA's GHGRP, the latest guidance from the IPCC on the use of facility-level data in national inventories will continue to be relied upon.[53]

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[51] Starting in 2017, EIA reclassified LPG as Hydrocarbon Gas Liquids (HGL) in the Monthly Energy Review. HGL is equivalent to LPG for all sectors except the industrial sector. EIA calculates LPG and HGL consumption estimates for the industrial sector using slightly different methodologies. EIA provided industrial LPG consumption data for this year's Inventory that align with industrial sector LPG consumption estimates from the previous Inventory (i.e., 1990 through 2015).

[52] See <https://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf#page=2>.

[53] See <http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf>.

An ongoing planned improvement is to develop improved estimates of domestic waterborne fuel consumption. The Inventory estimates for residual and distillate fuel used by ships and boats is based in part on data on bunker fuel use from the U.S. Department of Commerce. Domestic fuel consumption is estimated by subtracting fuel sold for international use from the total sold in the United States. It may be possible to more accurately estimate domestic fuel use and emissions by using detailed data on marine ship activity. The feasibility of using domestic marine activity data to improve the estimates will continue to be investigated.

EPA received a comment from FHWA that the trend of decreasing electricity use in the transportation sector does not align with increased sales of electric and plug-in hybrid vehicles. Electricity data is allocated between economic sectors based on electricity sales data provided by the industry through EIA reports. The data for electricity used in transportation only includes electricity used for railroads and railways. Electricity used to charge electric vehicles would fall under other sectors like residential and commercial use associated with home and public charging stations. As a planned improvement, EPA will look into the possibility of breaking out electricity used to charge electric vehicles and report that electricity use under the transportation sector.

EPA will evaluate and potentially update methods for allocating motor gasoline consumption to the transportation, industrial, and commercial sectors. In 2016, FHWA changed its methods for estimating the share of gasoline used in on-road and non-road applications, creating a time-series inconsistency in the current Inventory between 2015 and previous years.[54] EPA will continue to explore approaches to address this inconsistency, including using MOVES on-road fuel consumption output to define the percentage of the FHWA consumption totals (from MF-21) that are attributable to transportation, and applying that percentage to the EIA total. This would define gasoline consumption from transportation, such that the remainder would be defined as consumption by the industrial and commercial sectors.

CH_4 and N_2O from Stationary Combustion

Methodology

Methane and N_2O emissions from stationary combustion were estimated by multiplying fossil fuel and wood consumption data by emission factors (by sector and fuel type for industrial, residential, commercial, and U.S. Territories; and by fuel and technology type for the electric power sector). The electric power sector utilizes a Tier 2 methodology, whereas all other sectors utilize a Tier 1 methodology. The activity data and emission factors used are described in the following subsections.

Industrial, Residential, Commercial, and U.S. Territories

National coal, natural gas, fuel oil, and wood consumption data were grouped by sector: industrial, commercial, residential, and U.S. Territories. For the CH_4 and N_2O estimates, consumption data for each fuel were obtained from EIA's Monthly Energy Review (EIA 2018). Because the United States does not include territories in its national energy statistics, fuel consumption data for territories were provided separately by EIA's International Energy Statistics (EIA 2017).[55] Fuel consumption for the industrial sector was adjusted to subtract out construction and agricultural use, which is reported under mobile sources.[56] Construction and agricultural fuel use was obtained from EPA (2017b) and FHWA (1996 through 2016). Estimates for wood biomass consumption for fuel combustion do not include wood wastes, liquors, municipal solid waste, tires, etc., that are reported as biomass by EIA. Tier 1

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[54] The previous and new FHWA methodologies for estimating non-road gasoline are described in *Off-Highway and Public-Use Gasoline Consumption Estimation Models Used in the Federal Highway Administration*, Publication Number FHWA-PL-17-012. <https://www.fhwa.dot.gov/policyinformation/pubs/pl17012.pdf>

[55] U.S. Territories data also include combustion from mobile activities because data to allocate territories' energy use were unavailable. For this reason, CH_4 and N_2O emissions from combustion by U.S. Territories are only included in the stationary combustion totals.

[56] Though emissions from construction and farm use occur due to both stationary and mobile sources, detailed data was not available to determine the magnitude from each. Currently, these emissions are assumed to be predominantly from mobile sources.

default emission factors for these three end-use sectors were provided by the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006). U.S. Territories' emission factors were estimated using the U.S. emission factors for the primary sector in which each fuel was combusted.

Electric Power Sector

The electric power sector uses a Tier 2 emission estimation methodology as fuel consumption for the electric power sector by control-technology type was obtained from EPA's Acid Rain Program Dataset (EPA 2017a). These combustion technology- and fuel- use data were available by facility from 1996 to 2016. The Tier 2 emission factors used are based in part on emission factors published by EPA, and EPA's Compilation of Air Pollutant Emission Factors, AP-42 (EPA 1997) for combined cycle natural gas units.[57]

Since there was a difference between the EPA (2017a) and EIA (2018) total fuel consumption estimates, the remaining consumption from EIA (2018) was apportioned to each combustion technology type and fuel combination using a ratio of fuel consumption by technology type from 1996 to 2016.

Fuel consumption estimates were not available from 1990 to 1995 in the EPA (2017a) dataset, and as a result, consumption was calculated using total electric power production from EIA (2018) and the ratio of combustion technology and fuel types from EPA (2017a). The consumption estimates from 1990 to 1995 were estimated by applying the 1996 consumption ratio by combustion technology type to the total EIA consumption for each year from 1990 to 1995. Emissions were estimated by multiplying fossil fuel and wood consumption by technology- and fuel-specific Tier 2 country specific emission factors.

Lastly, there were significant differences between wood biomass consumption in the electric power sector between the EPA (2017a) and EIA (2018) datasets. The higher wood biomass consumption from EIA (2018) in the electric power sector was distributed to the residential, commercial, and industrial sectors according to their percent share of wood biomass energy consumption calculated from EIA (2018).

More detailed information on the methodology for calculating emissions from stationary combustion, including emission factors and activity data, is provided in Annex 3.1.

Uncertainty and Time-Series Consistency

Methane emission estimates from stationary sources exhibit high uncertainty, primarily due to difficulties in calculating emissions from wood combustion (i.e., fireplaces and wood stoves). The estimates of CH_4 and N_2O emissions presented are based on broad indicators of emissions (i.e., fuel use multiplied by an aggregate emission factor for different sectors), rather than specific emission processes (i.e., by combustion technology and type of emission control).

An uncertainty analysis was performed by primary fuel type for each end-use sector, using the IPCC-recommended Approach 2 uncertainty estimation methodology, Monte Carlo Stochastic Simulation technique, with @RISK software.

The uncertainty estimation model for this source category was developed by integrating the CH_4 and N_2O stationary source inventory estimation models with the model for CO_2 from fossil fuel combustion to realistically characterize the interaction (or endogenous correlation) between the variables of these three models. About 55 input variables were simulated for the uncertainty analysis of this source category (about 20 from the CO_2 emissions from fossil fuel combustion inventory estimation model and about 35 from the stationary source inventory models).

In developing the uncertainty estimation model, uniform distribution was assumed for all activity-related input variables and N_2O emission factors, based on the SAIC/EIA (2001) report.[58] For these variables, the uncertainty

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[57] Several of the U.S. Tier 2 emission factors were used in IPCC 2006 as Tier 1 emission factors.

[58] SAIC/EIA (2001) characterizes the underlying probability density function for the input variables as a combination of uniform and normal distributions (the former distribution to represent the bias component and the latter to represent the random component). However, for purposes of the current uncertainty analysis, it was determined that uniform distribution was more appropriate to characterize the probability density function underlying each of these variables.

ranges were assigned to the input variables based on the data reported in SAIC/EIA (2001).[59] However, the CH_4 emission factors differ from those used by EIA. These factors and uncertainty ranges are based on IPCC default uncertainty estimates (IPCC 2006).

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 3-17. Stationary combustion CH_4 emissions in 2016 (including biomass) were estimated to be between 5.1 and 15.7 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 30 percent below to 114 percent above the 2016 emission estimate of 7.3 MMT CO_2 Eq.[60] Stationary combustion N_2O emissions in 2016 (including biomass) were estimated to be between 14.4 and 28.2 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 22 percent below to 52 percent above the 2016 emission estimate of 18.6 MMT CO_2 Eq.

Table 3-17: Approach 2 Quantitative Uncertainty Estimates for CH_4 and N_2O Emissions from Energy-Related Stationary Combustion, Including Biomass (MMT CO_2 Eq. and Percent)

Source	Gas	2016 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Stationary Combustion	CH_4	7.3	5.1	15.7	-30%	+114%
Stationary Combustion	N_2O	18.6	14.4	28.2	-22%	+52%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

The uncertainties associated with the emission estimates of CH_4 and N_2O are greater than those associated with estimates of CO_2 from fossil fuel combustion, which mainly rely on the carbon content of the fuel combusted. Uncertainties in both CH_4 and N_2O estimates are due to the fact that emissions are estimated based on emission factors representing only a limited subset of combustion conditions. For the indirect greenhouse gases, uncertainties are partly due to assumptions concerning combustion technology types, age of equipment, emission factors used, and activity data projections.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2016 as discussed below. Details on the emission trends through time are described in more detail in the Methodology section, above. As discussed in Annex 5, data are unavailable to include estimates of CH_4 and N_2O emissions from biomass use in territories, but those emissions are assumed to insignificant.

For more information on the general QA/QC process applied to this source category, consistent with Volume 1, Chapter 6 of the *2006 IPCC Guidelines,* see QA/QC and Verification Procedures section in the introduction of the IPPU Chapter.

QA/QC and Verification

A source-specific QA/QC plan for stationary combustion was developed and implemented consistent with the *2006 IPCC Guidelines* and the QA/QC Management Plan referenced in this report and described further in Annex 8. This effort included a general (Tier 1) analysis, as well as portions of a category-specific (Tier 2) analysis. The Tier 2 procedures that were implemented involved checks specifically focusing on the activity data and emission factor sources and methodology used for estimating CH_4, N_2O, and the indirect greenhouse gases from stationary combustion in the United States. Emission totals for the different sectors and fuels were compared and trends were investigated.

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[59] In the SAIC/EIA (2001) report, the quantitative uncertainty estimates were developed for each of the three major fossil fuels used within each end-use sector; the variations within the sub-fuel types within each end-use sector were not modeled. However, for purposes of assigning uncertainty estimates to the sub-fuel type categories within each end-use sector in the current uncertainty analysis, SAIC/EIA (2001)-reported uncertainty estimates were extrapolated.

[60] The low emission estimates reported in this section have been rounded down to the nearest integer values and the high emission estimates have been rounded up to the nearest integer values.

Recalculations Discussion

Methane and N_2O emissions from stationary sources (excluding CO_2) across the entire time series were revised due to revised data from EIA (2018), EIA (2017), and EPA (2017a) relative to the previous Inventory. Methane and N_2O emission factors for combined cycle natural gas units were updated to be consistent with EPA's Compilation of Air Pollutant Emission Factors, AP-42 (EPA 1997). In addition, the GWPs for CH_4 and N_2O for the Acid Rain Program Dataset (EPA 2017a) were updated to be consistent with the *IPCC Fourth Assessment Report* (AR4) values. The historical data changes resulted in an average annual increase 0.4 MMT CO_2 Eq. (5.2 percent) in CH_4 emissions, and an average annual decrease 2.3 MMT CO_2 Eq. (12.4 percent) in N_2O emissions from stationary combustion for the 1990 through 2015 period.

Planned Improvements

Several items are being evaluated to improve the CH_4 and N_2O emission estimates from stationary combustion and to reduce uncertainty for U.S. Territories. Efforts will be taken to work with EIA and other agencies to improve the quality of the U.S. Territories data. Because these data are not broken out by stationary and mobile uses, further research will be aimed at trying to allocate consumption appropriately. In addition, the uncertainty of biomass emissions will be further investigated since it was expected that the exclusion of biomass from the estimates would reduce the uncertainty; and in actuality the exclusion of biomass increases the uncertainty. These improvements are not all-inclusive, but are part of an ongoing analysis and efforts to continually improve these stationary combustion estimates from U.S. Territories.

Fuel use was adjusted for the industrial sector to subtract out construction and agricultural use, which is reported under mobile sources. Mobile source CH_4 and N_2O also include emissions from sources that may be captured as part of the commercial sector. Future research will look into the need to adjust commercial sector fuel consumption to account for sources included elsewhere.

CH_4 and N_2O from Mobile Combustion

Methodology

Estimates of CH_4 and N_2O emissions from mobile combustion were calculated by multiplying emission factors by measures of activity for each fuel and vehicle type (e.g., light-duty gasoline trucks). Activity data included vehicle miles traveled (VMT) for on-road vehicles and fuel consumption for non-road mobile sources. The activity data and emission factors used are described in the subsections that follow. A complete discussion of the methodology used to estimate CH_4 and N_2O emissions from mobile combustion and the emission factors used in the calculations is provided in Annex 3.2.

On-Road Vehicles

Estimates of CH_4 and N_2O emissions from gasoline and diesel on-road vehicles are based on VMT and emission factors by vehicle type, fuel type, model year, and emission control technology. Emission estimates for alternative fuel vehicles (AFVs) are based on VMT and emission factors by vehicle and fuel type.[61]

Emissions factors for N_2O from newer on-road gasoline vehicles were calculated based upon a regression analysis done by EPA (Browning 2017). Methane emission factors were calculated based on the ratio of NMOG emission standards for newer vehicles. Older gasoline vehicles on-road emissions factors were developed by ICF (2004). These factors were derived from EPA, California Air Resources Board (CARB) and Environment Canada laboratory test results of different vehicle and control technology types. The EPA, CARB and Environment Canada tests were designed following the Federal Test Procedure (FTP), which covers three separate driving segments, since vehicles emit varying amounts of greenhouse gases depending on the driving segment. These driving segments are: (1) a transient driving cycle that includes cold start and running emissions, (2) a cycle that represents running emissions

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[61] Alternative fuel and advanced technology vehicles are those that can operate using a motor fuel other than gasoline or diesel. This includes electric or other bi-fuel or dual-fuel vehicles that may be partially powered by gasoline or diesel.

only, and (3) a transient driving cycle that includes hot start and running emissions. For each test run, a bag was affixed to the tailpipe of the vehicle and the exhaust was collected; the content of this bag was then analyzed to determine quantities of gases present. The emissions characteristics of segment 2 were used to define running emissions, and subtracted from the total FTP emissions to determine start emissions. These were then recombined based upon the ratio of start to running emissions for each vehicle class from MOBILE6.2, an EPA emission factor model that predicts gram per mile emissions of CO_2, CO, HC, NO_x, and PM from vehicles under various conditions, to approximate average driving characteristics.[62] Diesel on-road vehicle emission factors were developed by ICF (2006b).

CH_4 and N_2O emission factors for AFVs were developed based on the 2016 GREET model. For light-duty trucks, EPA used a curve fit of 1999 through 2011 travel fractions for LDT1 and LDT2 (MOVES Source Type 31 for LDT1 and MOVES Source Type 32 for LDT2). For medium-duty vehicles, EPA used emission factors for light heavy-duty vocational trucks. For heavy-duty vehicles, EPA used emission factors for long haul combination trucks. For buses, EPA used emission factors for transit buses. These values represent vehicle operation only (tank-to-wheels); well-to-tank emissions are calculated elsewhere in the Inventory.

Annual VMT data for 1990 through 2016 were obtained from the Federal Highway Administration's (FHWA) Highway Performance Monitoring System database as reported in Highway Statistics (FHWA 1996 through 2017).[63] VMT estimates were then allocated from FHWA's vehicle categories to fuel-specific vehicle categories using the calculated shares of vehicle fuel use for each vehicle category by fuel type reported in DOE (1993 through 2017) and information on total motor vehicle fuel consumption by fuel type from FHWA (1996 through 2017). VMT for AFVs were estimated based on Browning (2017). The age distributions of the U.S. vehicle fleet were obtained from EPA (2017b, 2000), and the average annual age-specific vehicle mileage accumulation of U.S. vehicles were obtained from EPA (2017b).

Control technology and standards data for on-road vehicles were obtained from EPA's Office of Transportation and Air Quality (EPA 2007a, 2007b, 2000, 1998, and 1997) and Browning (2005). These technologies and standards are defined in Annex 3.2, and were compiled from EPA (1994a, 1994b, 1998, 1999a) and IPCC (2006).

Non-Road Mobile Sources

To estimate emissions from non-road mobile sources, fuel consumption data were employed as a measure of activity, and multiplied by fuel-specific emission factors (in grams of N_2O and CH_4 per kilogram of fuel consumed).[64] Activity data were obtained from AAR (2008 through 2017), APTA (2007 through 2017), APTA (2006), BEA (1991 through 2015), Benson (2002 through 2004), DHS (2008), DLA Energy (2016), DOC (1991 through 2017), DOE (1993 through 2017), DOT (1991 through 2017), EIA (2002, 2007, 2016a), EIA (2007 through 2017), EIA (1991 through 2017), EPA (2017b), Esser (2003 through 2004), FAA (2018), FHWA (1996 through 2017),[65] Gaffney (2007), and Whorton (2006 through 2014). Emission factors for non-road modes were taken from IPCC (2006) and Browning (2017).

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[62] Additional information regarding the MOBILE model can be found online at <https://www.epa.gov/moves/description-and-history-mobile-highway-vehicle-emission-factor-model>.

[63] The source of VMT is FHWA Highway Statistics Table VM-1. In 2011, FHWA changed its methods for estimating data in the VM-1 table. These methodological changes included how vehicles are classified, moving from a system based on body-type to one that is based on wheelbase. These changes were first incorporated for the 1990 through 2010 Inventory and apply to the 2007 through 2016 time period. This resulted in large changes in VMT by vehicle class, thus leading to a shift in emissions among on-road vehicle classes. For example, the category "Passenger Cars" has been replaced by "Light-duty Vehicles-Short Wheelbase" and "Other 2 axle-4 Tire Vehicles" has been replaced by "Light-duty Vehicles, Long Wheelbase." This change in vehicle classification has moved some smaller trucks and sport utility vehicles from the light truck category to the passenger vehicle category in the current Inventory. These changes are reflected in a large drop in light-truck emissions between 2006 and 2007.

[64] The consumption of international bunker fuels is not included in these activity data, but is estimated separately under the International Bunker Fuels source category.

[65] This Inventory uses FHWA's Agriculture, Construction, and Commercial/Industrial MF-24 fuel volumes along with the MOVES NONROAD model gasoline volumes to estimate non-road mobile source CH_4 and N_20 emissions for these categories.

Uncertainty and Time-Series Consistency

A quantitative uncertainty analysis was conducted for the mobile source sector using the IPCC-recommended Approach 2 uncertainty estimation methodology, Monte Carlo Stochastic Simulation technique, using @RISK software. The uncertainty analysis was performed on 2016 estimates of CH_4 and N_2O emissions, incorporating probability distribution functions associated with the major input variables. For the purposes of this analysis, the uncertainty was modeled for the following four major sets of input variables: (1) VMT data, by on-road vehicle and fuel type and (2) emission factor data, by on-road vehicle, fuel, and control technology type, (3) fuel consumption, data, by non-road vehicle and equipment type, and (4) emission factor data, by non-road vehicle and equipment type.

Uncertainty analyses were not conducted for NO_x, CO, or NMVOC emissions. Emission factors for these gases have been extensively researched since emissions of these gases from motor vehicles are regulated in the United States, and the uncertainty in these emission estimates is believed to be relatively low. For more information, see Section 3.9 – Uncertainty Analysis of Emission Estimates. However, a much higher level of uncertainty is associated with CH_4 and N_2O emission factors due to limited emission test data, and because, unlike CO_2 emissions, the emission pathways of CH_4 and N_2O are highly complex.

Mobile combustion CH_4 emissions from all mobile sources in 2016 were estimated to be between 3.4 and 4.6 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 7 percent below to 26 percent above the corresponding 2016 emission estimate of 3.6 MMT CO_2 Eq. Also at a 95 percent confidence level, mobile combustion N_2O emissions from mobile sources in 2016 were estimated to be between 16.8 and 21.0 MMT CO_2 Eq., indicating a range of 9 percent below to 14 percent above the corresponding 2016 emission estimate of 18.4 MMT CO_2 Eq.

Table 3-18: Approach 2 Quantitative Uncertainty Estimates for CH_4 and N_2O Emissions from Mobile Sources (MMT CO_2 Eq. and Percent)

Source	Gas	2016 Emission Estimate[a] (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Mobile Sources	CH_4	3.6	3.4	4.6	-7%	+26%
Mobile Sources	N_2O	18.4	16.8	21.0	-9%	+14%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

This uncertainty analysis is a continuation of a multi-year process for developing quantitative uncertainty estimates for this source category using the IPCC Approach 2 uncertainty analysis. As a result, as new information becomes available, uncertainty characterization of input variables may be improved and revised. For additional information regarding uncertainty in emission estimates for CH_4 and N_2O please refer to the Uncertainty Annex. As discussed in Annex 5, data are unavailable to include estimates of CH_4 and N_2O emissions from any liquid fuel used in pipeline transport or some biomass used in transportation sources, but those emissions are assumed to insignificant.

QA/QC and Verification

A source-specific Quality Assurance/Quality Control (QA/QC) plan for mobile combustion was developed and implemented. This plan is based on the IPCC-recommended QA/QC Plan. The specific plan used for mobile combustion was updated prior to collection and analysis of this current year of data. This effort included a general (Tier 1) analysis, as well as portions of a category-specific (Tier 2) analysis. The Tier 2 procedures focused on the

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For agriculture, the MF-24 gasoline volume is used directly because it includes both off-road trucks and equipment. For construction and commercial/industrial gasoline estimates, the 2014 and older MF-24 volumes represented off-road trucks only; therefore, the MOVES NONROAD gasoline volumes for construction and commercial/industrial are added to the respective categories in the Inventory. Beginning in 2015, this addition is no longer necessary since the FHWA updated its methods for estimating on-road and non-road gasoline consumption. Among the method updates, FHWA now incorporates MOVES NONROAD equipment gasoline volumes in the construction and commercial/industrial categories.

emission factor and activity data sources, as well as the methodology used for estimating emissions. These procedures included a qualitative assessment of the emission estimates to determine whether they appear consistent with the most recent activity data and emission factors available. A comparison of historical emissions between the current Inventory and the previous Inventory was also conducted to ensure that the changes in estimates were consistent with the changes in activity data and emission factors.

Recalculations Discussion

Updates were made to the on-road, non-road and alternative fuel CH_4 and N_2O emissions calculations for the current Inventory resulting in both increases and decreases to different source categories. Decreases in on-road gasoline emissions were offset by large increases in alternative fuel and non-road emissions. The collective result of all of these changes was a net increase in CH_4 and N_2O emissions from mobile combustion relative to the previous Inventory. Methane emissions increased by 166.8 percent. Nitrous oxide emissions increased by 9.2 percent. Each of these changes is described below.

New emission factors for N_2O emissions were developed for on-road vehicles based on an EPA regression analysis of the relationship between NO_x and N_2O. New CH_4 emission factors were calculated based on the ratio of NMOG emission standards for newer vehicles. These new emission factors allowed the inclusion of additional emissions standards, including Federal Tier 3 emission standards and two levels of California emission standards (LEV II and LEV III) to the control technology breakouts.

In addition, new non-road emissions factors were developed. Previously, emission factors were taken from the *1996 IPCC Guidelines* and represented the IPCC Tier 1 factors. For the current Inventory, new emission factors were calculated using the updated 2006 IPCC Tier 3 guidance and EPA's MOVES2014a model. Methane emission factors were calculated directly from MOVES. Nitrous oxide emission factors were calculated using NONROAD activity and emission factors by fuel type from the European Environment Agency. Gasoline engines were broken out by 2- and 4-stroke engine types. Non-road equipment using liquefied petroleum gas (LPG) and compressed natural gas (CNG) were included.

New emission factors for AFVs were estimated using GREET 2016. The updated emission factors have been generated for CH_4 and N_2O. For light-duty trucks, EPA used a curve fit of 1999 through 2011 travel fractions for LDT1 and LDT2 (MOVES Source Type 31 for LDT1 and MOVES Source Type 32 for LDT2). For medium-duty vehicles, EPA used emission factors for Light Heavy-Duty Vocational Trucks. For heavy-duty vehicles, EPA used emission factors for Long Haul Combination Trucks. For buses, EPA used emission factors for Transit Buses. The emission factors developed represent vehicle operation only (tank-to-wheels).

In addition, changes were made to the historic allocation of gasoline to on-road and non-road applications. In 2016, the Federal Highway Administration (FHWA) changed its methods for estimating the share of gasoline used in on-road and non-road applications. Among other updates, FHWA included lawn and garden equipment as well as off-road recreational equipment in its estimates of non-road gasoline consumption for the first time. This change created a time-series inconsistency between the data reported for years 2015 and 2016 and previous years. To create a more consistent time series of motor gasoline consumption and emissions data for the current Inventory, the historical time series was modified. Specifically, the lawn, garden, and recreational vehicle gasoline consumption from EPA's NONROAD model is subtracted from the highway motor gasoline consumption from FHWA Table MF-21 when determining the total highway motor gasoline consumption for years 1990 through 2014.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2016 with one recent notable exception. An update by FHWA to the method for estimating on-road VMT created an inconsistency in on-road CH_4 and N_2O for the time periods 1990 to 2006 and 2007 to 2016. Details on the emission trends and methodological inconsistencies through time are described in the Methodology section, above.

Planned Improvements

While the data used for this report represent the most accurate information available, several areas have been identified that could potentially be improved in the near term given available resources.

- Evaluate and potentially update EPA's method for estimating motor gasoline consumption for non-road mobile sources to improve accuracy and create a more consistent time series. As discussed in the Methodology section above and in Annex 3.2, CH_4 and N_2O estimates for gasoline-powered non-road sources in this Inventory are based on a variety of inputs, including FHWA Highway Statistics Table MF-24. In 2016, FHWA changed its methods for estimating the share of gasoline used in on-road and non-road applications.[66] These method changes created a time-series inconsistency in the current Inventory between 2015 and previous years in CH_4 and N_2O estimates for agricultural, construction, commercial, and industrial non-road mobile sources. In the current Inventory EPA has implemented one approach to address this inconsistency. EPA will test other approaches including using MOVES on-road fuel consumption output to define the percentage of the FHWA consumption totals (from MF-21) that are attributable to on-highway transportation sources. This percentage would then be applied to the EIA total, thereby defining gasoline consumption from on-highway transportation sources, such that the remainder would be defined as consumption by the industrial and commercial sectors.

- Explore updates to on-road diesel emissions factors for CH_4 and N_2O to incorporate diesel after treatment technology for light-duty vehicles.
- Continue to explore potential improvements to estimates of domestic waterborne fuel consumption for future Inventories. The Inventory estimates for residual and distillate fuel used by ships and boats is based in part on data on bunker fuel use from the U.S. Department of Commerce. Domestic fuel consumption is estimated by subtracting fuel sold for international use from the total sold in the United States. It may be possible to more accurately estimate domestic fuel use and emissions by using detailed data on marine ship activity. The feasibility of using domestic marine activity data to improve the estimates continues to be investigated. Additionally, the feasibility of including data from a broader range of domestic and international sources for domestic bunker fuels, including data from studies such as the *Third IMO GHG Study 2014*, continues to be explored.

3.2 Carbon Emitted from Non-Energy Uses of Fossil Fuels (CRF Source Category 1A5)

In addition to being combusted for energy, fossil fuels are also consumed for non-energy uses in the United States. The fuels used for these purposes are diverse, including natural gas, liquefied petroleum gases (LPG), asphalt (a viscous liquid mixture of heavy crude oil distillates), petroleum coke (manufactured from heavy oil), and coal (metallurgical) coke (manufactured from coking coal). The non-energy applications of these fuels are equally diverse, including feedstocks for the manufacture of plastics, rubber, synthetic fibers and other materials; reducing agents for the production of various metals and inorganic products; and non-energy products such as lubricants, waxes, and asphalt (IPCC 2006). Emissions from non-energy uses of fossil fuels are reported in the Energy sector, as opposed to the Industrial Processes and Product Use (IPPU) sector, to reflect national circumstances in its choice of methodology and to increase transparency of this source category's unique country-specific data sources and methodology (see Box 3-6).

Carbon dioxide emissions arise from non-energy uses via several pathways. Emissions may occur during the manufacture of a product, as is the case in producing plastics or rubber from fuel-derived feedstocks. Additionally, emissions may occur during the product's lifetime, such as during solvent use. Overall, throughout the time series and across all uses, about 62 percent of the total C consumed for non-energy purposes was stored in products, and not released to the atmosphere; the remaining 38 percent was emitted.

There are several areas in which non-energy uses of fossil fuels are closely related to other parts of this Inventory. For example, some of the non-energy use products release CO_2 at the end of their commercial life when they are combusted after disposal; these emissions are reported separately within the Energy chapter in the Incineration of Waste source category. In addition, there is some overlap between fossil fuels consumed for non-energy uses and the

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[66] The previous and new FHWA methodologies for estimating non-road gasoline are described in *Off-Highway and Public-Use Gasoline Consumption Estimation Models Used in the Federal Highway Administration*, Publication Number FHWA-PL-17-012. <https://www.fhwa.dot.gov/policyinformation/pubs/pl17012.pdf>.

fossil-derived CO_2 emissions accounted for in the IPPU chapter, especially for fuels used as reducing agents. To avoid double counting, the "raw" non-energy fuel consumption data reported by EIA are modified to account for these overlaps. There are also net exports of petrochemicals that are not completely accounted for in the EIA data, and the Inventory calculations adjust for the effect of net exports on the mass of C in non-energy applications.

As shown in Table 3-19, fossil fuel emissions in 2016 from the non-energy uses of fossil fuels were 112.2 MMT CO_2 Eq., which constituted approximately 2 percent of overall fossil fuel emissions. In 2016, the consumption of fuels for non-energy uses (after the adjustments described above) was 4,844.8 TBtu (see Table 3-20). A portion of the C in the 4,844.8 TBtu of fuels was stored (216.6 MMT CO_2 Eq.), while the remaining portion was emitted (112.2 MMT CO_2 Eq.).

Table 3-19: CO_2 Emissions from Non-Energy Use Fossil Fuel Consumption (MMT CO_2 Eq. and Percent)

Year	1990		2005		2012	2013	2014	2015	2016
Potential Emissions	312.1		377.5		312.9	328.9	324.1	339.5	328.8
C Stored	192.5		238.6		204.9	205.4	205.3	213.8	216.6
Emissions as a % of Potential	38%		37%		35%	38%	37%	37%	34%
Emissions	**119.5**		**138.9**		**108.0**	**123.5**	**118.9**	**125.6**	**112.2**

Methodology

The first step in estimating C stored in products was to determine the aggregate quantity of fossil fuels consumed for non-energy uses. The C content of these feedstock fuels is equivalent to potential emissions, or the product of consumption and the fuel-specific C content values. Both the non-energy fuel consumption and C content data were supplied by the EIA (2017, 2018) (see Annex 2.1). Consumption of natural gas, LPG, pentanes plus, naphthas, other oils, and special naphtha were adjusted to subtract out net exports of these products that are not reflected in the raw data from EIA. Consumption values for industrial coking coal, petroleum coke, other oils, and natural gas in Table 3-20 and Table 3-21 have been adjusted to subtract non-energy uses that are included in the source categories of the Industrial Processes and Product Use chapter.[67,68] Consumption values were also adjusted to subtract net exports of intermediary chemicals.

For the remaining non-energy uses, the quantity of C stored was estimated by multiplying the potential emissions by a storage factor.

- For several fuel types—petrochemical feedstocks (including natural gas for non-fertilizer uses, LPG, pentanes plus, naphthas, other oils, still gas, special naphtha, and industrial other coal), asphalt and road oil, lubricants, and waxes—U.S. data on C stocks and flows were used to develop C storage factors, calculated as the ratio of (a) the C stored by the fuel's non-energy products to (b) the total C content of the fuel consumed. A lifecycle approach was used in the development of these factors in order to account for losses in the production process and during use. Because losses associated with municipal solid waste management are handled separately in the Energy sector under the Incineration of Waste source category, the storage factors do not account for losses at the disposal end of the life cycle.
- For industrial coking coal and distillate fuel oil, storage factors were taken from IPCC (2006), which in turn draws from Marland and Rotty (1984).

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[67] These source categories include Iron and Steel Production, Lead Production, Zinc Production, Ammonia Manufacture, Carbon Black Manufacture (included in Petrochemical Production), Titanium Dioxide Production, Ferroalloy Production, Silicon Carbide Production, and Aluminum Production.

[68] Some degree of double counting may occur between these estimates of non-energy use of fuels and process emissions from petrochemical production presented in the Industrial Processes and Produce Use sector. Data integration is not feasible at this time as feedstock data from EIA used to estimate non-energy uses of fuels are aggregated by fuel type, rather than disaggregated by both fuel type and particular industries (e.g., petrochemical production) as currently collected through EPA's GHGRP and used for the petrochemical production category.

- For the remaining fuel types (petroleum coke, miscellaneous products, and other petroleum), IPCC (2006) does not provide guidance on storage factors, and assumptions were made based on the potential fate of C in the respective non-energy use products. Carbon dioxide emissions from carbide production are implicitly accounted for in the storage factor calculation for the non-energy use of petroleum coke.

Table 3-20: Adjusted Consumption of Fossil Fuels for Non-Energy Uses (TBtu)

Year	1990	2005	2012	2013	2014	2015	2016
Industry	**4,215.8**	**5,110.7**	**4,377.3**	**4,621.1**	**4,597.6**	**4,759.1**	**4,626.9**
Industrial Coking Coal	0.0	80.4	132.5	119.3	48.8	121.8	88.8
Industrial Other Coal	8.2	11.9	10.3	10.3	10.3	10.3	10.3
Natural Gas to Chemical Plants	281.6	260.9	292.7	297.0	305.1	302.2	289.5
Asphalt & Road Oil	1,170.2	1,323.2	826.7	783.3	792.6	831.7	853.4
LPG	1,120.5	1,610.0	1,887.3	2,062.9	2,109.5	2,157.1	2,117.6
Lubricants	186.3	160.2	130.5	138.1	144.0	156.8	148.9
Pentanes Plus	117.6	95.5	40.3	45.4	43.5	78.4	53.0
Naphtha (<401 °F)	326.3	679.5	432.3	498.8	435.2	417.8	396.6
Other Oil (>401 °F)	662.1	499.4	267.4	209.1	236.2	216.8	203.8
Still Gas	36.7	67.7	160.6	166.7	164.5	162.2	166.1
Petroleum Coke	27.2	105.2	0.0	0.0	0.0	0.0	0.0
Special Naphtha	100.9	60.9	14.1	96.6	104.4	97.0	88.7
Distillate Fuel Oil	7.0	11.7	5.8	5.8	5.8	5.8	5.8
Waxes	33.3	31.4	15.3	16.5	14.8	12.4	12.9
Miscellaneous Products	137.8	112.8	161.6	171.2	182.7	188.9	191.3
Transportation	**176.0**	**151.3**	**123.2**	**130.4**	**136.0**	**148.1**	**140.6**
Lubricants	176.0	151.3	123.2	130.4	136.0	148.1	140.6
U.S. Territories	**85.6**	**123.2**	**72.0**	**82.4**	**77.3**	**77.3**	**77.3**
Lubricants	0.7	4.6	1.0	1.0	1.0	1.0	1.0
Other Petroleum (Misc. Prod.)	84.9	118.6	71.0	81.4	76.2	76.2	76.2
Total	**4,477.4**	**5,385.2**	**4,572.5**	**4,833.9**	**4,810.9**	**4,984.5**	**4,844.8**

Table 3-21: 2016 Adjusted Non-Energy Use Fossil Fuel Consumption, Storage, and Emissions

Sector/Fuel Type	Adjusted Non-Energy Use[a] (TBtu)	Carbon Content Coefficient (MMT C/QBtu)	Potential Carbon (MMT C)	Storage Factor	Carbon Stored (MMT C)	Carbon Emissions (MMT C)	Carbon Emissions (MMT CO_2 Eq.)
Industry	**4,626.9**	**NA**	**85.3**	**NA**	**58.6**	**26.6**	**97.6**
Industrial Coking Coal	88.8	31.00	2.8	0.10	0.3	2.5	9.1
Industrial Other Coal	10.3	25.82	0.3	0.70	0.2	0.1	0.3
Natural Gas to Chemical Plants	289.5	14.47	4.2	0.70	2.9	1.3	4.6
Asphalt & Road Oil	853.4	20.55	17.5	1.00	17.5	0.1	0.3
LPG	2117.6	17.06	36.1	0.70	25.3	10.8	39.7
Lubricants	148.9	20.20	3.0	0.09	0.3	2.7	10.0
Pentanes Plus	53.0	19.10	1.0	0.70	0.7	0.3	1.1
Naphtha (<401° F)	396.6	18.55	7.4	0.70	5.2	2.2	8.1
Other Oil (>401° F)	203.8	20.17	4.1	0.70	2.9	1.2	4.5
Still Gas	166.1	17.51	2.9	0.70	2.0	0.9	3.2
Petroleum Coke	0.0	27.85	0.0	0.30	0.0	0.0	0.0
Special Naphtha	88.7	19.74	1.8	0.70	1.2	0.5	1.9
Distillate Fuel Oil	5.8	20.17	0.1	0.50	0.1	0.1	0.2
Waxes	12.9	19.80	0.3	0.58	0.1	0.1	0.4

Miscellaneous Products	191.3	20.31	3.9	0.00	0.0	3.9	14.2
Transportation	**140.6**	**NA**	**2.8**	**NA**	**0.3**	**2.6**	**9.5**
Lubricants	140.6	20.20	2.8	0.09	0.3	2.6	9.5
U.S. Territories	**77.3**	**NA**	**1.5**	**NA**	**0.2**	**1.4**	**5.1**
Lubricants	1.0	20.20	0.0	0.09	0.0	0.0	0.1
Other Petroleum (Misc. Prod.)	76.2	20.00	1.5	0.10	0.2	1.4	5.0
Total	**4,844.8**		**89.7**		**59.1**	**30.6**	**112.2**

+ Does not exceed 0.05 TBtu, MMT C, MMT CO_2 Eq.

NA (Not Applicable)

[a] To avoid double counting, net exports have been deducted.

Note: Totals may not sum due to independent rounding.

Lastly, emissions were estimated by subtracting the C stored from the potential emissions (see Table 3-19). More detail on the methodology for calculating storage and emissions from each of these sources is provided in Annex 2.3.

Where storage factors were calculated specifically for the United States, data were obtained on (1) products such as asphalt, plastics, synthetic rubber, synthetic fibers, cleansers (soaps and detergents), pesticides, food additives, antifreeze and deicers (glycols), and silicones; and (2) industrial releases including energy recovery, Toxics Release Inventory (TRI) releases, hazardous waste incineration, and volatile organic compound, solvent, and non-combustion CO emissions. Data were taken from a variety of industry sources, government reports, and expert communications. Sources include EPA reports and databases such as compilations of air emission factors (EPA 2001), *National Emissions Inventory (NEI) Air Pollutant Emissions Trends Data* (EPA 2016a), *Toxics Release Inventory, 1998* (EPA 2000b), *Biennial Reporting System* (EPA 2000a, 2009), *Resource Conservation and Recovery Act Information System* (EPA 015, 2016c), pesticide sales and use estimates (EPA 1998, 1999, 2002, 2004, 2011, 2017), and the Chemical Data Access Tool (EPA 2012); the EIA Manufacturer's Energy Consumption Survey (MECS) (EIA 1994, 1997, 2001, 2005, 2010, 2013, 2017); the National Petrochemical & Refiners Association (NPRA 2002); the U.S. Census Bureau (1999, 2004, 2009, 2014); Bank of Canada (2012, 2013, 2014, 2016, 2017); Financial Planning Association (2006); INEGI (2006); the United States International Trade Commission (1990 through 2016); Gosselin, Smith, and Hodge (1984); EPA's *Municipal Solid Waste (MSW) Facts and Figures* (EPA 2013a, 2014a, 2016b); the Rubber Manufacturers' Association (RMA 2009, 2011, 2014, 2016); the International Institute of Synthetic Rubber Products (IISRP 2000, 2003); the Fiber Economics Bureau (FEB 2001, 2003, 2005, 2007, 2009, 2010, 2011, 2012, 2013, 2017); the EPA Chemical Data Access Tool (CDAT) (EPA 2014b); the American Chemistry Council (ACC 2003 through 2011, 2013, 2014, 2015a, 2016b, 2017b); and the *Guide to the Business of Chemistry* (ACC 2012, 2015b, 2016a, 2017a). Specific data sources are listed in full detail in Annex 2.3.

Uncertainty and Time-Series Consistency

An uncertainty analysis was conducted to quantify the uncertainty surrounding the estimates of emissions and storage factors from non-energy uses. This analysis, performed using @RISK software and the IPCC-recommended Approach 2 methodology (Monte Carlo Stochastic Simulation technique), provides for the specification of probability density functions for key variables within a computational structure that mirrors the calculation of the inventory estimate. The results presented below provide the 95 percent confidence interval, the range of values within which emissions are likely to fall, for this source category.

As noted above, the non-energy use analysis is based on U.S.-specific storage factors for (1) feedstock materials (natural gas, LPG, pentanes plus, naphthas, other oils, still gas, special naphthas, and other industrial coal), (2) asphalt, (3) lubricants, and (4) waxes. For the remaining fuel types (the "other" category in Table 3-20 and Table 3-21), the storage factors were taken directly from IPCC (2006), where available, and otherwise assumptions were made based on the potential fate of carbon in the respective NEU products. To characterize uncertainty, five separate analyses were conducted, corresponding to each of the five categories. In all cases, statistical analyses or expert judgments of uncertainty were not available directly from the information sources for all the activity variables; thus, uncertainty estimates were determined using assumptions based on source category knowledge.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 3-22 (emissions) and Table 3-23 (storage factors). Carbon emitted from non-energy uses of fossil fuels in 2016 was estimated to be between

90.6 and 156.3 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 19 percent below to 39 percent above the 2016 emission estimate of 112.2 MMT CO_2 Eq. The uncertainty in the emission estimates is a function of uncertainty in both the quantity of fuel used for non-energy purposes and the storage factor.

Table 3-22: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Non-Energy Uses of Fossil Fuels (MMT CO_2 Eq. and Percent)

Source	Gas	2016 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Feedstocks	CO_2	63.4	47.9	111.3	-24%	76%
Asphalt	CO_2	0.3	0.1	0.6	-58%	117%
Lubricants	CO_2	19.5	16.2	22.7	-17%	16%
Waxes	CO_2	0.4	0.3	0.7	-23%	77%
Other	CO_2	28.6	17.5	31.2	-39%	9%
Total	**CO_2**	**112.2**	**90.6**	**156.3**	**-19%**	**39%**

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Note: Totals may not sum due to independent rounding.

Table 3-23: Approach 2 Quantitative Uncertainty Estimates for Storage Factors of Non-Energy Uses of Fossil Fuels (Percent)

Source	Gas	2016 Storage Factor (%)	Uncertainty Range Relative to Emission Estimate[a] (%)		(%, Relative)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Feedstocks	CO_2	70.0%	57%	72%	-19%	3%
Asphalt	CO_2	99.6%	99%	100%	-0.5%	0.3%
Lubricants	CO_2	9.2%	4%	17%	-57%	91%
Waxes	CO_2	57.8%	47%	67%	-18%	17%
Other	CO_2	6.4%	6%	43%	-2%	568%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval, as a percentage of the inventory value (also expressed in percent terms).

As shown in Table 3-23, feedstocks and asphalt contribute least to overall storage factor uncertainty on a percentage basis. Although the feedstocks category—the largest use category in terms of total carbon flows—appears to have tight confidence limits, this is to some extent an artifact of the way the uncertainty analysis was structured. As discussed in Annex 2.3, the storage factor for feedstocks is based on an analysis of six fates that result in long-term storage (e.g., plastics production), and eleven that result in emissions (e.g., volatile organic compound emissions). Rather than modeling the total uncertainty around all of these fate processes, the current analysis addresses only the storage fates, and assumes that all C that is not stored is emitted. As the production statistics that drive the storage values are relatively well-characterized, this approach yields a result that is probably biased toward understating uncertainty.

As is the case with the other uncertainty analyses discussed throughout this document, the uncertainty results above address only those factors that can be readily quantified. More details on the uncertainty analysis are provided in Annex 2.3.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2016 as discussed below. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

A source-specific QA/QC plan for non-energy uses of fossil fuels was developed and implemented. This effort included a general analysis, as well as portions of a category specific analysis for non-energy uses involving petrochemical feedstocks and for imports and exports. The category-specific procedures that were implemented involved checks specifically focusing on the activity data and methodology for estimating the fate of C (in terms of storage and emissions) across the various end-uses of fossil C. Emission and storage totals for the different subcategories were compared, and trends across the time series were analyzed to determine whether any corrective actions were needed. Corrective actions were taken to rectify minor errors and to improve the transparency of the calculations, facilitating future QA/QC.

For petrochemical import and export data, special attention was paid to NAICS numbers and titles to verify that none had changed or been removed. Import and export totals were compared with 2015 totals as well as their trends across the time series.

Petrochemical input data reported by EIA will continue to be investigated in an attempt to address an input/output discrepancy in the NEU model. Prior to 2001, the C balance inputs exceed outputs, then starting in 2001 through 2009, outputs exceeded inputs. In 2010 through 2016, inputs exceeded outputs. A portion of this discrepancy has been reduced and two strategies have been developed to address the remaining portion (see the Planned Improvements section, below).

Recalculations Discussion

The Energy Information Administration (EIA 2018) updated energy consumption statistics across the time series relative to the previous Inventory.

Pesticide production data for 2007 through 2015 were updated using EPA's Pesticides Industry Sales and Usage 2008 – 2012 Market Estimates (EPA 2017). This resulted in a slight increase in emissions from pesticides compared to previous estimates for 2007 through 2015. Pesticide production data for 1990 through 2015 were updated by correcting rounding errors and molecular weights and chemical formulas for certain pesticides.

The calculated ratio of urea production to melamine production from 2001 to 2015 was updated to approximately 95/5 based on ICIS (2016) and ICIS (2008), rather than an even 50/50 split as previously estimated.

Overall, these changes resulted in an average annual increase of 2.8 MMT CO_2 Eq. (2.4 percent) in carbon emissions from non-energy uses of fossil fuels for the period 1990 through 2015, relative to the previous Inventory.

Planned Improvements

There are several future improvements planned:

- Analyzing the fuel and feedstock data from EPA's GHGRP subpart X (Petrochemical Production) to better disaggregate CO_2 emissions in NEU model and CO_2 process emissions from petrochemical production.
- More accurate accounting of C in petrochemical feedstocks. EPA has worked with EIA to determine the cause of input/output discrepancies in the C mass balance contained within the NEU model. In the future, two strategies to reduce or eliminate this discrepancy will continue to be pursued. First, accounting of C in imports and exports will be improved. The import/export adjustment methodology will be examined to ensure that net exports of intermediaries such as ethylene and propylene are fully accounted for. Second, the use of top-down C input calculation in estimating emissions will be reconsidered. Alternative approaches that rely more substantially on the bottom-up C output calculation will be considered instead.
- Improving the uncertainty analysis. Most of the input parameter distributions are based on professional judgment rather than rigorous statistical characterizations of uncertainty.
- Better characterizing flows of fossil C. Additional fates may be researched, including the fossil C load in organic chemical wastewaters, plasticizers, adhesives, films, paints, and coatings. There is also a need to further clarify the treatment of fuel additives and backflows (especially methyl tert-butyl ether, MTBE).

- Reviewing the trends in fossil fuel consumption for non-energy uses. Annual consumption for several fuel types is highly variable across the time series, including industrial coking coal and other petroleum (miscellaneous products). A better understanding of these trends will be pursued to identify any mischaracterized or misreported fuel consumption for non-energy uses. For example, "miscellaneous products" category includes miscellaneous products that are not reported elsewhere in the EIA data set. The EIA does not have firm data concerning the amounts of various products that are being reported in the "miscellaneous products" category; however, EIA has indicated that recovered sulfur from petroleum and natural gas processing, and potentially also C black feedstock could be reported in this category. Recovered sulfur would not be reported in the NEU calculation or elsewhere in the Inventory.
- Updating the average C content of solvents was researched, since the entire time series depends on one year's worth of solvent composition data. The data on C emissions from solvents that were readily available do not provide composition data for all categories of solvent emissions and also have conflicting definitions for volatile organic compounds, the source of emissive C in solvents. Additional sources of solvents data will be investigated in order to update the C content assumptions.
- Updating the average C content of cleansers (soaps and detergents) was researched; although production and consumption data for cleansers are published every 5 years by the Census Bureau, the composition (C content) of cleansers has not been recently updated. Recently available composition data sources may facilitate updating the average C content for this category.
- Revising the methodology for consumption, production, and C content of plastics was researched; because of recent changes to the type of data publicly available for plastics, the NEU model for plastics applies data obtained from personal communications. Potential revisions to the plastics methodology to account for the recent changes in published data will be investigated.
- Although U.S.-specific storage factors have been developed for feedstocks, asphalt, lubricants, and waxes, default values from IPCC are still used for two of the non-energy fuel types (industrial coking coal, distillate oil), and broad assumptions are being used for miscellaneous products and other petroleum. Over the long term, there are plans to improve these storage factors by analyzing C fate similar to those described in Annex 2.3 or deferring to more updated default storage factors from IPCC where available.
- Reviewing the storage of carbon black across various sectors in the Inventory; in particular, the carbon black abraded and stored in tires.

Box 3-6: Reporting of Lubricants, Waxes, and Asphalt and Road Oil Product Use in Energy Sector

IPCC (2006) provides methodological guidance to estimate emissions from the first use of fossil fuels as a product for primary purposes other than combustion for energy purposes (including lubricants, paraffin waxes, bitumen / asphalt, and solvents) under the IPPU sector.[69] In this Inventory, C storage and C emissions from product use of lubricants, waxes, and asphalt and road oil are reported under the Energy sector in the Carbon Emitted from Non-Energy Uses of Fossil Fuels source category (CRF Source Category 1A).[70]

The emissions are reported in the Energy sector, as opposed to the IPPU sector, to reflect national circumstances in its choice of methodology and to increase transparency of this source category's unique country-specific data sources and methodology. The country-specific methodology used for the Carbon Emitted from Non-Energy Uses of Fossil Fuels source category is based on a carbon balance (i.e., C inputs-outputs) calculation of the aggregate amount of fossil fuels used for non-energy uses, including inputs of lubricants, waxes, asphalt and road oil (see Section 3.2, Table 3-21). For those inputs, U.S. country-specific data on C stocks and flows are used to develop carbon storage factors, which are calculated as the ratio of the C stored by the fossil fuel non-energy products to the

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[69] See Volume 3: Industrial Processes and Product Use, Chapter 5: Non-Energy Products from Fuels and Solvent Use of the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006).

[70] Non-methane volatile organic compound (NMVOC) emissions from solvent use are reported separately in the IPPU sector, following Chapter 5 of the *2006 IPCC Guidelines*.

total C content of the fuel consumed, taking into account losses in the production process and during product use.[71] The country-specific methodology to reflect national circumstances starts with the aggregate amount of fossil fuels used for non-energy uses and applies a C balance calculation, breaking out the C emissions from non-energy use of lubricants, waxes, and asphalt and road oil. Due to U.S. national circumstances, reporting these C emissions separately under IPPU would involve making artificial adjustments to allocate both the C inputs and C outputs of the non-energy use C balance. These artificial adjustments would also result in the C emissions for lubricants, waxes, and asphalt and road oil being reported under IPPU, while the C storage for lubricants, waxes, and asphalt and road oil would be reported under Energy. To avoid presenting an incomplete C balance and a less transparent approach for the Carbon Emitted from Non-Energy Uses of Fossil Fuels source category calculation, the entire calculation of C storage and C emissions is therefore conducted in the Non-Energy Uses of Fossil Fuels category calculation methodology, and both the C storage and C emissions for lubricants, waxes, and asphalt and road oil are reported under the Energy sector.

However, portions of the fuel consumption data for seven fuel categories—coking coal, distillate fuel, industrial other coal, petroleum coke, natural gas, residual fuel oil, and other oil—were reallocated to the IPPU chapter, as they were consumed during non-energy related industrial activity. Emissions from uses of fossil fuels as feedstocks or reducing agents (e.g., petrochemical production, aluminum production, titanium dioxide and zinc production) are reported in the IPPU chapter, unless otherwise noted due to specific national circumstances.

3.3 Incineration of Waste (CRF Source Category 1A5)

Incineration is used to manage about 7 to 19 percent of the solid wastes generated in the United States, depending on the source of the estimate and the scope of materials included in the definition of solid waste (EPA 2000; Goldstein and Madtes 2001; Kaufman et al. 2004; Simmons et al. 2006; van Haaren et al. 2010). In the context of this section, waste includes all municipal solid waste (MSW) as well as scrap tires. In the United States, incineration of MSW tends to occur at waste-to-energy facilities or industrial facilities where useful energy is recovered, and thus emissions from waste incineration are accounted for in the Energy chapter. Similarly, scrap tires are combusted for energy recovery in industrial and utility boilers, pulp and paper mills, and cement kilns. Incineration of waste results in conversion of the organic inputs to CO_2. According to IPCC guidelines, when the CO_2 emitted is of fossil origin, it is counted as a net anthropogenic emission of CO_2 to the atmosphere. Thus, the emissions from waste incineration are calculated by estimating the quantity of waste combusted and the fraction of the waste that is C derived from fossil sources.

Most of the organic materials in municipal solid wastes are of biogenic origin (e.g., paper, yard trimmings), and have their net C flows accounted for under the Land Use, Land-Use Change, and Forestry chapter. However, some components—plastics, synthetic rubber, synthetic fibers, and carbon black in scrap tires—are of fossil origin. Plastics in the U.S. waste stream are primarily in the form of containers, packaging, and durable goods. Rubber is found in durable goods, such as carpets, and in non-durable goods, such as clothing and footwear. Fibers in municipal solid wastes are predominantly from clothing and home furnishings. As noted above, scrap tires (which contain synthetic rubber and carbon black) are also considered a “non-hazardous” waste and are included in the waste incineration estimate, though waste disposal practices for tires differ from municipal solid waste. Estimates on emissions from hazardous waste incineration can be found in Annex 2.3 and are accounted for as part of the C mass balance for non-energy uses of fossil fuels.

Approximately 30.1 million metric tons of MSW were incinerated in the United States in 2014 (EPA 2016). Data for the amount of MSW incinerated in 2015 and 2016 were not available, so data for 2015 and 2016 were assumed to be equal to data for 2014. Carbon dioxide emissions from incineration of waste increased 34 percent since 1990, to an

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[71] Data and calculations for lubricants and waxes and asphalt and road oil are in Annex 2.3 – Methodology and Data for Estimating CO_2 Emissions from Fossil Fuel Combustion.

estimated 10.7 MMT CO_2 (10,676 kt) in 2016, as the volume of scrap tires and other fossil C-containing materials in waste increased (see Table 3-24 and Table 3-25). Waste incineration is also a source of CH_4 and N_2O emissions (De Soete 1993; IPCC 2006). Methane emissions from the incineration of waste were estimated to be less than 0.05 MMT CO_2 Eq. (less than 0.5 kt CH_4) in 2016, and have decreased by 32 percent since 1990. Nitrous oxide emissions from the incineration of waste were estimated to be 0.3 MMT CO_2 Eq. (1 kt N_2O) in 2016, and have decreased by 32 percent since 1990.

Table 3-24: CO_2, CH_4, and N_2O Emissions from the Incineration of Waste (MMT CO_2 Eq.)

Gas/Waste Product	1990	2005	2012	2013	2014	2015	2016
CO_2	**8.0**	**12.5**	**10.4**	**10.4**	**10.6**	**10.7**	**10.7**
Plastics	5.6	6.9	5.7	5.8	5.9	5.9	5.9
Synthetic Rubber in Tires	0.3	1.6	1.3	1.2	1.2	1.2	1.2
Carbon Black in Tires	0.4	2.0	1.5	1.4	1.4	1.5	1.5
Synthetic Rubber in MSW	0.9	0.8	0.7	0.7	0.7	0.7	0.7
Synthetic Fibers	0.8	1.2	1.1	1.3	1.3	1.3	1.3
CH_4	+	+	+	+	+	+	+
N_2O	**0.5**	**0.4**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**
Total	**8.4**	**12.9**	**10.7**	**10.7**	**10.9**	**11.0**	**11.0**

Table 3-25: CO_2, CH_4, and N_2O Emissions from the Incineration of Waste (kt)

Gas/Waste Product	1990	2005	2012	2013	2014	2015	2016
CO_2	**7,950**	**12,469**	**10,392**	**10,361**	**10,604**	**10,670**	**10,676**
Plastics	5,588	6,919	5,709	5,815	5,928	5,928	5,928
Synthetic Rubber in Tires	308	1,599	1,261	1,158	1,189	1,220	1,220
Carbon Black in Tires	385	1,958	1,537	1,412	1,449	1,487	1,487
Synthetic Rubber in MSW	854	766	706	729	729	729	729
Synthetic Fibers	816	1,227	1,179	1,247	1,309	1,307	1,313
CH_4	+	+	+	+	+	+	+
N_2O	**2**	**1**	**1**	**1**	**1**	**1**	**1**

Methodology

Emissions of CO_2 from the incineration of waste include CO_2 generated by the incineration of plastics, synthetic fibers, and synthetic rubber in MSW, as well as the incineration of synthetic rubber and carbon black in scrap tires. The emission estimates are calculated for all four sources on a mass-basis based on the data available. These emissions were estimated by multiplying the mass of each material incinerated by the C content of the material and the fraction oxidized (98 percent). Plastics incinerated in municipal solid wastes were categorized into seven plastic resin types, each material having a discrete C content. Similarly, synthetic rubber is categorized into three product types, and synthetic fibers were categorized into four product types, each having a discrete C content. Scrap tires contain several types of synthetic rubber, carbon black, and synthetic fibers. Each type of synthetic rubber has a discrete C content, and carbon black is 100 percent C. Emissions of CO_2 were calculated based on the amount of scrap tires used for fuel and the synthetic rubber and carbon black content of scrap tires. More detail on the methodology for calculating emissions from each of these waste incineration sources is provided in Annex 3.7.

For each of the methods used to calculate CO_2 emissions from the incineration of waste, data on the quantity of product combusted and the C content of the product are needed. For plastics, synthetic rubber, and synthetic fibers in MSW, the amount of specific materials discarded as municipal solid waste (i.e., the quantity generated minus the quantity recycled) was taken from *Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures* (EPA 2000 through 2003, 2005 through 2014), and *Advancing Sustainable Materials Management: Facts and Figures: Assessing Trends in Material Generation, Recycling and Disposal in the United States* (EPA 2015, 2016) and detailed unpublished backup data for some years not shown in the reports (Schneider 2007). For 2016, the amount of MSW incinerated was assumed to be equal to that in 2014, due to the lack of available data. The proportion of total waste discarded that is incinerated was derived from Shin (2014). Data on total waste incinerated was not available in detail for 2012 through 2016, so these values were assumed to equal to the 2011 value (Shin 2014). For synthetic rubber and carbon black in scrap tires, information was obtained biannually from U.S. Scrap Tire Management Summary for 2005 through 2015 data (RMA 2016). The 2016 values were assumed to equal the 2015 value. Average C contents for the "Other" plastics category and synthetic rubber in municipal solid wastes were calculated from 1998 and 2002 production statistics; C content for 1990 through 1998 is based on the 1998 value; C content for 1999 through 2001 is the average of 1998 and 2002 values; and C content for 2002 to date is based on the 2002 value. Carbon content for synthetic fibers was calculated from a weighted average of production statistics from 1990 to date. Information about scrap tire composition was taken from the Rubber Manufacturers' Association internet site (RMA 2012a). The mass of incinerated material is multiplied by its C content to calculate the total amount of carbon stored.

The assumption that 98 percent of organic C is oxidized (which applies to all waste incineration categories for CO_2 emissions) was reported in EPA's life cycle analysis of greenhouse gas emissions and sinks from management of solid waste (EPA 2006). This percentage is multiplied by the carbon stored to estimate the amount of carbon emitted.

Incineration of waste, including MSW, also results in emissions of CH_4 and N_2O. These emissions were calculated as a function of the total estimated mass of waste incinerated and emission factors. As noted above, CH_4 and N_2O emissions are a function of total waste incinerated in each year; for 1990 through 2008, these data were derived from the information published in *BioCycle* (van Haaren et al. 2010). Data for 2009 and 2010 were interpolated between 2008 and 2011 values. Data for 2011 were derived from Shin (2014). Data on total waste incinerated was not available in the *BioCycle* data set for 2012 through 2016, so these values were assumed to equal the 2011 *BioCycle* dataset value.

Table 3-26 provides data on municipal solid waste discarded and percentage combusted for the total waste stream. The emission factors of N_2O and CH_4 emissions per quantity of municipal solid waste combusted are default emission factors for the default continuously-fed stoker unit MSW incineration technology type and were taken from IPCC (2006).

Table 3-26: Municipal Solid Waste Generation (Metric Tons) and Percent Combusted (BioCycle dataset)

Year	Waste Discarded	Waste Incinerated	Incinerated (% of Discards)
1990	235,733,657	30,632,057	13.0%
2005	259,559,787	25,973,520	10.0%
2012	273,116,704[a]	20,756,870	7.6%
2013	273,116,704[a]	20,756,870	7.6%
2014	273,116,704[a]	20,756,870	7.6%
2015	273,116,704[a]	20,756,870	7.6%
2016	273,116,704[a]	20,756,870	7.6%

[a] Assumed equal to 2011 value.

Source: van Haaren et al. (2010)

Uncertainty and Time-Series Consistency

An Approach 2 Monte Carlo analysis was performed to determine the level of uncertainty surrounding the estimates of CO_2 emissions and N_2O emissions from the incineration of waste (given the very low emissions for CH_4, no uncertainty estimate was derived). IPCC Approach 2 analysis allows the specification of probability density functions for key variables within a computational structure that mirrors the calculation of the Inventory estimate. Uncertainty estimates and distributions for waste generation variables (i.e., plastics, synthetic rubber, and textiles generation) were obtained through a conversation with one of the authors of the Municipal Solid Waste in the United States reports. Statistical analyses or expert judgments of uncertainty were not available directly from the information sources for the other variables; thus, uncertainty estimates for these variables were determined using assumptions based on source category knowledge and the known uncertainty estimates for the waste generation variables.

The uncertainties in the waste incineration emission estimates arise from both the assumptions applied to the data and from the quality of the data. Key factors include MSW incineration rate; fraction oxidized; missing data on waste composition; average C content of waste components; assumptions on the synthetic/biogenic C ratio; and combustion conditions affecting N_2O emissions. The highest levels of uncertainty surround the variables that are based on assumptions (e.g., percent of clothing and footwear composed of synthetic rubber); the lowest levels of uncertainty surround variables that were determined by quantitative measurements (e.g., combustion efficiency, C content of C black).

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 3-27. Waste incineration CO_2 emissions in 2016 were estimated to be between 8.3 and 13.4 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 22 percent below to 26 percent above the 2016 emission estimate of 10.7 MMT CO_2 Eq. Also at a 95 percent confidence level, waste incineration N_2O emissions in 2016 were estimated to be between 0.2 and 1.3 MMT CO_2 Eq. This indicates a range of 51 percent below to 327 percent above the 2016 emission estimate of 0.3 MMT CO_2 Eq.

Table 3-27: Approach 2 Quantitative Uncertainty Estimates for CO_2 and N_2O from the Incineration of Waste (MMT CO_2 Eq. and Percent)

Source	Gas	2016 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Incineration of Waste	CO_2	10.7	8.3	13.4	-22%	+26%
Incineration of Waste	N_2O	0.3	0.2	1.3	-51%	+327%

[a] Range of emission estimates predicted by Monte Carlo Simulation for a 95 percent confidence interval.

QA/QC and Verification

A source-specific Quality Assurance/Quality Control plan was implemented for incineration of waste. This effort included a general (Tier 1) analysis, as well as portions of a category-specific (Tier 2) analysis. The Tier 2 procedures that were implemented involved checks specifically focusing on the activity data and specifically focused on the emission factor and activity data sources and methodology used for estimating emissions from incineration of waste. Trends across the time series were analyzed to determine whether any corrective actions were needed. Actions were taken to streamline the activity data throughout the calculations on incineration of waste.

Recalculations Discussion

No methodological changes occurred since the previous Inventory.

Planned Improvements

The waste incineration inventory has recently relied on MSW mass flow (i.e., tonnage) for data that has not been updated since 2011. These values previously came from *BioCycle* (Shin 2014) and *EPA Facts and Figures* (EPA 2015). To update these values, the next Inventory will primarily use facility-level MSW tonnage data from EPA's Greenhouse Gas Reporting Program (GHGRP).

For the current Inventory, an examination of facility-level MSW tonnage data availability was performed, primarily focusing on GHGRP data, Energy Information Administration (EIA) waste-to-energy data, and other sources. EPA concluded that the GHGRP data were more complete (i.e., included more facilities), but did not contain data for all inventory years (1990 through 2016). The EIA data will be used to supplement years not available in the GHGRP data. The GHGRP data do not include specific waste components outside of an assumed biogenic and fossil component, which is necessary for CO_2 emission calculations. For the calculation of CO_2 emissions, EPA's GHGRP fossil CO_2 emissions will be used to benchmark results for other waste components in the next Inventory.

Additional improvements will be conducted to improve the transparency in the current reporting of waste incineration. Currently, hazardous industrial waste incineration is included within the overall calculations for the Carbon Emitted from Non-Energy Uses of Fossil Fuels source category. Waste incineration activities that do not include energy recovery will be examined. Synthetic fibers within scrap tires are not included in this analysis and will be explored for future Inventories. The C content of fibers within scrap tires will be used to calculate the associated incineration emissions. Updated fiber content data from the Fiber Economics Bureau will also be explored.

3.4 Coal Mining (CRF Source Category 1B1a)

Three types of coal mining-related activities release CH_4 to the atmosphere: underground mining, surface mining, and post-mining (i.e., coal-handling) activities. While surface mines account for the majority of U.S. coal production, underground coal mines contribute the largest share of CH_4 emissions (see Table 3-29 and Table 3-30) due to the higher CH_4 content of coal in the deeper underground coal seams. In 2016, 251 underground coal mines and 439 surface mines were operating in the United States. In recent years the total number of active coal mines in the United States has declined. In 2016, the United States was the third largest coal producer in the world (660 MMT), after China (3,242 MMT) and India (708 MMT) (IEA 2017).

Table 3-28: Coal Production (kt)

Year	Underground		Surface		Total	
	Number of Mines	Production	Number of Mines	Production	Number of Mines	Production
1990	1,683	384,244	1,656	546,808	3,339	931,052
2005	586	334,398	789	691,448	1,398	1,025,846
2012	488	310,608	719	610,307	1,207	920,915
2013	395	309,546	637	581,270	1,032	890,815
2014	345	321,783	613	583,974	958	905,757
2015	305	278,342	529	534,127	834	812,469
2016	251	228,403	439	431,485	690	659,888

Underground mines liberate CH_4 from ventilation systems and from degasification systems. Ventilation systems pump air through the mine workings to dilute noxious gases and ensure worker safety; these systems can exhaust significant amounts of CH_4 to the atmosphere in low concentrations. Degasification systems are wells drilled from the surface or boreholes drilled inside the mine that remove large, often highly concentrated volumes of CH_4 before, during, or after mining. Some mines recover and use CH_4 generated from ventilation and degasification systems, thereby reducing emissions to the atmosphere.

Surface coal mines liberate CH_4 as the overburden is removed and the coal is exposed to the atmosphere. CH_4 emissions are normally a function of coal rank (a classification related to the percentage of carbon in the coal) and depth. Surface coal mines typically produce lower-rank coals and remove less than 250 feet of overburden, so their level of emissions is much lower than from underground mines.

In addition, CH_4 is released during post-mining activities, as the coal is processed, transported, and stored for use.

Total CH_4 emissions in 2016 were estimated to be 2,153 kt (53.8 MMT CO_2 Eq.), a decline of 44 percent since 1990 (see Table 3-29 and Table 3-30). Of these total emissions, underground mines accounted for approximately 76 percent, surface mines accounted for 13 percent, and post-mining activities accounted for 12 percent.

Table 3-29: CH_4 Emissions from Coal Mining (MMT CO_2 Eq.)

Activity	1990	2005	2012	2013	2014	2015	2016
Underground (UG) Mining	74.2	42.0	47.3	46.2	46.1	44.9	40.7
Liberated	80.8	59.7	65.8	64.5	63.1	61.2	57.1
Recovered & Used	(6.6)	(17.7)	(18.5)	(18.3)	(17.0)	(16.4)	(16.3)
Surface Mining	10.8	11.9	10.3	9.7	9.6	8.7	6.8

Post-Mining (UG)	9.2	7.6	6.7	6.6	6.7	5.8	4.8
Post-Mining (Surface)	2.3	2.6	2.2	2.1	2.1	1.9	1.5
Total	**96.5**	**64.1**	**66.5**	**64.6**	**64.6**	**61.2**	**53.8**

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values.

Table 3-30: CH_4 Emissions from Coal Mining (kt)

Activity	1990	2005	2012	2013	2014	2015	2016
UG Mining	2,968	1,682	1,891	1,849	1,844	1,796	1,629
Liberated	3,234	2,390	2,631	2,580	2,524	2,450	2,282
Recovered & Used	(266)	(708)	(740)	(730)	(680)	(654)	(654)
Surface Mining	430	475	410	388	386	347	273
Post-Mining (UG)	368	306	268	263	270	231	192
Post-Mining (Surface)	93	103	89	84	84	75	59
Total	**3,860**	**2,565**	**2,658**	**2,584**	**2,583**	**2,449**	**2,153**

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values.

Methodology

The methodology for estimating CH_4 emissions from coal mining consists of two steps:

- Estimate emissions from underground mines. These emissions have two sources: ventilation systems and degasification systems. They are estimated using mine-specific data, then summed to determine total CH_4 liberated. The CH_4 recovered and used is then subtracted from this total, resulting in an estimate of net emissions to the atmosphere.
- Estimate CH_4 emissions from surface mines and post-mining activities. Unlike the methodology for underground mines, which uses mine-specific data, the methodology for estimating emissions from surface mines and post-mining activities consists of multiplying basin-specific coal production by basin-specific gas content and an emission factor.

Step 1: Estimate CH_4 Liberated and CH_4 Emitted from Underground Mines

Underground mines generate CH_4 from ventilation systems and from degasification systems. Some mines recover and use the generated CH_4, thereby reducing emissions to the atmosphere. Total CH_4 emitted from underground mines equals the CH_4 liberated from ventilation systems, plus the CH_4 liberated from degasification systems, minus the CH_4 recovered and used.

Step 1.1: Estimate CH_4 Liberated from Ventilation Systems

To estimate CH_4 liberated from ventilation systems, EPA uses data collected through its Greenhouse Gas Reporting Program (GHGRP)[72] (subpart FF, "Underground Coal Mines"), data provided by the U.S. Mine Safety and Health Administration (MSHA), and occasionally data collected from other sources on a site-specific level (e.g., state gas production databases). Since 2011, the nation's "gassiest" underground coal mines—those that liberate more than 36,500,000 actual cubic feet of CH_4 per year (about 17,525 MT CO_2 Eq.)—have been required to report to EPA's GHGRP (EPA 2016).[73] Mines that report to EPA's GHGRP must report quarterly measurements of CH_4 emissions from ventilation systems to EPA; they have the option of recording their own measurements, or using the

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[72] In implementing improvements and integrating data from EPA's GHGRP, EPA followed the latest guidance from the IPCC on the use of facility-level data in national inventories (IPCC 2011).

[73] Underground coal mines report to EPA under subpart FF of the GHGRP (40 CFR part 98). In 2016, 90 underground coal mines reported to the program.

measurements taken by MSHA as part of that agency's quarterly safety inspections of all mines in the United States with detectable CH_4 concentrations.[74]

Since 2013, ventilation emission estimates have been calculated based on both GHGRP data submitted by underground mines, and on quarterly measurement data obtained directly from MSHA for the remaining mines. The quarterly measurements are used to determine the average daily emissions rate for the reporting year quarter. Because not all mines report under EPA's GHGRP, the emissions of the mines that do not report must be calculated using MSHA data. The MSHA data also serves as a quality assurance tool for validating GHGRP data.

Step 1.2: Estimate CH_4 Liberated from Degasification Systems

Particularly gassy underground mines also use degasification systems (e.g., wells or boreholes) to remove CH_4 before, during, or after mining. This CH_4 can then be collected for use or vented to the atmosphere. Twenty-five mines used degasification systems in 2016, and the CH_4 removed through these systems was reported to EPA's GHGRP under subpart FF (EPA 2017). Based on the weekly measurements reported to EPA's GHGRP, degasification data summaries for each mine were added to estimate the CH_4 liberated from degasification systems. Fifteen of the 25 mines with degasification systems had operational CH_4 recovery and use projects (see step 1.3 below), and EPA's GHGRP reports show the remaining ten mines vented CH_4 from degasification systems to the atmosphere.[75]

Degasification data reported to EPA's GHGRP by underground coal mines is the primary source of data used to develop estimates of CH_4 liberated from degasification systems. Data reported to EPA's GHGRP were used to estimate CH_4 liberated from degasification systems at 20 of the 25 mines that used degasification systems in 2016.

For pre-mining wells, cumulative degasification volumes that occur prior to the well being mined through are attributed to the mine in the inventory year in which the well is mined through.[76] EPA's GHGRP does not require gas production from virgin coal seams (coalbed methane) to be reported by coal mines under subpart FF.[77] Most pre-mining wells drilled from the surface are considered coalbed methane wells prior to mine-through and associated CH_4 emissions are reported under another subpart of the program (subpart W, "Petroleum and Natural Gas Systems"). As a result, GHGRP data must be supplemented to estimate cumulative degasification volumes that occurred prior to well mine-through. For five mines with degasification systems that include pre-mining wells that were mined through in 2016, GHGRP data were supplemented with historical data from state gas well production databases (DMME 2017; GSA 2017; WVGES 2017), as well as with mine-specific information regarding the locations and dates on which the pre-mining wells were mined through (JWR 2010; El Paso 2009).

EPA's GHGRP reports with CH_4 liberated from degasification systems are reviewed for errors in reporting. For one of the 25 mines, due to a lack of mine-provided information used in prior years and a GHGRP reporting discrepancy, the CH_4 liberated was based on both an estimate from historical mine-provided CH_4 recovery and use rates and state gas sales records (DMME 2017).

Step 1.3: Estimate CH_4 Recovered from Ventilation and Degasification Systems, and Utilized or Destroyed (Emissions Avoided)

Fifteen mines had CH_4 recovery and use projects in place in 2016. Fourteen of these mines sold the recovered CH_4 to a pipeline, including one that also used CH_4 to fuel a thermal coal dryer. In addition, one mine used recovered CH_4 to heat mine ventilation air.

EPA's GHGRP data was exclusively used to estimate the CH_4 recovered and used from ten of the 15 mines that deployed degasification systems in 2016. Based on weekly measurements, the GHGRP degasification destruction

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[74] MSHA records coal mine CH_4 readings with concentrations of greater than 50 ppm (parts per million) CH_4. Readings below this threshold are considered non-detectable.

[75] Several of the mines venting CH_4 from degasification systems use a small portion the gas to fuel gob well blowers in remote locations where electricity is not available. However, this CH_4 use is not considered to be a formal recovery and use project.

[76] A well is "mined through" when coal mining development or the working face intersects the borehole or well.

[77] This applies for pre-drainage in years prior to the well being mined through. Beginning with the year the well is mined through, the annual volume of CH_4 liberated from a pre-drainage well is reported under subpart FF of EPA's GHGRP.

data summaries for each mine were added together to estimate the CH_4 recovered and used from degasification systems.

All 10 mines with degasification systems used pre-mining wells as part of those systems, but only four of the mines intersected pre-mining wells in 2016. EPA's GHGRP and supplemental data were used to estimate CH_4 recovered and used at two of these four mines; supplemental data alone (GSA 2017) was used to estimate CH_4 recovered and used at the other two mines. Supplemental information was used for these four mines because estimating CH_4 recovery and use from pre-mining wells requires additional data (not reported under subpart FF of EPA's GHGRP; see discussion in step 1.2 above) to account for the emissions avoided. The supplemental data came from state gas production databases as well as mine-specific information on the timing of mined-through pre-mining wells.

EPA's GHGRP information was not used to estimate CH_4 recovered and used at two mines. At one of these mines, a portion of reported CH_4 vented was applied to an ongoing mine air heating project. Because of a lack of mine-provided information used in prior years and a GHGRP reporting discrepancy, the 2016 CH_4 recovered and used from pre-mining wells at the other mine was based on an estimate from historical mine-provided CH_4 recovery and use rates. Emissions recovered and used from the active mine degasification system were estimated based on a state gas production data information system.

In 2016, one mine destroyed a portion of its CH_4 emissions from ventilation systems using thermal oxidation technology. The amount of CH_4 recovered and destroyed by the project was determined through publicly-available emission reduction project information (ACR 2017).

Step 2: Estimate CH_4 Emitted from Surface Mines and Post-Mining Activities

Mine-specific data are not available for estimating CH_4 emissions from surface coal mines or for post-mining activities. For surface mines, basin-specific coal production obtained from the Energy Information Administration's *Annual Coal Report* (EIA 2017) was multiplied by basin-specific CH_4 contents (EPA 1996, 2005) and a 150 percent emission factor (to account for CH_4 from over- and under-burden) to estimate CH_4 emissions (King 1994; Saghafi 2013). For post-mining activities, basin-specific coal production was multiplied by basin-specific gas contents and a mid-range 32.5 percent emission factor for CH_4 desorption during coal transportation and storage (Creedy 1993). Basin-specific *in situ* gas content data were compiled from AAPG (1984) and USBM (1986).

Uncertainty and Time-Series Consistency

A quantitative uncertainty analysis was conducted for the coal mining source category using the IPCC-recommended Approach 2 uncertainty estimation methodology. Because emission estimates from underground ventilation systems were based on actual measurement data from EPA's GHGRP or from MSHA, uncertainty is relatively low. A degree of imprecision was introduced because the ventilation air measurements used were not continuous but rather quarterly instantaneous readings that were used to determine the average daily emissions rate for the quarter. Additionally, the measurement equipment used can be expected to have resulted in an average of 10 percent overestimation of annual CH_4 emissions (Mutmansky & Wang 2000). GHGRP data were used for a significant number of the mines that reported their own measurements to the program beginning in 2013; however, the equipment uncertainty is applied to both GHGRP and MSHA data.

Estimates of CH_4 recovered by degasification systems are relatively certain for utilized CH_4 because of the availability of EPA's GHGRP data and gas sales information. Many of the recovery estimates use data on wells within 100 feet of a mined area. However, uncertainty exists concerning the radius of influence of each well. The number of wells counted, and thus the avoided emissions, may vary if the drainage area is found to be larger or smaller than estimated.

EPA's GHGRP requires weekly CH_4 monitoring of mines that report degasification systems, and continuous CH_4 monitoring is required for utilized CH_4 on- or off-site. Since 2012, GHGRP data have been used to estimate CH_4 emissions from vented degasification wells, reducing the uncertainty associated with prior MSHA estimates used for this subsource. Beginning in 2013, GHGRP data were also used for determining CH_4 recovery and use at mines without publicly available gas usage or sales records, which has reduced the uncertainty from previous estimation methods that were based on information from coal industry contacts.

In 2015 and 2016, a small level of uncertainty was introduced with using estimated rather than measured values of recovered methane from two of the mines with degasification systems. An increased level of uncertainty was applied to these two subsources, but the change had little impact on the overall uncertainty.

Surface mining and post-mining emissions are associated with considerably more uncertainty than underground mines, because of the difficulty in developing accurate emission factors from field measurements. However, since underground emissions constitute the majority of total coal mining emissions, the uncertainty associated with underground emissions is the primary factor that determines overall uncertainty.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 3-31. Coal mining CH_4 emissions in 2016 were estimated to be between 47.4 and 61.6 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 11.8 percent below to 14.4 percent above the 2016 emission estimate of 53.8 MMT CO_2 Eq.

Table 3-31: Approach 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Coal Mining (MMT CO_2 Eq. and Percent)

Source	Gas	2016 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Coal mining	CH_4	53.8	47.4	61.6	-11.8%	+14.4%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

Methodological recalculations were applied to the entire time series to ensure consistency from 1990 through 2016. Details on the emission trends through time are described in more detail in the methodology section.

Recalculations Discussion

For the current Inventory, revisions were made to the 2014 and 2015 underground liberated and recovered emissions. The EPA's GHGRP data that was used to calculate the emissions liberated and destroyed in 2014 and 2015 from a mine with a ventilation air methane (VAM) project was incorrect. The GHGRP spreadsheet for subpart FF reporting does not accommodate methane destruction from VAM, and therefore the emissions avoided are reported as degasification. In 2016, the VAM project's verified emission reductions registered with the California Air Resources Board were deducted from the total reported destroyed methane; and the remaining emissions destroyed were applied to the mine's degasification emissions recovered and destroyed total. The revised methodology was used to recalculate and update the emissions avoided in 2014 and 2015.

3.5 Abandoned Underground Coal Mines (CRF Source Category 1B1a)

Underground coal mines contribute the largest share of coal mine methane (CMM) emissions, with active underground mines the leading source of underground emissions. However, mines also continue to release CH_4 after closure. As mines mature and coal seams are mined through, mines are closed and abandoned. Many are sealed and some flood through intrusion of groundwater or surface water into the void. Shafts or portals are generally filled with gravel and capped with a concrete seal, while vent pipes and boreholes are plugged in a manner similar to oil and gas wells. Some abandoned mines are vented to the atmosphere to prevent the buildup of CH_4 that may find its way to surface structures through overburden fractures or via ground water aquifers. As work stops within the mines, CH_4 liberation decreases but it does not stop completely. Following an initial decline, abandoned mines can liberate CH_4 at a near-steady rate over an extended period of time, or, if flooded, produce gas for only a few years. The gas can migrate to the surface through the conduits described above, particularly if they have not been sealed adequately. In addition, diffuse emissions can occur when CH_4 migrates to the surface through cracks and fissures in the strata overlying the coal mine. The following factors influence abandoned mine emissions:

- Time since abandonment;
- Gas content and adsorption characteristics of coal;
- CH_4 flow capacity of the mine;
- Mine flooding;
- Presence of vent holes; and
- Mine seals.

Annual gross abandoned mine CH_4 emissions ranged from 7.2 to 10.8 MMT CO_2 Eq. from 1990 through 2016, varying, in general, by less than 1 percent to approximately 19 percent from year to year. Fluctuations were due mainly to the number of mines closed during a given year as well as the magnitude of the emissions from those mines when active. Gross abandoned mine emissions peaked in 1996 (10.8 MMT CO_2 Eq.) due to the large number of gassy mine[78] closures from 1994 to 1996 (72 gassy mines closed during the three-year period). In spite of this rapid rise, abandoned mine emissions have been generally on the decline since 1996. Since 2002, there have been fewer than twelve gassy mine closures each year. There were five gassy mine closures in 2016. In 2016, gross abandoned mine emissions increased slightly from 9.0 to 9.5 MMT CO_2 Eq. (see Table 3-32 and Table 3-33). Gross emissions are reduced by CH_4 recovered and used at 45 mines, resulting in net emissions in 2016 of 6.7 MMT CO_2 Eq.

Table 3-32: CH_4 Emissions from Abandoned Coal Mines (MMT CO_2 Eq.)

Activity	1990		2005		2012	2013	2014	2015	2016
Abandoned Underground Mines	7.2		8.4		8.9	8.8	8.7	9.0	9.5
Recovered & Used	+		1.8		2.7	2.6	2.4	2.6	2.8
Total	**7.2**		**6.6**		**6.2**	**6.2**	**6.3**	**6.4**	**6.7**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table 3-33: CH_4 Emissions from Abandoned Coal Mines (kt)

Activity	1990		2005		2012	2013	2014	2015	2016
Abandoned Underground Mines	288		334		358	353	350	359	380
Recovered & Used	+		70		109	104	97	102	112
Total	**288**		**264**		**249**	**249**	**253**	**256**	**268**

+ Does not exceed 0.5 kt

Note: Totals may not sum due to independent rounding.

Methodology

Estimating CH_4 emissions from an abandoned coal mine requires predicting the emissions of a mine from the time of abandonment through the inventory year of interest. The flow of CH_4 from the coal to the mine void is primarily dependent on the mine's emissions when active and the extent to which the mine is flooded or sealed. The CH_4 emission rate before abandonment reflects the gas content of the coal, the rate and method of coal mining, and the flow capacity of the mine in much the same way as the initial rate of a water-free conventional gas well reflects the gas content of the producing formation and the flow capacity of the well. A well or a mine which produces gas from a coal seam and the surrounding strata will produce less gas through time as the reservoir of gas is depleted. Depletion of a reservoir will follow a predictable pattern depending on the interplay of a variety of natural physical conditions imposed on the reservoir. The depletion of a reservoir is commonly modeled by mathematical equations and mapped as a type curve. Type curves, which are referred to as decline curves, have been developed for abandoned coal mines. Existing data on abandoned mine emissions through time, although sparse, appear to fit the hyperbolic type of decline curve used in forecasting production from natural gas wells.

In order to estimate CH_4 emissions over time for a given abandoned mine, it is necessary to apply a decline function, initiated upon abandonment, to that mine. In the analysis, mines were grouped by coal basin with the assumption

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[78] A mine is considered a "gassy" mine if it emits more than 100 thousand cubic feet of CH_4 per day (100 mcfd).

that they will generally have the same initial pressures, permeability and isotherm. As CH_4 leaves the system, the reservoir pressure (Pr) declines as described by the isotherm's characteristics. The emission rate declines because the mine pressure (Pw) is essentially constant at atmospheric pressure for a vented mine, and the productivity index (PI), which is expressed as the flow rate per unit of pressure change, is essentially constant at the pressures of interest (atmospheric to 30 psia). The CH_4 flow rate is determined by the laws of gas flow through porous media, such as Darcy's Law. Permeability and isotherm data were gathered from each coal basin and histograms were generated. The low, mid and high values of each parameter were combined in nine separate flow simulations for each coal basin using a computational fluid dynamics simulation model used in the oil and gas industry, which generated individual decline curves. These decline curves fit a hyperbolic equation commonly used in the oil and gas industry for forecasting gas well production. A rate-time equation can be generated that can be used to predict future emissions. This equation is expressed as:

$$q = q_i (1 + bD_i t)^{(-1/b)}$$

where,

q = Gas flow rate at time t in million cubic feet per day (mmcfd)
q_i = Initial gas flow rate at time zero (t_o), mmcfd
b = The hyperbolic exponent, dimensionless
D_i = Initial decline rate, 1/year
t = Elapsed time from t_o (years)

This equation is applied to mines of various initial emission rates that have similar initial pressures, permeability and adsorption isotherms relative to their coal basin (EPA 2004).

The decline curves created to model the gas emission rate of coal mines must account for factors that decrease the rate of emissions after mining activities cease, such as sealing and flooding. Based on field measurement data, it was assumed that most U.S. mines prone to flooding will become completely flooded within eight years and therefore will no longer have any measurable CH_4 emissions. Based on this assumption, an average decline rate for flooded mines was established by fitting a decline curve to emissions from field measurements. An exponential equation was developed from emissions data measured at eight abandoned mines known to be filling with water located in two of the five basins. Using a least squares, curve-fitting algorithm, emissions data were matched to the exponential equation shown below. There was not enough data to establish basin-specific equations as was done with the vented, non-flooding mines (EPA 2004).

$$q = q_i e^{(-Dt)}$$

where,

q = Gas flow rate at time t in mmcfd
q_i = Initial gas flow rate at time zero (t_o), mmcfd
D = Decline rate, 1/year
t = Elapsed time from t_o (years)

Seals have an inhibiting effect on the flow rate of CH_4 into the atmosphere compared to the flow rate that would exist if the mine had an open vent. The total volume emitted will be the same, but emissions will occur over a longer period of time. The methodology, therefore, treats the emissions prediction from a sealed mine similarly to the emissions prediction from a vented mine, but uses a lower initial rate depending on the degree of sealing. A computational fluid dynamics simulator was used with the conceptual abandoned mine model to predict the decline curve for inhibited flow. The percent sealed is defined as 100 × (1 – [initial emissions from sealed mine / emission rate at abandonment prior to sealing]). Significant differences are seen between 50 percent, 80 percent and 95 percent closure. These decline curves were therefore used as the high, middle, and low values for emissions from sealed mines (EPA 2004).

For active coal mines, those mines producing over 100 thousand cubic feet per day (mcfd) account for about 98 percent of all CH_4 emissions. This same relationship is assumed for abandoned mines. It was determined that the 531 abandoned mines closed after 1972 produced emissions greater than 100 mcfd when active. Further, the status of 304 of the 531 mines (or 57 percent) is known to be either: 1) vented to the atmosphere; 2) sealed to some degree (either earthen or concrete seals); or, 3) flooded (enough to inhibit CH_4 flow to the atmosphere). The remaining 43 percent of the mines whose status is unknown were placed in one of these three categories by applying a probability distribution analysis based on the known status of other mines located in the same coal basin (EPA 2004).

Table 3-34: Number of Gassy Abandoned Mines Present in U.S. Basins in 2016, grouped by Class according to Post-Abandonment State

Basin	Sealed	Vented	Flooded	Total Known	Unknown	Total Mines
Central Appl.	40	26	52	118	147	265
Illinois	34	3	14	51	31	82
Northern Appl.	47	22	16	85	39	124
Warrior Basin	0	0	16	16	0	16
Western Basins	28	4	2	34	10	44
Total	**149**	**55**	**100**	**304**	**227**	**531**

Inputs to the decline equation require the average emission rate and the date of abandonment. Generally, this data is available for mines abandoned after 1971; however, such data are largely unknown for mines closed before 1972, which marks the beginning of comprehensive methane emissions data by the Bureau of Mines. Information that is readily available, such as coal production by state and county, is helpful but does not provide enough data to directly employ the methodology used to calculate emissions from mines abandoned before 1972. It is assumed that pre-1972 mines are governed by the same physical, geologic, and hydrologic constraints that apply to post-1971 mines; thus, their emissions may be characterized by the same decline curves.

During the 1970s, 78 percent of CH_4 emissions from coal mining came from seventeen counties in seven states. In addition, mine closure dates were obtained for two states, Colorado and Illinois, for the hundred-year period extending from 1900 through 1999. The data were used to establish a frequency of mine closure histogram (by decade) and applied to the other five states with gassy mine closures. As a result, basin-specific decline curve equations were applied to the 145 gassy coal mines estimated to have closed between 1920 and 1971 in the United States, representing 78 percent of the emissions. State-specific, initial emission rates were used based on average coal mine CH_4 emissions rates during the 1970s (EPA 2004) and closure dates were summarized by decade. Emissions from pre-1972 mines represent approximately 17 percent of total abandoned mine methane emissions.

Abandoned mine emission estimates are based on all closed mines known to have active mine CH_4 ventilation emission rates greater than 100 mcfd at the time of abandonment. For example, for 1990 the analysis included 145 mines closed before 1972 and 258 mines closed between 1972 and 1990. Initial emission rates based on MSHA reports, time of abandonment, and basin-specific decline curves influenced by a number of factors were used to calculate annual emissions for each mine in the database (MSHA 2016). Coal mine degasification data are not available for years prior to 1990, thus the initial emission rates used reflect ventilation emissions only for pre-1990 closures. CH_4 degasification amounts were added to the quantity of CH_4 vented to determine the total CH_4 liberation rate for all mines that closed between 1992 and 2016. Since the sample of gassy mines is assumed to account for 78 percent of the pre-1972 and 98 percent of the post-1971 abandoned mine emissions, the modeled results were multiplied by 1.22 and 1.02 to account for all U.S. abandoned mine emissions.

From 1993 through 2016, emission totals were reduced by subtracting abandoned mine CH_4 emissions avoided. The Inventory totals were not adjusted for abandoned mine reductions from 1990 through 1992 because no data was reported for abandoned coal mining CH_4 recovery projects during that time.

Uncertainty and Time-Series Consistency

A quantitative uncertainty analysis was conducted to estimate the uncertainty surrounding the estimates of emissions from abandoned underground coal mines. The uncertainty analysis described below provides for the specification of probability density functions for key variables within a computational structure that mirrors the calculation of the inventory estimate. The results provide the range within which, with 95 percent certainty, emissions from this source category are likely to fall.

As discussed above, the low, mid and high model generated decline curves for each basin were fitted to a hyperbolic decline curve. The decline curve parameters, Di and b, for the low, mid and high decline curves were then used to define a triangular distribution and together with the initial rate value of a mine’s emissions and time from abandonment, a probability density function for each mine in the coal basin was generated. These density functions were then summed together using Monte Carlo simulation software to produce the AMM inventory which would be expressed in terms of a 95 percent confidence interval.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 3-35. Annual abandoned coal mine CH_4 emissions in 2016 were estimated to be between 5.5 and 8.2 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 18 percent below to 22 percent above the 2016 emission estimate of 6.7 MMT CO_2 Eq. One of the reasons for the relatively narrow range is that mine-specific data is available for use in the methodology for mines closed after 1972. Emissions from mines closed prior to 1972 have the largest degree of uncertainty because no mine-specific CH_4 liberation rates exist. Pre-1972 mines represent 17 percent of the total abandoned mine inventory.

Table 3-35: Approach 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Abandoned Underground Coal Mines (MMT CO_2 Eq. and Percent)

Source	Gas	2016 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Abandoned Underground Coal Mines	CH_4	6.7	5.5	8.2	-18%	+22%

[a] Range of emission estimates predicted by Monte Carlo Simulation for a 95 percent confidence interval.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2016. Details on the emission trends through time are described in more detail in the Methodology section, above.

3.6 Petroleum Systems (CRF Source Category 1B2a)

Methane emissions from petroleum systems are primarily associated with onshore and offshore crude oil production, transportation, and refining operations. During these activities, CH_4 is released to the atmosphere as leak emissions, vented emissions (including emissions from operational upsets) and emissions from fuel combustion. Leak and vented CO_2 emissions from petroleum systems are primarily associated with crude oil production and refining operations but are negligible in transportation operations. Total CH_4 emissions from petroleum systems in 2016 were 38.6 MMT CO_2 Eq. (1,544 kt), a decrease of 3 percent from 1990. Total CO_2 emissions from petroleum systems in 2016 were 22.8 MMT CO_2 Eq. (22,767 kt), an increase of a factor of 3 from 1990.

Each year, some estimates in the Inventory are recalculated with improved methods and/or data. These improvements are implemented consistently across the previous Inventory's time series (i.e., 1990 to 2015) to ensure that the trend is accurate. Recalculations in petroleum systems in this year's Inventory include:

- Estimated flaring emissions specific to petroleum production; where previous methodology assigned all emissions (including flaring from miscellaneous sources and associated gas) to the natural gas production segment.
- Revised CO_2 emission estimation methods for production segment sources to use GHGRP data (for consistency with the approach applied for CH_4 emission estimates): associated gas venting and flaring, oil tanks, pneumatic controllers, and chemical injection pumps.

The section below, titled Recalculations Discussion, provides more details on the updated methods.

Exploration. Exploration includes well drilling, testing, and completions. Exploration accounts for approximately 5 percent of total CH_4 emissions from petroleum systems. The predominant sources of emissions from exploration are hydraulically fractured oil well completions and well testing. Other sources include well completions without hydraulic fracturing and well drilling. Since 1990, exploration CH_4 emissions have increased 168 percent due to increases in the number of wells completed. Emissions of CH_4 from exploration decreased 7 percent from 2015 to 2016. Exploration accounts for less than 1 percent of total CO_2 emissions from petroleum systems. Emissions of CO_2 from exploration in 2016 decreased by 84 percent from 1990, and 85 percent from 2015, due to a decrease in well testing flaring CO_2 emissions.

Production. Production accounts for approximately 92 percent of total CH_4 emissions from petroleum systems. The predominant sources of emissions from production field operations are pneumatic controllers, offshore oil platforms, oil tanks, gas engines, chemical injection pumps, and leaks from oil wellheads. Since 1990, CH_4 emissions from production have decreased by 7 percent, due to decreases in emissions from tanks, pneumatic controllers, and offshore platforms. Overall, production segment methane emissions increased by 1 percent from 2015 levels, although emissions from tanks increased by 54 percent, emissions from associated gas venting and flaring decreased by 36 percent, and emissions from miscellaneous production flaring decreased by 34 percent in 2016 compared to 2015. The change in CH_4 emissions from 2015 to 2016 for tanks, associated gas venting and flaring, and miscellaneous production flaring reflects differences in reported GHGRP subpart W emissions levels for reporting year (RY) 2016 as compared to RY2015. Production emissions account for approximately 84 percent of the total CO_2 emissions from petroleum systems. The principal sources of CO_2 emissions are associated gas flaring, oil tanks with flares, and miscellaneous production flaring. These three sources together account for over 99 percent of the CO_2 emissions from production.

Crude Oil Transportation. Crude oil transportation activities account for less than 1 percent of total CH_4 emissions from the oil industry. Vented emissions from tanks, truck loading, rail loading, and marine vessel loading operations account for 85 percent of CH_4 emissions from crude oil transportation. Leak emissions, almost entirely from floating roof tanks, account for approximately 11 percent of CH_4 emissions from crude oil transportation. Since 1990, CH_4 emissions from transportation have increased by 27 percent. However, because emissions from crude oil transportation account for such a small percentage of the total emissions from the petroleum industry, this has had little impact on the overall emissions. Methane emissions from transportation in 2016 decreased by less than 1 percent from 2015 levels.

Crude Oil Refining. Crude oil refining processes and systems account for approximately 2 percent of total CH_4 emissions from the oil industry. This low share is because most of the CH_4 in crude oil is removed or escapes before the crude oil is delivered to the refineries. There is an insignificant amount of CH_4 in all refined products. Within refineries, incomplete combustion accounts for 38 percent of the CH_4 emissions, while vented and leak emissions account for approximately 52 and 10 percent, respectively. Flaring accounts for 82 percent of combustion CH_4 emissions. Refinery system blowdowns for maintenance and process vents are the primary venting contributors (97 percent). Most of the leak CH_4 emissions from refineries are from equipment leaks and storage tanks (85 percent). Methane emissions from refining of crude oil have increased by approximately 51 percent since 1990; however, similar to the transportation subcategory, this increase has had little effect on the overall emissions of CH_4. From 1990 to 2015, CH_4 emissions from crude oil refining fluctuated between 24 and 28 kt; in 2016, emissions increased to 37 kt as process vent emissions increased. Crude oil refining processes and systems account for approximately 16 percent of total CO_2 emissions from the oil industry. Almost all (97 percent) of the CO_2 from refining is from flaring. Refinery CO_2 emissions increased by approximately 13 percent from 1990 to 2016.

Table 3-36: CH_4 Emissions from Petroleum Systems (MMT CO_2 Eq.)

Activity	1990		2005		2012	2013	2014	2015	2016
Exploration[a]	**0.8**		**1.0**		**2.8**	**3.0**	**3.3**	**2.2**	**2.1**
Production (Total)	**38.3**		**30.3**		**29.0**	**32.7**	**34.4**	**34.9**	**35.4**
Pneumatic controller venting	19.1		16.6		14.3	17.2	17.9	18.0	18.5
Offshore platforms	5.3		4.6		4.7	4.7	4.7	4.7	4.7
Associated gas venting and flaring	1.0		0.7		1.1	1.3	1.6	1.7	1.1
Tanks	6.4		2.1		1.4	1.6	1.9	2.1	3.2
Gas engines	2.1		1.8		2.1	2.2	2.3	2.3	2.2
Chemical injection pumps	1.2		1.7		2.0	2.1	2.1	2.1	2.0
Other Sources	3.0		2.8		3.4	3.7	3.9	4.0	3.7
Crude Oil Transportation	**0.2**		**0.1**		**0.2**	**0.2**	**0.2**	**0.2**	**0.2**
Refining	**0.6**		**0.7**		**0.7**	**0.7**	**0.7**	**0.7**	**0.9**

Total	**39.8**	**32.1**	**32.7**	**36.6**	**38.6**	**38.1**	**38.6**

[a] Exploration includes well drilling, testing, and completions.
Note: Totals may not sum due to independent rounding.

Table 3-37: CH_4 Emissions from Petroleum Systems (kt)

Activity	1990	2005	2012	2013	2014	2015	2016
Exploration[a]	**31**	**39**	**113**	**120**	**131**	**89**	**82**
Production (Total)	**1,531**	**1,212**	**1,161**	**1,309**	**1,377**	**1,398**	**1,416**
Pneumatic controller venting	766	663	570	687	716	721	739
Offshore platforms	211	185	188	188	188	188	188
Associated gas venting and flaring	40	30	45	52	62	67	43
Tanks	258	84	57	65	77	82	127
Gas Engines	85	70	83	87	92	93	89
Chemical injection pumps	49	67	80	82	85	85	81
Other Sources	122	113	138	147	158	161	150
Crude Oil Transportation	**7**	**5**	**6**	**7**	**8**	**8**	**8**
Refining	**24**	**28**	**27**	**27**	**26**	**28**	**37**
Total	**1,592**	**1,284**	**1,307**	**1,463**	**1,543**	**1,523**	**1,544**

[a] Exploration includes well drilling, testing, and completions.
Note: Totals may not sum due to independent rounding.

Table 3-38: CO_2 Emissions from Petroleum Systems (MMT CO_2)

Activity	1990	2005	2012	2013	2014	2015	2016
Exploration	0.2	0.2	0.2	0.3	0.3	0.3	+
Production	4.2	7.8	15.6	18.8	22.6	24.5	19.0
Transportation	NE	NE	NE	NE	NE	NE	NE
Crude Refining	3.3	3.7	3.4	3.6	3.4	4.0	3.7
Total	**7.7**	**11.7**	**19.3**	**22.6**	**26.3**	**28.8**	**22.8**

Note: Totals may not sum due to independent rounding.
+ Does not exceed 0.05 MMT CO_2.
NE (Not Estimated)

Table 3-39: CO_2 Emissions from Petroleum Systems (kt)

Activity	1990	2005	2012	2013	2014	2015	2016
Exploration	243	207	247	255	264	262	39
Production	4,164	7,768	15,628	18,752	22,645	24,476	19,018
Transportation	NE	NE	NE	NE	NE	NE	NE
Crude Refining	3,282	3,726	3,425	3,605	3,414	4,014	3,710
Total	**7,689**	**11,700**	**19,300**	**22,611**	**26,324**	**28,752**	**22,767**

Note: Totals may not sum due to independent rounding.
NE (Not Estimated)

Methodology

See Annex 3.5 for the full time series of emissions data, activity data, and emission factors, and additional information on methods and data sources.

Petroleum systems includes emission estimates for activities occurring in petroleum systems from the oil wellhead through crude oil refining, including activities for crude oil exploration, production field operations, crude oil transportation activities, and refining operations. Emissions are estimated for each activity by multiplying emission factors (e.g., emission rate per equipment or per activity) by corresponding activity data (e.g., equipment count or frequency of activity).

Emission Factors. References for emission factors include *Methane Emissions from the Natural Gas Industry by the Gas Research Institute and EPA* (EPA/GRI 1996), *Estimates of Methane Emissions from the U.S. Oil Industry* (EPA 1999), DrillingInfo (2017), consensus of industry peer review panels, Bureau of Ocean Energy Management (BOEM) reports and analysis of GHGRP data (EPA 2017).

The emission factors for pneumatic controllers and chemical injection pumps were developed using GHGRP data for reporting year 2014. The emission factors for tanks, well testing, associated gas venting and flaring, and miscellaneous production flaring were developed using GHGRP data for reporting year 2015 and 2016. Emission factors for hydraulically fractured (HF) oil well completions (controlled and uncontrolled) were developed using DrillingInfo data analyzed for the 2015 NSPS OOOOa proposal. For offshore oil production, two emission factors were calculated using data collected for all federal offshore platforms; one for oil platforms in shallow water, and one for oil platforms in deep water. For most sources, emission factors were held constant for the period 1990 through 2016, and trends in emissions reflect changes in activity levels. For tanks, well testing, and associated gas venting and flaring, year-specific emission factors were developed for 2015 and 2016 and the 2015 emission factors were applied back to 1990. For miscellaneous production flaring, year-specific emission factors were developed for 2015 and 2016, an emission factor of 0 was assumed for 1990 through 1992, and linear interpolation was applied to develop emission factors for 1993 through 2014. Emission factors from EPA 1999 are used for all other production and transportation activities.

For associated gas venting and flaring and miscellaneous production flaring, emission factors were developed on a production basis (i.e., emissions per unit oil produced). Additionally, for these two sources, basin-specific activity and emission factors were developed for each basin that in any year from 2011 through 2016 contributed at least 10 percent of total source emissions (on a CO_2 Eq. basis) in the GHGRP. For associated gas venting and flaring, basin-specific factors were developed for four basins: Williston, Permian, Gulf Coast, and Anadarko; for miscellaneous production flaring, basin-specific factors were developed for three basins: Williston, Permian, and Gulf Coast. Data from all other basins were combined, and activity and emission factors developed for the other basins as a single group for each emission source.

Activity Data. References for activity data include DrillingInfo (2017), Energy Information Administration (EIA) reports, *Methane Emissions from the Natural Gas Industry by the Gas Research Institute and EPA* (EPA/GRI 1996), *Estimates of Methane Emissions from the U.S. Oil Industry* (EPA 1999), consensus of industry peer review panels, BOEM reports, the Oil & Gas Journal, the Interstate Oil and Gas Compact Commission, the United States Army Corps of Engineers, and analysis of GHGRP data (EPA 2017).

For many sources, complete activity data were not available for all years of the time series. In such cases, one of three approaches was employed to estimate values, consistent with IPCC good practice. Where appropriate, the activity data were calculated from related statistics using ratios developed based on EPA/GRI 1996 and/or GHGRP data. For floating roof tanks, the activity data were held constant from 1990 through 2016 based on EPA 1999. In some cases, activity data are developed by interpolating between recent data points (such as from GHGRP) and earlier data points, such as from EPA/GRI 1996. Lastly, the previous year's data were used for domestic barges and tankers as current year were not yet available. For offshore production, the number of platforms in shallow water and the number of platforms in deep water are used as activity data and are taken from BOEM datasets.

For the production segment, in general, CO_2 emissions for each source are estimated with GHGRP data or by multiplying CO_2 emission factors by the corresponding CH_4 data, as the CO_2 content of gas relates to the CH_4 content of gas. Sources with CO_2 emissions calculated from GHGRP data are associated gas venting and flaring, tanks, well testing, pneumatic controllers, chemical injection pumps, and miscellaneous production flaring. For these sources, CO_2 was calculated using the same methods as used for CH_4. Emission factors for offshore oil production (shallow and deep water) were derived using data from BOEM. For other sources, the production field operations emission factors for CO_2 are generally estimated by multiplying the CH_4 emission factors by a conversion factor, which is the ratio of CO_2 content and CH_4 content in produced associated gas.

For petroleum refining activities, 2010 to 2016 emissions were directly obtained from EPA's GHGRP. All U.S. refineries have been required to report CH_4 and CO_2 emissions for all major activities starting with emissions that occurred in 2010. However, GHGRP does have provisions that refineries are not required to report to the GHGRP if their emissions fall below certain thresholds (see Planned Improvements for additional discussion). The reported total of CH_4 and CO_2 emissions for each activity was used for the 2010 to 2016 emissions. To estimate CH_4 and CO_2 emissions for 1990 to 2009, the 2010 to 2013 emissions data from GHGRP along with the refinery feed data for

2010 to 2013 were used to derive CH_4 and CO_2 emission factors (i.e., sum of activity emissions/sum of refinery feed), which were then applied to the annual refinery feed in years 1990 to 2009..

A complete list of references for emission factors and activity data by emission source is provided in Annex 3.5.

EPA received stakeholder feedback on updates in the Inventory through EPA's stakeholder process on oil and gas in the Inventory. Stakeholder feedback is noted below in Uncertainty and Time-Series Consistency, Recalculations Discussion, and Planned Improvements.

Uncertainty and Time-Series Consistency

In recent years, EPA has made significant revisions to the Inventory methodology to use updated activity and emissions data. To update its characterization of uncertainty, EPA has conducted a quantitative uncertainty analysis using the IPCC Approach 2 methodology (Monte Carlo Simulation technique). For more information, please see the memorandum *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2016: Natural Gas and Petroleum Systems Uncertainty Estimates* (*2018 Uncertainty Memo*).[79]

EPA used Microsoft Excel's @RISK add-in tool to estimate the 95 percent confidence bound around methane emissions from petroleum systems for the current Inventory, then applied the calculated bounds to both CH_4 and CO_2 emissions estimates. For the analysis, EPA focused on the five highest methane-emitting sources for the year 2016, which together emitted 78 percent of methane from petroleum systems in 2016, and extrapolated the estimated uncertainty for the remaining sources. The @RISK add-in provides for the specification of probability density functions (PDFs) for key variables within a computational structure that mirrors the calculation of the inventory estimate. The IPCC guidance notes that in using this method, "some uncertainties that are not addressed by statistical means may exist, including those arising from omissions or double counting, or other conceptual errors, or from incomplete understanding of the processes that may lead to inaccuracies in estimates developed from models." As a result, the understanding of the uncertainty of emission estimates for this category evolves and improves as the underlying methodologies and datasets improve. The uncertainty bounds reported below only reflect those uncertainties that EPA has been able to quantify and do not incorporate considerations such as modeling uncertainty, data representativeness, measurement errors, misreporting or misclassification.

The results presented below provide the 95 percent confidence bound within which actual emissions from this source category are likely to fall for the year 2016, using the recommended IPCC methodology. The results of the Approach 2 uncertainty analysis are summarized in Table 3-40. Petroleum systems CH_4 emissions in 2016 were estimated to be between 27.1 and 51.9 MMT CO_2 Eq., while CO_2 emissions were estimated to be between 16.0 and 30.6 MMT CO_2 Eq. at a 95 percent confidence level. Uncertainty bounds for other years of the time series have not been calculated, but uncertainty is expected to vary over the time series. For example, years where many emission sources are calculated with interpolated data would likely have higher uncertainty than years with predominantly year-specific data.

Table 3-40: Approach 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Petroleum Systems (MMT CO_2 Eq. and Percent)

Source	Gas	2016 Emission Estimate (MMT CO_2 Eq.)[b]	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Petroleum Systems	CH_4	38.6	27.1	51.9	-30%	+34%
Petroleum Systems[c]	CO_2	22.8	16.0	30.6	-30%	+34%

[a] Range of emission estimates estimated by applying the 95 percent confidence intervals obtained from the Monte Carlo Simulation analysis conducted for the year 2016 CH_4 emissions.
[b] All reported values are rounded after calculation. As a result, lower and upper bounds may not be duplicable from other rounded values as shown in table.
[c] An uncertainty analysis for the petroleum systems CO_2 emissions was not performed. The relative uncertainty estimated (expressed as a percent) from the CH_4 uncertainty analysis was applied to the point estimate of petroleum systems CO_2

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[79] See <https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems>

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emissions.

GHGRP data available starting in 2010 for refineries and in 2011 for other sources have improved estimates of emissions from petroleum systems. Many of the previously available datasets were collected in the 1990s. To develop a consistent time series for 1990 through 2016, for sources with new data, EPA reviewed available information on factors that may have resulted in changes over the time series (e.g., regulations, voluntary actions) and requested stakeholder feedback on trends as well. For most sources, EPA developed annual data for 1993 through 2014 by interpolating activity data or emission factors or both between 1992 and 2010 or 2015 data points. Information on time-series consistency for sources updated in this year's Inventory can be found in the Recalculations Discussion below, with additional detail provided in supporting memos (relevant memos are cited in the Recalculations Discussion). For information on other sources, please see the Methodology Discussion above.

QA/QC and Verification Discussion

The petroleum systems emission estimates in the Inventory are continually being reviewed and assessed to determine whether emission factors and activity factors accurately reflect current industry practices. A QA/QC analysis was performed for data gathering and input, documentation, and calculation. QA/QC checks are consistently conducted to minimize human error in the model calculations. EPA performs a thorough review of information associated with new studies, GHGRP data, regulations, public webcasts, and the Natural Gas STAR Program to assess whether the assumptions in the Inventory are consistent with current industry practices. EPA has a multi-step data verification process for GHGRP data, including automatic checks during data-entry, statistical analyses on completed reports, and staff review of the reported data. Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred.[80]

As in previous years, EPA conducted early engagement and communication with stakeholders on updates prior to Public Review. EPA held stakeholder workshops on greenhouse gas data for oil and gas in June and October of 2017, and held webinars in April and August of 2017 and March of 2018. In advance of each workshop, EPA released memos detailing updates under consideration and requesting stakeholder feedback. Stakeholder feedback received through these processes is discussed in the Recalculations Discussion and Planned Improvements sections below.

In recent years, several studies have measured emissions at the source level and at the national or regional level and calculated emission estimates that may differ from the Inventory. There are a variety of potential uses of data from new studies, including replacing a previous estimate or factor, verifying or QA of an existing estimate or factor, and identifying areas for updates. In general, there are two major types of studies related to oil and gas greenhouse gas data: studies that focus on measurement or quantification of emissions from specific activities, processes, and equipment, and studies that use tools such as inverse modeling to estimate the level of overall emissions needed to account for measured atmospheric concentrations of greenhouse gases at various scales. The first type of study can lead to direct improvements to or verification of Inventory estimates. In the past few years, EPA has reviewed and in many cases, incorporated data from these data sources. The second type of study can provide general indications on potential over- and under-estimates. A key challenge in using these types of studies to assess Inventory results is having a relevant basis for comparison (i.e., the independent study should assess data from the Inventory and not another data set, such as EDGAR). In an effort to improve the ability to compare the national-level Inventory with measurement results that may be at other scales, a team at Harvard University along with EPA and other coauthors developed a gridded inventory of U.S. anthropogenic methane emissions with 0.1 degree x 0.1 degree spatial resolution, monthly temporal resolution, and detailed scale-dependent error characterization.[81] The gridded methane inventory is designed to be consistent with the U.S. EPA *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2014* estimates for the year 2012, which presents national totals.[82]

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[80] See <https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf>

[81] See <https://www.epa.gov/ghgemissions/gridded-2012-methane-emissions>

[82] See <https://www.epa.gov/ghgemissions/us-greenhouse-gas-inventory-report-1990-2014>

Recalculations Discussion

EPA received information and data related to the emission estimates through GHGRP reporting, the annual Inventory formal public notice periods, stakeholder feedback on updates under consideration, and new studies. In June and October 2017, EPA released draft memoranda that discussed changes under consideration, and requested stakeholder feedback on those changes. EPA then created updated versions of the memoranda to document the methodology implemented into the current Inventory.[83] Final memoranda cited in the Recalculations Discussion below are, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2016: Revisions to Create Year-Specific Emissions and Activity Factors (2018 Year-Specific Revisions Memo)* and *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2016: Revisions to CO_2 Emissions Estimation Methodologies (2018 CO_2 Memo).*

EPA thoroughly evaluated relevant information available, and made updates to exploration and production segment methodologies for the Inventory, including to define an exploration segment separate from production (not a methodological change, but a change in presentation of information), revising activity and CH_4 and CO_2 emissions data for associated gas venting and flaring, miscellaneous production flaring, and well testing. Production segment CO_2 emissions data were also revised for oil tanks, pneumatic controllers, and chemical injection pumps.

The combined impact of revisions to 2015 petroleum systems CH_4 emissions, compared to the previous Inventory, is a decrease from 39.9 to 38.1 MMT CO_2 Eq. (1.8 MMT CO_2 Eq., or 4.5 percent). The recalculations resulted in an average decrease in CH_4 emission estimates across the 1990 through 2015 time series, compared to the previous Inventory, of 13 MMT CO_2 Eq., or 28 percent. The CH_4 emissions estimate decrease was primarily due to recalculations related to associated gas venting and flaring which were updated to use a basin-level approach, and has the largest impact on years prior to 2013.

The combined impact of revisions to 2015 petroleum systems CO_2 emissions, compared to the previous Inventory, is an increase from 3.6 to 28.8 MMT CO_2 (25.2 MMT CO_2, or by a factor of 7). The recalculations resulted in an average increase in emission estimates across the 1990 through 2015 time series, compared to the previous Inventory, of 9.1 MMT CO_2 Eq., or 240 percent. The CO_2 emissions estimate increase was primarily due to recalculations related to the reallocation of CO_2 from flaring to petroleum systems from natural gas systems. Previously, data were not available to disaggregate flared emissions between natural gas systems and petroleum systems. The largest sources of CO_2 from flaring are associated gas flaring, tanks with flares, and miscellaneous production flaring.

In Table 3-41 and Table 3-42 below are categories in Petroleum Systems with recalculations resulting in a change of greater than 0.05 MMT CO_2 Eq., comparing the previous estimate for 2015 to the current (recalculated) estimate for 2015. For more information, please see the Recalculations Discussion, below.

Table 3-41: Recalculations of CO_2 in Petroleum Systems (MMT CO_2)

	Previous Estimate Year 2015, 2017 Inventory	**Current Estimate Year 2015, 2018 Inventory**	**Current Estimate Year 2016, 2018 Inventory**
Exploration	*NA*	**0.3**	+
Well Testing	*NE*	**0.3**	+
Production	*0.6*	**24.5**	**19.0**
Associated Gas Venting & Flaring	*NE*	**12.2**	**9.1**
Tanks	*0.5*	**8.7**	**7.4**
Miscellaneous Flaring*	*NE*	**3.4**	**2.5**
Transportation	*NE*	**NE**	**NE**
Refining	*2.9*	**4.0**	**3.7**
Petroleum Systems Total	*3.6*	**28.8**	**22.8**

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[83] Draft and final memoranda for the 1990-2016 Inventory are available here < https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems>

*In the 2017 Inventory, emissions were generally included within the natural gas production flaring emissions estimate.
NA (Not Applicable)
NE (Not Estimated)
+ Does not exceed 0.05 MMT CO_2.

Table 3-42: Recalculations of CH_4 in Petroleum Systems (MMT CO_2 Eq.)

	Previous Estimate Year 2015, 2017 Inventory	**Current Estimate Year 2015, 2018 Inventory**	**Current Estimate Year 2016, 2018 Inventory**
Exploration	***NA***	**2.2**	**2.1**
Well Testing	*NE*	0.2	0.1
Production	***39.0***	**34.9**	**35.4**
Associated Gas Venting & Flaring	*3.7*	1.7	1.1
Tanks	*2.0*	2.1	3.2
Miscellaneous Flaring*	*NE*	0.3	0.2
Transportation	***0.2***	**0.2**	**0.2**
Refining	***0.6***	**0.7**	**0.9**
Petroleum Systems Total	***39.9***	**38.1**	**38.6**

*In the 2017 Inventory, emissions were generally included within the natural gas production flaring emissions estimate.
NA (Not Applicable)
NE (Not Estimated)
+ Does not exceed 0.05 MMT CO_2.

Exploration

Petroleum systems was reorganized for the current Inventory to include an exploration segment to improve conformance with the IPCC guidelines. Exploration activities were previously included under the production segment. The activities included under exploration are hydraulically fractured oil well completions, oil well completions without hydraulic fracturing, well drilling, and well testing. Of these activities, well testing was the only source with a new methodology, which is discussed below.

Well Testing

EPA developed a new estimate for oil well testing (during non-completion events) using GHGRP data. In previous Inventories, only well testing conducted as part of a completion event was included. CH_4 and CO_2 emission factors were developed, on a per-event basis, for vented and flared oil well testing events using RY2015 and RY2016 data. EPA developed activity factors (i.e., number of events per oil well) to determine the number of well testing events in a year, also using RY2015 and RY2016 data. GHGRP RY2015 activity and emission factors are applied to all prior years of the time series. Methane emissions from well testing averaged 8.1 kt (or 0.2 MMT CO_2 Eq.) over the time series. There was a large decrease in emissions from oil well testing from 2015 to 2016 as observed in reported GHGRP data. Carbon dioxide emissions from well testing averaged 216 kt (0.2 MMT CO_2) over the time series. See the *2018 Year-Specific Revisions Memo* for additional discussion.

Table 3-43: Oil Well Testing National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2012	2013	2014	2015	2016
Non-Completion Well Testing - Vented	8,043	6,819	8,022	8,272	8,559	8,567	2,811
Non-Completion Well Testing - Flared	961	815	959	989	1,023	1,024	157

Table 3-44: Oil Well Testing National CO_2 Emissions (Metric Tons CO_2)

Source	1990	2005	2012	2013	2014	2015	2016
Non-Completion Well Testing - Vented	363	308	363	374	387	387	566
Non-Completion Well Testing - Flared	241,362	204,643	240,754	248,234	256,853	257,101	34,481

Production

CO_2 Updates

EPA updated CO_2 emissions for a number of sources in the Inventory. See the *2018 CO_2 Memo* for more details. The overall impact was an average increase of 9.1 MMT CO_2 (or 240 percent) over the time series in petroleum systems, which is primarily due to the reallocation of flaring CO_2 emissions from natural gas systems to petroleum systems, which was not possible in the past because the previous data source aggregated venting and flaring activity data from both petroleum and natural gas systems, but is now possible through use of the GHGRP data. A stakeholder noted that the update uses the best available data for this source.

Sources with the largest impacts include associated gas flaring, tanks with flares, and miscellaneous production flaring. These sources are discussed in detail below. Other sources (i.e., pneumatic controllers and chemical injection pumps) had increases or decreases of less than 1 MMT CO_2.

Associated Gas Venting and Flaring

EPA developed a new estimate for CO_2 from associated gas venting and flaring. EPA's final methodology for this source is documented in the *2018 CO_2 Memo*. As noted above in the Methodology section, EPA used a basin-level aggregation and production-based scaling approach to calculate emissions from this source. EPA evaluated basin-level associated gas venting and flaring data reported to GHGRP from 2011 to 2016; if a basin contributed at least 10 percent of total annual emissions (on a CO_2 Eq. basis) from associated gas venting and flaring in any year, then basin-specific emission factors and activity factors were developed. Four basins met this criteria: Williston, Permian, Gulf Coast, and Anadarko. Associated gas venting and flaring data in all other basins were combined, and emission factors and activity factors developed for the other basins as a single group. For each basin or group, emission factors were calculated for 2015 and 2016; the 2015 emission factors were applied to all prior years. Two activity factors were also calculated for each basin or group: the percent of oil production with either flaring or venting of associated gas and, within that subset of production, the fraction that vents and the fraction that flares. Each activity factor was calculated for 2015 and 2016, and the 2015 activity factors applied to all prior years. Stakeholder comments support the updates, though stakeholders have noted that past (e.g., 1990 through 2010) associated gas venting and flaring likely varied significantly from year to year and from region to region. However, data are not presently available to take variation prior to 2011 into account.

Table 3-45: Associated Gas Venting and Flaring National CO_2 Emissions (kt CO_2)

Source	1990	2005	2012	2013	2014	2015	2016
Associated Gas Venting Emissions	27	19	19	20	22	23	5
Associated Gas Flaring Emissions	4,001	3,295	7,475	9,173	11,226	12,211	9,103
Total Associated Gas Venting and Flaring	4,028	3,314	7,494	9,193	11,248	12,234	9,108
Previous Estimated emissions from stripper wells	*1*	*1*	*1*	*1*	*1*	*1*	*NA*

NA (Not Applicable)

Table 3-46: Basin-Level Detail Associated Gas Venting and Flaring CO_2 Emissions (kt CO_2)

Source	1990	2005	2012	2013	2014	2015	2016
Gulf Coast Basin	202	108	283	420	553	590	299
Anadarko Basin	101	61	160	195	229	232	2
Williston Basin	925	1,186	4,721	6,006	7,463	8,049	6,193
Permian Basin	1,636	1,124	1,555	1,767	2,126	2,440	2,325
Other basins	1,165	835	774	804	877	924	289

Total Associated Gas Venting and Flaring	4,028	3,314	7,494	9,193	11,248	12,234	9,108

The CH_4 methodology was developed for the previous Inventory and used a national-level approach. EPA updated its CH_4 calculations for associated gas venting and flaring to be consistent with the basin-level, production based approach to calculate CO_2 emissions from this source. Overall, the change decreased calculated CH_4 emissions over the time series by around 90 percent for combined associated gas venting and associated gas flaring, with the largest decreases occurring early in the time series.

Table 3-47: Associated Gas Venting and Flaring National CH_4 Emissions (Metric Tons CH_4)

Source	**1990**	**2005**	**2012**	**2013**	**2014**	**2015**	**2016**
Associated Gas Well Venting Emissions	24,159	17,133	19,018	20,827	23,746	25,564	14,375
Associated Gas Well Flaring Emissions	15,671	12,413	25,807	31,452	38,358	41,749	28,782
Previous Associated Gas Well Venting Emissions	*608,758*	*511,701*	*482,816*	*214,665*	*89,333*	*42,518*	*NA*
Previous Associated Gas Well Flaring Emissions	*76,176*	*64,031*	*104,513*	*146,292*	*149,694*	*105,706*	*NA*

NA (Not Applicable)

Tanks

EPA developed CO_2 emissions estimates for oil tanks using GHGRP data and a throughput-based approach. This approach is identical to the methodology to calculate CH_4 emissions; for more information, please see the *2017 Production Memo*.[84] The overall impact of the change is an increase in calculated CO_2 emissions by a factor of nine on average over the time series.

Table 3-48: National Tank CO_2 Emissions by Category and National Emissions (kt CO_2)

CO_2 Emissions	**1990**	**2005**	**2012**	**2013**	**2014**	**2015**	**2016**
Large Tanks w/ Flares	NO	3,407	5,978	6,870	8,054	8,657	7,282
Large Tanks w/ VRU	NO	6	11	13	15	16	11
Large Tanks w/o Control	25	7	4	5	6	6	9
Small Tanks w/ Flares	NO	4	7	8	9	10	21
Small Tanks w/o Flares	9	5	6	7	8	8	7
Malfunctioning Dump Valves	20	14	17	20	23	25	22
Total Emissions	**53**	**3,444**	**6,023**	**6,922**	**8,115**	**8,722**	**7,351**
Previous Estimated Emissions	*329*	*247*	*366*	*433*	*520*	*520*	*NA*

NO (Not Occurring)
NA (Not Applicable)

Miscellaneous Production Flaring

The EPA developed new estimates for CO_2 and CH_4 emissions from miscellaneous production flaring using GHGRP subpart W data. Along with other updates to flaring emissions in both oil and gas production, this replaces the estimate for flaring that was previously reported in the natural gas systems emissions totals. As noted above in the Methodology section, EPA used a production-based scaling and basin-level aggregation approach to calculate emissions from this source. To implement the production-based scaling approach, EPA apportioned miscellaneous production flaring emissions reported to GHGRP (as "flare stacks" emissions) between natural gas and petroleum systems according to the reported counts of gas and oil wells at each facility, then calculated production type-

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[84] *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2015: Revisions to Natural Gas and Petroleum Production Emissions*, available online at: <https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems-ghg-inventory-additional-information-1990-2015-ghg>

specific emission factors as emissions per unit gas or unit oil production. To implement the basin-level approach, EPA evaluated basin-level miscellaneous production flaring data reported to GHGRP from 2011 to 2016; if a basin contributed at least 10 percent of total annual emissions (on a CO_2 Eq. basis) from flare stacks in any year, then basin-specific emission factors and activity data were developed. Three basins met this criteria: Gulf Coast, Williston, and Permian. Miscellaneous production flaring data in all other basins were combined, and emission factors and activity data developed for the other basins as a single group. For each basin or group, emission factors were calculated for 2015 and 2016, an emission factor of 0 was assumed for 1990 through 1992, and linear interpolation was applied to develop emission factors for 1993 through 2014. Stakeholder comments support this approach for calculating emissions from miscellaneous production flaring. Details are provided in the *2018 CO_2 Memo*.

Table 3-49: Miscellaneous Production Flaring National CO_2 Emissions (kt CO_2)

Source	1990	2005	2012	2013	2014	2015	2016
Miscellaneous Flaring-Gulf Coast Basin	NO	99	379	587	806	860	389
Miscellaneous Flaring-Williston Basin	NO	78	468	624	811	874	337
Miscellaneous Flaring-Permian Basin	NO	139	288	342	430	494	775
Miscellaneous Flaring-Other basins	NO	612	896	988	1,134	1,190	953
Miscellaneous Flaring-National Total	**NO**	**929**	**2,031**	**2,541**	**3,181**	**3,418**	**2,455**
Previous Estimated emissions from flaring (natural gas and petroleum)[a]	*9,093*	*7,193*	*12,704*	*15,684*	*17,629*	*17,629*	*NA*

[a] The previous estimated emissions from flaring included emissions from multiple sources in the production and processing segments, and also included petroleum systems flaring emissions.
NO (Not Occurring)
NA (Not Applicable)

Table 3-50: Miscellaneous Production Flaring National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2012	2013	2014	2015	2016
Miscellaneous Flaring-Gulf Coast Basin	NO	409	1,563	2,421	3,328	3,548	1,630
Miscellaneous Flaring-Williston Basin	NO	196	1,172	1,562	2,029	2,188	957
Miscellaneous Flaring-Permian Basin	NO	533	1,103	1,312	1,650	1,893	2,738
Miscellaneous Flaring-Other basins	NO	2,106	3,083	3,398	3,902	4,094	2,378
Miscellaneous Production Flaring – National Total	**NO**	**3,245**	**6,921**	**8,694**	**10,909**	**11,724**	**7,703**
Previous Estimated emissions from flaring[a]	*NE*	*NE*	*NE*	*NE*	*NE*	*NE*	*NA*

[a] Prior Inventories did not estimate methane emissions from a source similar to miscellaneous production flaring.
NO (Not Occurring)
NE (Not Estimated)
NA (Not Applicable)

Activity Data Updates

Well Counts

EPA has used a more recent version of the DrillingInfo data set to update well counts data in the Inventory. There are not methodological changes to this source in the current Inventory or major changes to the activity data, but because this is a key input, results are highlighted here.

Table 3-51: Producing Oil Well Count Data

Oil Well Count	**1990**		**2005**		**2012**	**2013**	**2014**	**2015**	**2016**
Number of Oil Wells	553,899		469,632		552,504	569,670	589,450	590,017	561,964
Previous Estimate	*572,639*		*481,340*		*564,348*	*580,960*	*598,627*	*586,896*	*NA*

NA (Not Applicable)

In December 2017, EIA released a 2000 through 2016 time series of national oil and gas well counts. EIA total (oil and gas) well counts for 2016 were 1,010,441. EPA's total well counts were 978,845. Over the 2000 to 2016 time series, EPA's well counts were on average 2 percent lower than EIA's. EIA's well counts include side tracks, completions, and recompletions, and therefore are expected to be higher than EPA's which include only producing wells. EPA and EIA use a different threshold for distinguishing between oil versus gas (EIA uses 6 mcf/bbl, while EPA uses 100 mcf/bbl), which results in EIA having a lower fraction of oil wells and a higher fraction of gas wells than EPA. Across the 2000 through 2016 EIA time series, EIA estimates on average 111,420 (or 20 percent) fewer oil wells in each year than EPA.

Equipment Counts

EPA recalculated activity factors of equipment per well using the GHGRP RY2015 data, which included some resubmissions. This resulted in minor changes across the time series. For example, the number of heater/treaters per well decreased by 9 percent over the time series, the number of separators and headers per well decreased by 4 percent and 3 percent, respectively, while chemical injection pumps and pneumatic controllers per well increased by 4 percent and less than 1 percent, respectively. The impact of the changes in equipment counts per well along with changes in well counts resulted in minor changes in methane emissions across the time series for heater/treaters (-12 percent), separators (17 percent), headers (-5 percent), pneumatic controllers (-2 percent), and chemical injection pumps (2 percent).

Transportation

Recalculations due to updated activity data for quantity of petroleum transported by barge or tanker in the transportation segment have resulted in an average decrease in calculated emissions over the time series from this segment of less than 0.01 percent.

Refining

Recalculations due to resubmitted GHGRP data-in particular from flaring in the refining segment have resulted in an average increase in calculated CH_4 emissions over the time series from this segment of 3 percent and an average increase in calculated CO_2 emissions over the time series of 6 percent.

Planned Improvements

Oil Well Completions with Hydraulic Fracturing

The GHGRP began collecting data on oil well completions with hydraulic fracturing in RY2016; for the 2019 Inventory, two years of reporting data will be available, which EPA plans to review for consideration toward implementing methodological improvements for this emission source. Stakeholders support considering this data source and developing annual emission factors.

Refineries

The GHGRP includes provisions at 40 CFR 98.2(i) that allows facilities to discontinue complying with the GHGRP if their emissions fall below certain thresholds. EPA is assessing to what extent this provision has affected the subpart Y reported emissions. Based on preliminary assessments of subpart Y data for years 2011 through 2016, EPA has not identified active refineries that have discontinued reporting to the GHGRP. If certain refineries are identified as not reporting emissions to the GHGRP, options to address this will be considered.

Offshore Platforms

EPA is considering updates to the offshore platform emissions calculation methodology, as discussed in the memorandum *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2016: Additional Revisions Under Consideration* (*2018 Other Updates Memo)*.[85] The current emission factors were based on data from the 2011 DOI/Bureau of Ocean Energy Management's (BOEM) Gulf Offshore Activity Data System (GOADS), and 2014 GOADS data is available. A different source for platform counts is also being considered.

N_2O Emissions

N_2O emissions are currently not included in petroleum systems estimates, but EPA is considering developing a methodology to estimate N_2O emissions. The *2018 Other Updates Memo* provides discussion on this topic. EPA will consider options such as using GHGRP data for sources that already rely on GHGRP data for CH_4 or CO_2 estimates. GHGRP RY2015 and RY2016 reported N_2O flaring emissions specific to petroleum systems were 124 metric tons (or 0.04 MMT CO_2 Eq.) and 110 metric tons (or 0.03 MMT CO_2 Eq.), respectively. In addition, reported N_2O flaring emissions were 36 metric tons (or 0.01 MMT CO_2 Eq.) and 48 metric tons (or 0.01 MMT CO_2 Eq.) for GHGRP RY2015 and RY2016, respectively, for sources that fall within both natural gas and petroleum systems.

Well-Related Activity Data

As described in the Recalculations Discussion, EPA has updated the emission factors for certain well-related emission sources, including well testing. EPA will continue to assess available data, including data from the GHGRP and stakeholder feedback on considerations, to improve activity estimates for sources that rely on well-related activity data. For example, EPA will review GHGRP data regarding reported well workover rates; review DrillingInfo data to possibly estimate numbers of wells drilled in recent years (as the current EIA data source is not maintained after 2010); and seek information on other data sets that might inform estimates of non-hydraulically fractured oil well completions and workovers.

Floating Roof Tanks

EPA is considering removing production segment floating roof tanks from the Inventory or revising the methodology. The number of floating roof tanks and their emissions are minimal in the context of the petroleum production segment, and available data are limited; data on the number of floating roof tanks are only available for 1995, and the 1995 count is applied to all other years. EPA seeks stakeholder input on whether and how is it appropriate to include floating roof tank emission estimates in the production segment. The emission estimate for this source is 159 metric tons CH_4 in each year, or 0.01 percent of CH_4 emissions in 2016.

Upcoming Data, and Additional Data that Could Inform the Inventory

EPA will assess new data received by the Methane Challenge Program on an ongoing basis, which may be used to confirm or improve existing estimates and assumptions.

EPA continues to track studies that contain data that may be used to update the Inventory, such as an upcoming field study by API on pneumatic controllers. EPA will also continue to assess studies that include and compare both top-down and bottom-up estimates, and which could lead to improved understanding of unassigned high emitters (e.g., identification of emission sources and information on frequency of high emitters) as recommended in stakeholder comments.

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[85] See < https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems>

EPA also continues to seek new data that could be used to assess or update the estimates in the Inventory. For example, stakeholder comments have highlighted areas where additional data that could inform the Inventory are currently limited or unavailable:

- Tank malfunction and control efficiency data.
- Activity data and emissions data for production facilities that do not report to GHGRP.
- Associated gas venting and flaring data on practices from 1990 through 2010.
- Refineries emissions data. One stakeholder noted a recent study (Lavoie et al. 2017) that measured three refineries and found higher average emissions than in the Inventory, and the stakeholder suggested that EPA evaluate the study and any additional information available on this source.

One stakeholder suggested that the Inventory should be updated with site-level and basin-level data, noting the EPA could first use basin-level data to assess the inventory, and that future research could focus on collecting data in basins with the largest discrepancies.

EPA will continue to seek available data on these and other sources as part of the process to update the Inventory.

Box 3-7: Carbon Dioxide Transport, Injection, and Geological Storage

Carbon dioxide is produced, captured, transported, and used for Enhanced Oil Recovery (EOR) as well as commercial and non-EOR industrial applications. This CO_2 is produced from both naturally-occurring CO_2 reservoirs and from industrial sources such as natural gas processing plants and ammonia plants. In the Inventory, emissions from naturally-produced CO_2 are estimated based on the specific application.

In the Inventory, CO_2 that is used in non-EOR industrial and commercial applications (e.g., food processing, chemical production) is assumed to be emitted to the atmosphere during its industrial use. These emissions are discussed in the Carbon Dioxide Consumption section. The naturally-occurring CO_2 used in EOR operations is assumed to be fully sequestered. Additionally, all anthropogenic CO_2 emitted from natural gas processing and ammonia plants is assumed to be emitted to the atmosphere, regardless of whether the CO_2 is captured or not. These emissions are currently included in the Natural Gas Systems and the Ammonia Production sections of the Inventory report, respectively.

IPCC includes methodological guidance to estimate emissions from the capture, transport, injection, and geological storage of CO_2. The methodology is based on the principle that the carbon capture and storage system should be handled in a complete and consistent manner across the entire Energy sector. The approach accounts for CO_2 captured at natural and industrial sites as well as emissions from capture, transport, and use. For storage specifically, a Tier 3 methodology is outlined for estimating and reporting emissions based on site-specific evaluations. However, IPCC (IPCC 2006) notes that if a national regulatory process exists, emissions information available through that process may support development of CO_2 emission estimates for geologic storage.

In the United States, facilities that produce CO_2 for various end-use applications (including capture facilities such as acid gas removal plants and ammonia plants), importers of CO_2, exporters of CO_2, facilities that conduct geologic sequestration of CO_2, and facilities that inject CO_2 underground, are required to report greenhouse gas data annually to EPA through its GHGRP. Facilities conducting geologic sequestration of CO_2 are required to develop and implement an EPA-approved site-specific monitoring, reporting and verification plan, and to report the amount of CO_2 sequestered using a mass balance approach.

GHGRP data relevant for this inventory estimate consists of national-level annual quantities of CO_2 captured and extracted for EOR applications for 2010 to 2016. However, for 2015 and 2016, data from EPA's GHGRP (Subpart PP) were unavailable for use in the current Inventory report due to data confidentiality reasons. The estimate for 2014 was held constant here to estimate 2015 and 2016 emissions. EPA will continue to evaluate the availability of additional GHGRP data and other opportunities for improving the emission estimates. For reporting year 2016, one facility reported data to the GHGRP under subpart RR (Geologic Sequestration of Carbon Dioxide). This facility reported 3.1 MMT of CO_2 sequestered in subsurface geological formations and 56 metric tons of CO_2 emitted from surface equipment leaks and vents.

These estimates indicate that the amount of CO_2 captured and extracted from natural and industrial sites for EOR applications in 2016 is 59.3 MMT CO_2 Eq. (59,318 kt) (see Table 3-52 and Table 3-53). Site-specific monitoring and reporting data for CO_2 injection sites (i.e., EOR operations) were not readily available, therefore, the quantity of

CO_2 captured and extracted is noted here for information purposes only; CO_2 captured and extracted from industrial and commercial processes is assumed to be emitted and included in emissions totals from those processes.

Table 3-52: Quantity of CO_2 Captured and Extracted for EOR Operations (MMT CO_2)

Stage	1990	2005	2012	2013	2014	2015	2016
Capture Facilities	4.8	6.5	9.3	12.2	13.1	13.1	13.1
Extraction Facilities	20.8	28.3	48.9	47.0	46.2	46.2	46.2
Total	**25.6**	**34.7**	**58.1**	**59.2**	**59.3**	**59.3**	**59.3**

Note: Totals may not sum due to independent rounding.

Table 3-53: Quantity of CO_2 Captured and Extracted for EOR Operations (kt)

Stage	1990	2005	2012	2013	2014	2015	2016
Capture Facilities	4,832	6,475	9,267	12,205	13,093	13,093	13,093
Extraction Facilities	20,811	28,267	48,869	46,984	46,225	46,225	46,225
Total	**25,643**	**34,742**	**58,136**	**59,189**	**59,318**	**59,318**	**59,318**

Note: Totals may not sum due to independent rounding.

3.7 Natural Gas Systems (CRF Source Category 1B2b)

The U.S. natural gas system encompasses hundreds of thousands of wells, hundreds of processing facilities, and over a million miles of transmission and distribution pipelines. Overall, natural gas systems emitted 163.5 MMT CO_2 Eq. (6,541 kt) of CH_4 in 2016, a 16 percent decrease compared to 1990 emissions, and a 1.7 percent decrease compared to 2015 emissions (see Table 3-54, Table 3-55, and Table 3-56) and 25.5 MMT CO_2 Eq. (25,516 kt) of non-combustion CO_2 in 2016, a 14 percent decrease compared to 1990 emissions.

The 1990 to 2016 trend in CH_4 is not consistent across segments. Overall, the 1990 to 2016 decrease in CH_4 emissions is due primarily to the decrease in emissions from distribution (72 percent decrease), transmission and storage (44 percent decrease), processing (48 percent decrease), and exploration (81 percent decrease) segments. Over the same time period, the production segments saw increased methane emissions of 58 percent (with onshore production emissions increasing 27 percent, offshore production emissions increasing 7 percent, and gathering and boosting emissions increasing 103 percent). The 1990 to 2016 decrease in CO_2 is due primarily to decreases in acid gas removal emissions in the processing segment, where acid gas removal emissions per plant have decreased over time.

Methane and non-combustion CO_2 emissions from natural gas systems include those resulting from normal operations, routine maintenance, and system upsets. Emissions from normal operations include: natural gas engine and turbine uncombusted exhaust, bleed and discharge emissions from pneumatic controllers, and fugitive emissions from system components. Routine maintenance emissions originate from pipelines, equipment, and wells during repair and maintenance activities. Pressure surge relief systems and accidents can lead to system upset emissions. Below is a characterization of the five major stages of the natural gas system. Each of the stages is described and the different factors affecting CH_4 and non-combustion CO_2 emissions are discussed.

Each year, some estimates in the Inventory are recalculated with improved methods and/or data. These improvements are implemented consistently across the previous Inventory's time series (i.e., 1990 to 2015) to ensure that the trend is accurate. Recalculations in natural gas systems in this year's Inventory include:

- Estimated flaring emissions specific to natural gas production, natural gas processing, and petroleum production; where previous methodology assigned all emissions (including flaring from miscellaneous sources and associated gas) to the natural gas production segment.

- Added emissions from flaring at transmission and storage stations that were not previously reported in the inventory.
- Revised CO_2 emission estimation methods for production segment sources to use GHGRP data (for consistency with the approach applied for CH_4 emission estimates): gas well hydraulically fractured completions and workovers, pneumatic controllers, chemical injection pumps, and liquids unloading.
- Revised CO_2 emission estimation methods for processing segment sources to use GHGRP data (for consistency with the approach applied for CH_4 emission estimates): grouped emission sources (reciprocating compressors, centrifugal compressors, dehydrators, flares, and fugitives), blowdowns, and acid gas removal (AGR) units.
- Revised CO_2 emission estimation methods for transmission and storage pneumatic controllers to use GHGRP data (for consistency with the approach applied for CH_4 emission estimates).

Exploration. Exploration includes well drilling, testing, and completions. Emissions from exploration account for 0.5 percent of both CH_4 emissions and of CO_2 emissions from natural gas systems in 2016. Well completions account for most of the CH_4 emissions in 2016, with well testing and drilling also contributing emissions. Flaring emissions account for most of the non-combustion CO_2 emissions. Methane emissions from exploration decreased by 81 percent from 1990 to 2016, with the largest decreases coming from hydraulically fractured gas well completions without reduced emissions completions (RECs) or flaring. Carbon dioxide emissions from exploration decreased by 66 percent from 1990 to 2016 due to decreases in flaring.

Production (including gathering and boosting). In the production stage, wells are used to withdraw raw gas from underground formations. Emissions arise from the wells themselves, and well-site gas treatment equipment such as dehydrators and separators. Gathering and boosting emission sources are included within the production sector. The gathering and boosting sources include gathering and boosting stations (with multiple emission sources on site) and gathering pipelines. The gathering and boosting stations receive natural gas from production sites and transfer it, via gathering pipelines, to transmission pipelines or processing facilities (custody transfer points are typically used to segregate sources between each segment). Emissions from production (including gathering and boosting) account for 65 percent of CH_4 emissions and 13 percent of non-combustion CO_2 emissions from natural gas systems in 2016. Emissions from gathering stations, pneumatic controllers, gas engines, gathering pipelines, liquids unloading, and offshore platforms account for most of the CH_4 emissions in 2016. Flaring emissions account for most of the non-combustion CO_2 emissions with the highest emissions coming from flaring from tanks, miscellaneous production flaring, and offshore flaring. Methane emissions from production increased by 58 percent from 1990 to 2016, due primarily to increases in emissions from gathering and boosting stations (driven by an increase in gas production), increases in emissions from pneumatic controllers (due to an increase in the number of controllers, particularly in the number of intermittent bleed controllers), and gas engines. Carbon dioxide emissions from production increased by a factor of 2.7 from 1990 to 2016 due to increases in flaring.

Processing. In this stage, natural gas liquids and various other constituents from the raw gas are removed, resulting in "pipeline quality" gas, which is injected into the transmission system. Fugitive CH_4 emissions from compressors, including compressor seals, are the primary emission source from this stage. Most of the non-combustion CO_2 emissions come from acid gas removal (AGR) units, which are designed to remove CO_2 from natural gas. Processing plants account for 7 percent of CH_4 emissions and 86 percent of non-combustion CO_2 emissions from natural gas systems. Methane emissions from processing decreased by 48 percent from 1990 to 2016 as emissions from compressors (leaks and venting) and equipment leaks decreased. Carbon dioxide emissions from processing decreased by 22 percent from 1990 to 2016, due to a decrease in acid gas removal emissions.

Transmission and Storage. Natural gas transmission involves high pressure, large diameter pipelines that transport gas long distances from field production and processing areas to distribution systems or large volume customers such as power plants or chemical plants. Compressor station facilities are used to move the gas throughout the U.S. transmission system. Leak CH_4 emissions from these compressor stations, and venting from pneumatic controllers account for most of the emissions from this stage. Uncombusted engine exhaust and pipeline venting are also sources of CH_4 emissions from transmission. Natural gas is also injected and stored in underground formations, or liquefied and stored in above ground tanks, during periods of low demand (e.g., summer), and withdrawn, processed, and distributed during periods of high demand (e.g., winter). In 2016, emissions from the final months of the Aliso Canyon leak event in Southern California contributed 0.5 MMT CO_2 Eq. to transmission and storage emissions, around 2 percent of total emissions for this segment. Compressors and dehydrators are the primary contributors to emissions from storage. Methane emissions from the transmission and storage sector account for approximately 20 percent of emissions from natural gas systems, while CO_2 emissions from transmission and storage account for less than 1 percent of the non-combustion CO_2 emissions from natural gas systems. CH_4 emissions from this source decreased by 44 percent from 1990 to 2016 due to reduced compressor station emissions (including emissions from compressors and leaks). CO_2 emissions from transmission and storage have decreased by 14 percent from 1990 to 2016, also due to reduced compressor station emissions.

Distribution. Distribution pipelines take the high-pressure gas from the transmission system at "city gate" stations, reduce the pressure and distribute the gas through primarily underground mains and service lines to individual end users. There were 1,284,241 miles of distribution mains in 2016, an increase of over 340,000 miles since 1990 (PHMSA 2017a; PHMSA 2017b). Distribution system emissions, which account for 7 percent of CH_4 emissions from natural gas systems and less than 1 percent of non-combustion CO_2 emissions, result mainly from leak emissions from pipelines and stations. An increased use of plastic piping, which has lower emissions than other pipe materials, has reduced both CH_4 and CO_2 emissions from this stage, as have station upgrades at metering and regulating (M&R) stations. Distribution system CH_4 emissions in 2016 were 72 percent lower than 1990 levels (changed from 43.5 MMT CO_2 Eq. to 12.0 MMT CO_2 Eq.), while distribution CO_2 emissions in 2016 were 72 percent lower than 1990 levels (CO_2 emission from this segment are less than 0.1 MMT CO_2 Eq. across the time series).

Total CH_4 emissions for the five major stages of natural gas systems are shown in MMT CO_2 Eq. (Table 3-54) and kt (Table 3-55). Table 3-56 provides additional information on how the estimates in Table 3-52 were calculated. With recent updates to the Inventory, most emissions are calculated using a net emission approach. However, certain sources are still calculated with a potential emission approach. Table 3-56 shows the calculated potential CH_4 release (i.e., potential emissions before any controls are applied) from each stage, and the amount of CH_4 that is estimated to have been flared, captured, or otherwise controlled, and therefore not emitted to the atmosphere. Subtracting the value for CH_4 that is controlled, from the value for calculated potential release of CH_4, results in the total net emissions values. More disaggregated information on potential emissions and emissions is available in Annex 3.6. See Methodology for Estimating CH_4 and CO_2 Emissions from Natural Gas Systems.

Table 3-54: CH_4 Emissions from Natural Gas Systems (MMT CO_2 Eq.)[a]

Stage	1990	2005	2012	2013	2014	2015	2016
Exploration[b]	**4.0**	**11.0**	**2.5**	**3.0**	**1.0**	**1.1**	**0.7**
Production	**67.7**	**88.5**	**106.5**	**106.9**	**107.8**	**108.0**	**106.8**
Onshore Production	35.8	50.3	52.0	51.5	48.4	46.2	45.4
Offshore Production	3.5	4.3	3.8	3.8	3.8	3.8	3.8
Gathering and Boosting[c]	28.4	33.8	50.8	51.7	55.7	58.2	57.7
Processing	**21.3**	**11.6**	**10.0**	**10.8**	**11.0**	**11.0**	**11.2**
Transmission and Storage	**58.6**	**34.7**	**28.1**	**30.9**	**32.3**	**34.1**	**32.8**
Distribution	**43.5**	**23.3**	**12.4**	**12.3**	**12.2**	**12.0**	**12.0**
Total	**195.2**	**169.1**	**159.6**	**163.8**	**164.3**	**166.3**	**163.5**

[a] These values represent CH_4 emitted to the atmosphere. CH_4 that is captured, flared, or otherwise controlled (and not emitted to the atmosphere) has been calculated and removed from emission totals.

[b] Exploration includes well drilling, testing, and completions.

[c] Gathering and boosting includes gathering and boosting stations, gathering pipeline leaks, and gathering and boosting station episodic events.

Note: Totals may not sum due to independent rounding.

Table 3-55: CH_4 Emissions from Natural Gas Systems (kt)[a]

Stage	1990	2005	2012	2013	2014	2015	2016
Exploration[b]	**161**	**439**	**101**	**119**	**39**	**42**	**30**
Production	**2,708**	**3,541**	**4,261**	**4,276**	**4,313**	**4,322**	**4,272**
Onshore Production	1,432	2,014	2,081	2,062	1,936	1,848	1,815
Offshore Production	141	173	151	151	151	151	151
Gathering and Boosting[c]	1,136	1,354	2,029	2,064	2,226	2,324	2,307
Processing	**853**	**463**	**401**	**430**	**441**	**441**	**448**
Transmission and Storage	**2,343**	**1,389**	**1,125**	**1,237**	**1,292**	**1,365**	**1,311**
Distribution	**1,741**	**932**	**496**	**490**	**488**	**481**	**480**
Total	**7,806**	**6,765**	**6,384**	**6,553**	**6,572**	**6,651**	**6,541**

[a] These values represent CH_4 emitted to the atmosphere. CH_4 that is captured, flared, or otherwise controlled (and not emitted to the atmosphere) has been calculated and removed from emission totals.

[b] Exploration includes well drilling, testing, and completions.

[c] Gathering and boosting includes gathering and boosting stations, gathering pipeline leaks, and gathering and boosting station episodic events.

Note: Totals may not sum due to independent rounding.

Table 3-56: Calculated Potential CH_4 and Captured/Combusted CH_4 from Natural Gas Systems (MMT CO_2 Eq.)

	1990	2005	2012	2013	2014	2015	2016
Calculated Potential[a]	**195.2**	**183.0**	**175.6**	**178.9**	**179.4**	**181.4**	**178.6**
Exploration	4.0	11.0	2.5	3.0	1.0	1.1	0.7
Production	67.7	94.0	113.3	113.8	114.8	115.0	113.7
Processing	21.3	11.6	10.0	10.8	11.0	11.0	11.2
Transmission and Storage	58.6	43.2	37.3	39.1	40.5	42.3	40.9
Distribution	43.5	23.3	12.4	12.3	12.2	12.0	12.0
Captured/Combusted	**NA**	**13.9**	**16.0**	**15.1**	**15.1**	**15.1**	**15.1**
Exploration	NA	NA	NA	NA	NA	NA	NA
Production	NA	5.5	6.8	6.9	6.9	6.9	6.9
Processing	NA	NA	NA	NA	NA	NA	NA
Transmission and Storage	NA	8.4	9.2	8.2	8.2	8.2	8.2
Distribution	NA	NA	NA	NA	NA	NA	NA
Net Emissions	**195.2**	**169.1**	**159.6**	**163.8**	**164.3**	**166.3**	**163.5**
Exploration	4.0	11.0	2.5	3.0	1.0	1.1	0.7
Production	67.7	88.5	106.5	106.9	107.8	108.0	106.8
Processing	21.3	11.6	10.0	10.8	11.0	11.0	11.2
Transmission and Storage	58.6	34.7	28.1	30.9	32.3	34.1	32.8
Distribution	43.5	23.3	12.4	12.3	12.2	12.0	12.0

[a] In this context, "potential" means the total emissions calculated before voluntary reductions and regulatory controls are applied.

NA (Not Applicable)

Note: Totals may not sum due to independent rounding.

Table 3-57: Non-combustion CO_2 Emissions from Natural Gas Systems (MMT)

Stage	1990	2005	2012	2013	2014	2015	2016
Exploration	0.4	1.8	1.3	1.2	0.9	0.3	0.1
Production	0.9	1.7	2.7	3.0	3.3	3.4	3.2
Processing	28.3	18.9	19.1	20.5	21.0	21.0	22.0
Transmission and Storage	0.2	0.1	0.1	0.1	0.1	0.1	0.1
Distribution	0.1	+	+	+	+	+	+
Total	**29.8**	**22.5**	**23.3**	**24.8**	**25.3**	**24.9**	**25.5**

+ Does not exceed 0.1 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table 3-58: Non-combustion CO_2 Emissions from Natural Gas Systems (kt)

Stage	1990	2005	2012	2013	2014	2015	2016
Exploration	404	1,761	1,323	1,159	851	287	138
Production	871	1,709	2,683	3,003	3,278	3,396	3,212
Processing	28,338	18,875	19,120	20,508	21,044	21,044	22,009
Transmission and Storage	166	140	135	142	148	147	143
Distribution	51	27	15	14	14	14	14
Total	**29,831**	**22,512**	**23,276**	**24,827**	**25,336**	**24,888**	**25,516**

Note: Totals may not sum due to independent rounding.

Methodology

See Annex 3.6 for the full time series of emissions data, activity data, and emission factors, and additional information on methods and data sources—for example, the specific years of reporting data from EPA's Greenhouse Gas Reporting Program (GHGRP) that are used to develop certain factors.

This section provides a general overview of the methodology for natural gas emission estimates in the Inventory, which involves the calculation of CH_4 and CO_2 emissions for over 100 emissions sources, and then the summation of emissions for each natural gas segment.

The approach for calculating emissions for natural gas systems generally involves the application of emission factors to activity data. For most sources, the approach uses technology-specific emission factors or emission factors that vary over time and take into account changes to technologies and practices, which are used to calculate net emissions directly. For others, the approach uses what are considered "potential methane factors" and reduction data to calculate net emissions.

Emission Factors. Key references for emission factors for CH_4 and non-combustion-related CO_2 emissions from the U.S. natural gas industry include a 1996 study published by the Gas Research Institute (GRI) and EPA (GRI/EPA 1996), the EPA's GHGRP (EPA 2017), and others.

The EPA/GRI study developed over 80 CH_4 emission factors to characterize emissions from the various components within the operating stages of the U.S. natural gas system. The EPA/GRI study was based on a combination of process engineering studies, collection of activity data, and measurements at representative gas facilities conducted in the early 1990s. Year-specific natural gas CH_4 compositions are calculated using U.S. Department of Energy's Energy Information Administration (EIA) annual gross production for National Energy Modeling System (NEMS) oil and gas supply module regions in conjunction with data from the Gas Technology Institute (GTI, formerly GRI) Unconventional Natural Gas and Gas Composition Databases (GTI 2001). These year-specific CH_4 compositions are applied to emission factors, which therefore may vary from year to year due to slight changes in the CH_4 composition for each NEMS region.

GHGRP Subpart W data were used to develop both CH_4 and CO_2 emission factors for several sources in the Inventory. In the onshore production segment, GHGRP data were used to develop emission factors used for all time series years for well testing, gas well completions and workovers with and without hydraulic fracturing, pneumatic controllers and chemical injection pumps, condensate tanks, liquids unloading, and miscellaneous flaring. In the processing segment, for recent years of the times series, GHGRP data were used to develop emission factors for fugitives, compressors, flares, dehydrators, and blowdowns/venting. In the transmission and storage segment, for recent years of the times series, GHGRP data were used to develop factors for pneumatic controllers.

Other data sources used for CH_4 emission factors include Marchese et al. (2015) for gathering stations, Zimmerle et al. (2015) for transmission and storage station fugitives and compressors, and Lamb et al. (2015) for recent years for distribution pipelines and meter/regulator stations.

For sources in the exploration, production and processing segments that use emission factors not directly calculated from GHGRP data, data from the 1996 GRI/EPA study and a 2001 GTI publication were used to adapt the CH_4 emission factors into non-combustion related CO_2 emission factors. For sources in the transmission and storage segment that use emission factors not directly calculated from GHGRP data, and for sources in the distribution segment, data from the 1996 GRI/EPA study and a 1993 GTI publication were used to adapt the CH_4 emission factors into non-combustion related CO_2 emission factors. See Annex 3.6 for more detailed information on the methodology and data used to calculate CH_4 and non-combustion CO_2 emissions from natural gas systems.

Activity Data. Activity data were taken from various published data sets, as detailed in Annex 3.6. Key activity data sources include data sets developed and maintained by EPA's GHGRP; DrillingInfo, Inc.; U.S. Department of the Interior's Bureau of Ocean Energy Management, Regulation and Enforcement (BOEMRE, previously Minerals and Management Service); Federal Energy Regulatory Commission (FERC); EIA; the Natural Gas STAR Program annual emissions savings data; Oil and Gas Journal; PHMSA; the Wyoming Conservation Commission; and the Alabama State Oil and Gas Board.

For a few sources, recent direct activity data are not available. For these sources, either 2015 data were used as a proxy for 2016 data, or a set of industry activity data drivers was developed and used to calculate activity data over the time series. Drivers include statistics on gas production, number of wells, system throughput, miles of various kinds of pipe, and other statistics that characterize the changes in the U.S. natural gas system infrastructure and operations. More information on activity data and drivers is available in Annex 3.6.

A complete list of references for emission factors and activity data by emission source is provided in Annex 3.6.

Calculating Net Emissions. For most sources, net emissions are calculated directly by applying emission factors to activity data. Emission factors used in net emission approaches reflect technology-specific information, and take into account regulatory and voluntary reductions. However, for certain sectors, some sources are calculated using potential emission factors, and the step of deducting CH_4 that is not emitted from the total CH_4 potential estimates to develop net CH_4 emissions is applied. To take into account use of such technologies and practices that result in lower emissions but are not reflected in "potential" emission factors, data are collected on both regulatory and voluntary reductions. Regulatory actions addressed using this method include National Emission Standards for Hazardous Air Pollutants (NESHAP) regulations for dehydrator vents. Voluntary reductions included in the Inventory are those reported to Natural Gas STAR for certain sources in the production and transmission and storage segments.

In fall of 2015, a well in a California storage field began leaking methane at an initial average rate of around 50 metric tons (MT) of methane (CH_4) an hour, and continued leaking until it was permanently sealed in February of 2016.[86] An emission estimate from the leak event was included for 2015 and 2016, using the estimate of the leak published by the California Air Resources Board (99,638 MT CH_4 for the duration of the leak). The 2015 and 2016 emission estimates of 78,350 MT CH_4 and 21,288 MT CH_4, respectively, were added to the 2015 and 2016 estimates of fugitive emissions from storage wells. For more information, please see *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2015: Update for Storage Segment Emissions*.[87]

Through EPA's stakeholder process on oil and gas in the Inventory, EPA received initial stakeholder feedback on updates under consideration for the Inventory. Stakeholder feedback is noted below in Uncertainty and Time-Series Consistency, Recalculations Discussion, and Planned Improvements.

Uncertainty and Time-Series Consistency

In recent years, EPA has made significant revisions to the Inventory methodology to use updated activity and emissions data. To update its characterization of uncertainty, EPA has conducted a quantitative uncertainty analysis using the IPCC Approach 2 methodology (Monte Carlo Simulation technique). For more information, please see the memorandum *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2016: Natural Gas and Petroleum Systems Uncertainty Estimates* (*2018 Uncertainty Memo).*[88] EPA used Microsoft Excel's @RISK add-in tool to estimate the 95 percent confidence bound around CH_4 emissions from natural gas systems for the current Inventory, then applied the calculated bounds to both CH_4 and CO_2 emissions estimates. For the analysis, EPA focused on the 16 highest-emitting sources for the year 2016, which together emitted 78 percent of methane from natural gas systems in 2016, and extrapolated the estimated uncertainty for the remaining sources. The @RISK add-in provides for the specification of probability density functions (PDFs) for key variables within a computational structure that mirrors the calculation of the inventory estimate. The IPCC guidance notes that in using this method, "some uncertainties that are not addressed by statistical means may exist, including those arising from omissions or double counting, or other conceptual errors, or from incomplete understanding of the processes that may lead to inaccuracies in estimates developed from models." The uncertainty bounds reported below only reflect those uncertainties that EPA has been able to quantify and do not incorporate considerations such as modeling uncertainty, data representativeness, measurement errors, misreporting or misclassification. The understanding of the uncertainty of emission estimates for this category evolves and improves as the underlying methodologies and datasets improve.

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[86] For more information on the Aliso Canyon event, and the measurements conducted of the leak, please see Ensuring Safe and Reliable Underground Natural Gas Storage, *Final Report of the Interagency Task Force on Natural Gas Storage Safety*, available at <http://www.energy.gov/sites/prod/files/2016/10/f33/Ensuring%20Safe%20and%20Reliable%20Underground%20Natural%20Gas%20Storage%20-%20Final%20Report.pdf>.

[87] <https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems-ghg-inventory-additional-information-1990-2015-ghg>.

[88] See < https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems>.

The results presented below provide the 95 percent confidence bound within which actual emissions from this source category are likely to fall for the year 2016, using the IPCC methodology. The results of the Approach 2 uncertainty analysis are summarized in Table 3-59. Natural gas systems CH_4 emissions in 2016 were estimated to be between 138.0 and 191.8 MMT CO_2 Eq. at a 95 percent confidence level. Natural gas systems non-energy CO_2 emissions in 2016 were estimated to be between 21.5 and 29.9 MMT CO_2 Eq. at a 95 percent confidence level. Uncertainty bounds for other years of the time series have not been calculated, but uncertainty is expected to vary over the time series. For example, years where many emission sources are calculated with interpolated data would likely have higher uncertainty than years with predominantly year-specific data.

Table 3-59: Approach 2 Quantitative Uncertainty Estimates for CH_4 and Non-energy CO_2 Emissions from Natural Gas Systems (MMT CO_2 Eq. and Percent)

Source	Gas	2016 Emission Estimate (MMT CO_2 Eq.)[b]	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound[b]	Upper Bound[b]	Lower Bound[b]	Upper Bound[b]
Natural Gas Systems	CH_4	163.5	138.0	191.8	-16%	+17%
Natural Gas Systems[c]	CO_2	25.5	21.5	29.9	-16%	+17%

[a] Range of emission estimates estimated by applying the 95 percent confidence intervals obtained from the Monte Carlo Simulation analysis conducted for the year 2016 CH_4 emissions.

[b] All reported values are rounded after calculation. As a result, lower and upper bounds may not be duplicable from other rounded values as shown in Table 3-54 and Table 3-55.

[c] An uncertainty analysis for the non-energy CO_2 emissions was not performed. The relative uncertainty estimated (expressed as a percent) from the CH_4 uncertainty analysis was applied to the point estimate of non-energy CO_2 emissions.

GHGRP data available (starting in 2011) and other recent data sources have improved estimates of emissions from natural gas systems. To develop a consistent time series for 1990 through 2016, for sources with new data, EPA reviewed available information on factors that may have resulted in changes over the time series (e.g., regulations, voluntary actions) and requested stakeholder feedback on trends as well. For most sources, EPA developed annual data for 1993 through 2010 by interpolating activity data or emission factors or both between 1992 and 2011 data points. Information on time-series consistency for sources updated in this year's Inventory can be found in the Recalculations Discussion below, with additional detail provided in supporting memos (relevant memos are cited in the Recalculations Discussion). For detailed documentation of methodologies, please see Annex 3.5.

QA/QC and Verification Discussion

The natural gas emission estimates in the Inventory are continually being reviewed and assessed to determine whether emission factors and activity factors accurately reflect current industry practices. A QA/QC analysis was performed for data gathering and input, documentation, and calculation. QA/QC checks are consistently conducted to minimize human error in the model calculations. EPA performs a thorough review of information associated with new studies, GHGRP data, regulations, public webcasts, and the Natural Gas STAR Program to assess whether the assumptions in the Inventory are consistent with current industry practices. The EPA has a multi-step data verification process for GHGRP data, including automatic checks during data-entry, statistical analyses on completed reports, and staff review of the reported data. Based on the results of the verification process, the EPA follows up with facilities to resolve mistakes that may have occurred.[89]

As in previous years, EPA conducted early engagement and communication with stakeholders on updates prior to public review. EPA held stakeholder workshops on greenhouse gas data for oil and gas in June and October of 2017, and held webinars in April and August of 2017, and March of 2018. In advance of each workshop, EPA released memos detailing updates under consideration and requesting stakeholder feedback. Stakeholder feedback received through these processes is discussed in the Recalculations Discussion and Planned Improvements sections below.

In recent years, several studies have measured emissions at the source level and at the national or regional level and calculated emission estimates that may differ from the Inventory. There are a variety of potential uses of data from

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[89] See <https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf>.

new studies, including replacing a previous estimate or factor, verifying or QA of an existing estimate or factor, and identifying areas for updates. In general, there are two major types of studies related to oil and gas greenhouse gas data: studies that focus on measurement or quantification of emissions from specific activities, processes and equipment, and studies that use tools such as inverse modeling to estimate the level of overall emissions needed to account for measured atmospheric concentrations of greenhouse gases at various scales. The first type of study can lead to direct improvements to or verification of Inventory estimates. In the past few years, EPA has reviewed and in many cases, incorporated data from these data sources. The second type of study can provide general indications on potential over- and under-estimates. A key challenge in using these types of studies to assess Inventory results is having a relevant basis for comparison (i.e., the independent study should assess data from the Inventory and not another data set, such as EDGAR.). In an effort to improve the ability to compare the national-level inventory with measurement results that may be at other scales, a team at Harvard University along with EPA and other coauthors developed a gridded inventory of U.S. anthropogenic methane emissions with 0.1° x 0.1° spatial resolution, monthly temporal resolution, and detailed scale-dependent error characterization.[90] The gridded methane inventory is designed to be consistent with the 2016 *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2014* estimates for the year 2012, which presents national totals.[91]

Recalculations Discussion

EPA received information and data related to the emission estimates through GHGRP reporting, the annual Inventory formal public notice periods, stakeholder feedback on updates under consideration, and new studies. In June and October 2017, EPA released draft memoranda that discussed changes under consideration, and requested stakeholder feedback on those changes. EPA then created updated versions of the memoranda to document the methodology implemented into the current Inventory.[92] Final memoranda cited in the Recalculations Discussion below are, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2016: Revisions to Create Year-Specific Emissions and Activity Factors (2018 Year-Specific Revisions Memo)* and *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2016: Revisions to CO_2 Emissions Estimation Methodologies (2018 CO_2 Memo).*

EPA thoroughly evaluated relevant information available, and made several updates to the Inventory, including: to define an exploration segment separate from production (not a methodological change, but a change in presentation of information); calculate activity and emission factors for well testing and non-hydraulically fractured completions from GHGRP data; using GHGRP data to calculate year-specific emission factors for hydraulically fractured gas well completions and workovers and liquids unloading; recalculate production segment major equipment activity factors using updated GHGRP data; and calculate new CO_2 emission factors for several sources throughout all segments directly from GHGRP data.

The combined impact of revisions to 2015 natural gas sector CH_4 emissions, compared to the previous Inventory, is an increase from 162.4 to 166.3 MMT CO_2 Eq. (3.9 MMT CO_2 Eq., or 2.4 percent). The recalculations resulted in an average increase in CH_4 emission estimates across the 1990 through 2015 time series, compared to the previous Inventory, of 5.1 MMT CO_2 Eq., or 3.1 percent.

The combined impact of revisions to 2015 natural gas sector CO_2 emissions, compared to the previous Inventory, is a decrease from 42.4 to 24.9 MMT CO_2 (17.5 MMT CO_2, or 41 percent). The recalculations resulted in an average decrease in emission estimates across the 1990 through 2015 time series, compared to the previous Inventory, of 10.5 MMT CO_2 Eq., or 29 percent. The decreased estimate results primarily from recalculations related to the reallocation of CO_2 from flaring to petroleum systems from natural gas systems. Previously, data were not available to disaggregate flared emissions between natural gas and petroleum.

In Table 3-60 and Table 3-61 below are categories in Natural Gas Systems with recalculations resulting in a change of greater than 0.05 MMT CO_2 Eq., comparing the previous estimate for 2015 to the current (recalculated) estimate for 2015.

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[90] See <https://www.epa.gov/ghgemissions/gridded-2012-methane-emissions>.

[91] See <https://www.epa.gov/ghgemissions/us-greenhouse-gas-inventory-report-1990-2014>.

[92] Draft and final memoranda for the 1990-2016 Inventory are available here < https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems>

Table 3-60: Recalculations of CO_2 in Natural Gas Systems (MMT CO_2)

Stage and Emission Source	***Previous Estimate Year 2015, 2017 Inventory***	**Current Estimate Year 2015, 2018 Inventory**	**Current Estimate Year 2016, 2018 Inventory**
Exploration	***NA***	**0.3**	**0.1**
HF Completions	*0.1*	0.3	0.1
Production	***17.6***	**3.4**	**3.2**
Miscellaneous Flaring[a]	*17.6*	1.4	1.1
Tanks	+	1.1	1.2
HF Workovers	+	0.1	+
Processing	***23.7***	**21.0**	**22.0**
AGR Vents	*23.6*	14.9	16.6
Plant Grouped Sources	*0.1*	6.1	5.4
Transmission and Storage	**+**	**0.1**	**0.1**
Transmission Flares	*0.0*	0.1	0.1
Distribution	**+**	**+**	**+**
Total	***42.4***	**24.9**	**25.5**

[a] The previous estimate represents flaring from natural gas production, gas processing, and petroleum production.

NA (Not Applicable)

+ Does not exceed 0.05 MMT CO_2.

Table 3-61: Recalculations of CH_4 in Natural Gas Systems (MMT CO_2 Eq.)

Stage and Emission Source	***Previous Estimate Year 2015, 2017 Inventory***	**Current Estimate Year 2015, 2018 Inventory**	**Current Estimate Year 2016, 2018 Inventory**
Exploration	***NA***	**1.1**	**0.7**
Non-HF Completions	+	0.3	0.2
Well Testing	*NE*	0.1	0.0
Production	***106.6***	**108.0**	**106.8**
Miscellaneous Flaring[a]	*NE*	0.1	0.1
HF Workovers	+	0.3	0.4
Liquids Unloading	*5.2*	3.8	3.3
Processing	***111***	**11.0**	**11.2**
Transmission and Storage	***33.7***	**34.1**	**32.8**
Distribution	***11.0***	**0.5**	**0.5**
Total	***162.4***	**166.3**	**163.5**

[a] The previous estimate represents flaring from natural gas production, gas processing, and petroleum production.

NA (Not Applicable)

NE (Not Estimated)

+ Does not exceed 0.05 MMT CO_2 Eq.

Exploration

The natural gas system segments were reorganized for the current Inventory and now include a specific exploration segment to improve conformance with the IPCC guidelines. Exploration activities were previously included under the production segment. The activities included under exploration are hydraulically fractured (HF) gas well completions, gas well completions without HF, well drilling, and well testing. EPA developed a new methodology to estimate emissions from well testing (not during completions) using GHGRP data, revised the methodology for non-HF gas well completions to use GHGRP data, and updated the HF gas well completions methodology for CO_2 emissions. These recalculations are discussed below.

Well Testing

EPA developed a new estimate for gas well testing (during non-completion events) using GHGRP data. In previous Inventories, only well testing conducted as part of a completion event was included. CH_4 and CO_2 emission factors were developed, on a per-event basis, for vented and flared gas well testing events using RY2015 and RY2016 data. EPA developed activity factors (i.e., number of events per gas well) to determine the number of well testing events in a year, also using RY2015 and RY2016 data. GHGRP RY2015 activity and emission factors are applied to all prior years of the time series. Methane emissions from well testing averaged 1.5 kt (or less than 0.05 MMT CO_2 Eq.) over the time series. There was a large decrease in methane emissions from gas well testing from 2015 to 2016 as observed in reported GHGRP data. Carbon dioxide emission from well testing averaged 3.1 kt (or less than 0.05 MMT CO_2) over the time series. See the *2018Year-Specific Revisions Memo* for additional discussion.

Table 3-62: Gas Well Testing National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2012	2013	2014	2015	2016
Non-Completion Well Testing - Vented	949	1,673	2,080	2,054	2,071	2,043	614
Non-Completion Well Testing - Flared	13	23	29	29	29	29	2

Table 3-63: Gas Well Testing National CO_2 Emissions (Metric Tons CO_2)

Source	1990	2005	2012	2013	2014	2015	2016
Non-Completion Well Testing - Vented	30	53	66	65	65	64	39
Non-Completion Well Testing - Flared	1,914	3,375	4,198	4,144	4,179	4,123	323

Non-HF Gas Well Completions

EPA developed new emission factors for controlled and uncontrolled non-HF gas well completions using GHGRP data, and applied the new factors over all time series years. The emission factor for non-HF gas well completions in the Inventory was previously derived from the GRI 1996 study which defines the factor as covering both gas well completions and well flow testing, and based on the assumption that all gas is flared. CH_4 and CO_2 emission factors were developed, on a per-event basis, for vented and flared gas well non-HF completion events using RY2011 through RY2016 GHGRP data. EPA did not revise the overall counts of non-HF gas well completions. For the split between vented and flared events, EPA used GHGRP data for year 2011 forward, and 2011 data (which show 3 percent of events flared) as a proxy for all earlier years. Methane emissions from non-HF completions averaged 8.6 kt CH_4 (or 0.2 MMT CO_2 Eq.) over the time series. The previous estimate was an average of 0.01 kt CH_4 over the time series. Carbon dioxide emission from non-HF completions averaged 7.3 kt (or less than 0.05 MMT CO_2) over the time series. The previous estimate was an average of 0.001 kt CH_4 over the time series. See the *2018 Year-Specific Revisions Memo* for additional discussion.

Table 3-64: Non-HF Gas Well Completions National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2012	2013	2014	2015	2016
Non-HF Completions - Vented	5,713	10,074	11,009	5,890	1,404	13,680	8,065
Non-HF Completions - Flared	20	35	2	39	12	36	89

Table 3-65: Non-HF Gas Well Completions National CO_2 Emissions (Metric Tons CO_2)

Source	1990	2005	2012	2013	2014	2015	2016
Non-HF Completions - Vented	216	381	101	182	72	172	829
Non-HF Completions - Flared	4,643	8,187	565	6,695	2,683	5,909	16,407

HF Gas Well Completions

EPA revised the HF gas well completions CH_4 methodology to calculate year-specific emission factors from GHGRP data. Year-specific emission factors were developed for 2011 through 2016. The 2011 emission factors were then applied for all prior years. The emission factors are also specific to the type of completion event: non-reduced emission completions (REC) with venting, non-REC with flaring, REC with venting, and REC with flaring. The previous methodology calculated an average emission factor from 2011 through 2013 GHGRP emissions data. EPA did not change the activity data methodology for this source, other than to break out HF completions and workovers as separate line items (where completions are included in Exploration and workovers remain within the Production segment). Stakeholder feedback supported the approach of calculating emission factors on an annual basis from 2011-on. See the *2018 Year-Specific Revisions Memo* for additional discussion.

Table 3-66: HF Gas Well Completions National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2012	2013	2014	2015	2016
HF Completions - Non-REC with Venting	151,134	409,344	67,918	94,813	28,287	923	1,210
HF Completions - Non-REC with Flaring	2,140	7,305	3,404	1,623	1,837	781	57
HF Completions - REC with Venting	NO	6,943	11,060	9,238	2,768	14,913	13,775
HF Completions - REC with Flaring	NO	1,984	4,025	4,732	1,608	8,777	5,184
Total Emissions	**153,273**	**425,576**	**86,406**	**110,405**	**34,499**	**25,395**	**20,226**
Previous Estimated Emissions[a]	*119,901*	*338,215*	124,026	94,442	92,931	24,813	*NA*

[a] Completions and workover emissions were calculated together in the previous Inventory. Completion-specific emissions were estimated based on underlying activity data.
NO (Not Occurring)
NA (Not Applicable)

EPA developed new CO_2 emission factors for the four control categories of HF gas well completions using the same GHGRP data sets and methodology used to calculate CH_4 emissions.

Table 3-67: HF Gas Well Completions National CO_2 Emissions (kt CO_2)

Source	1990	2005	2012	2013	2014	2015	2016
HF Completions - Non-REC with Venting	10	28	3	11	2	+	+
HF Completions - Non-REC with Flaring	387	1,322	621	324	487	58	9
HF Completions - REC with Venting	0	3	1	2	+	1	+
HF Completions - REC with Flaring	0	396	693	812	354	218	111
Total Emissions	**387**	**1,748**	**1,318**	**1,148**	**844**	**277**	**120**
Previous Estimated Emissions	*74*	*305*	*99*	*75*	*66*	*66*	*NA*

NA (Not Applicable)
+ Does not exceed 0.5 kt CO_2.

Production

In addition to the memos discussed above, this section references the memorandum, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2015: Revisions for Natural Gas and Petroleum Systems Production Emissions* (*2017 Production Memo*).[93]

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[93] See <https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems-ghg-inventory-additional-information-1990-2015-ghg>.

Non-HF Gas Well Workovers

EPA developed new emission factors for controlled and uncontrolled non-HF gas well workovers using GHGRP data, and applied the new factors over all time series years. The emission factor for non-HF gas well workovers in the Inventory was previously derived from the GRI 1996 study. Methane and CO_2 emission factors were developed, on a per-event basis, for vented and flared gas well non-HF workover events using RY2011 through RY2016 GHGRP data. EPA did not revise the overall counts of non-HF gas well workovers. For the split between vented and flared events, EPA used GHGRP data for year 2011 forward, and interpolated to 100 percent vented and 0 percent flared in year 1992 (GRI basis). Methane emissions from non-HF workovers averaged 0.6 kt CH_4 (or 0.02 MMT CO_2 Eq.) over the time series. The previous estimate was an average of 0.4 kt CH_4 over the time series. Carbon dioxide emission from non-HF workovers averaged 2.2 kt (or less than 0.05 MMT CO_2) over the time series. The previous estimate was an average of 0.03 kt CH_4 over the time series. See the *2018 Year-Specific Revisions Memo* for additional discussion.

Table 3-68: Non-HF Gas Well Workovers National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2012	2013	2014	2015	2016
Non-HF Workovers - Vented	509	631	1,486	429	441	525	517
Non-HF Workovers - Flared	NO	19	+	6	2	26	1

NO (Not Occurring)
+ Does not exceed 0.5 mt CH_4.

Table 3-69: Non-HF Gas Well Workovers National CO_2 Emissions (Metric Tons CO_2)

Source	1990	2005	2012	2013	2014	2015	2016
Non-HF Workovers - Vented	30	38	92	24	28	45	25
Non-HF Workovers - Flared	NO	3,164	97	942	548	3,192	5,836

NO (Not Occurring)

HF Gas Well Workovers

EPA revised the HF gas well workovers methodology to calculate year-specific emission factors from GHGRP data. Year-specific emission factors were developed for 2011 through 2016. The 2011 emission factors were then applied for all prior years. The emission factors are also specific to the type of workover event: non-REC with venting, non-REC with flaring, REC with venting, and REC with flaring. The previous methodology calculated an average emission factor from 2011 through 2013 GHGRP emissions data. EPA did not change the activity data methodology for this source, other than to break out HF completions and workovers as separate line items (where completions are included in Exploration and workovers remain within the Production segment). Stakeholder feedback supported the approach of calculating emission factors on an annual basis from 2011-on. See the *2018 Year-Specific Revisions Memo* for additional discussion.

Table 3-70: HF Gas Well Workovers National CH_4 Emissions (MMT CO_2 Eq.)

Source	1990	2005	2012	2013	2014	2015	2016
HF Workovers - Non-REC with Venting	0.6	1.6	1.4	1.7	0.6	0.1	0.2
HF Workovers - Non-REC with Flaring	+	+	+	+	+	+	+
HF Workovers - REC with Venting	NO	+	+	0.1	+	0.2	0.2
HF Workovers - REC with Flaring	NO	+	+	+	+	0.1	+
Total Emissions	**0.6**	**1.7**	**1.5**	**1.8**	**0.7**	**0.3**	**0.4**
Previous Estimated Emissions	*0.5*	*1.2*	*0.5*	*0.2*	*0.2*	+	*NA*

NO (Not Occurring)
NA (Not Applicable)
+ Does not exceed 0.05 MMT CO_2 Eq.

EPA developed new CO_2 emission factors for the four control categories of HF gas well workovers using the same GHGRP data sets and methodology used to calculate CH_4 emissions.

Table 3-71: HF Gas Well Workovers National CO_2 Emissions (kt CO_2)

Source	1990	2005	2012	2013	2014	2015	2016
HF Workovers - Non-REC with Venting	2	4	3	8	2	+	+
HF Workovers - Non-REC with Flaring	64	185	52	69	150	17	11
HF Workovers - REC with Venting	NO	+	+	+	+	+	+
HF Workovers - REC with Flaring	NO	1	10	47	4	59	33
Total Emissions	**65**	**190**	**65**	**125**	**156**	**77**	**44**
Previous Estimated Emissions	*15*	*44*	*26*	*26*	*26*	*26*	*NA*

NO (Not Occurring)
NA (Not Applicable)
+ Does not exceed 0.5 kt CO_2.

Liquids Unloading

EPA revised the liquids unloading methodology to calculate year-specific emission factors from GHGRP data. Year-specific emission factors were developed for 2011 through 2016. The 2011 emission factors were then applied for all prior years. The emission factors are also specific to the type of event: liquids unloading with plunger lifts and liquids unloading without plunger lifts. The previous methodology calculated an average emission factor from 2011 through 2015 GHGRP emissions data. The methodology to calculate activity data did not change from the previous Inventory. Methane emissions from liquids unloading averaged 8.6 MMT CO_2 Eq. over the time series, which is an average increase across the time series of 14 percent (or 1.1 MMT CO_2 Eq.).

Table 3-72: Liquids Unloading National CH_4 Emissions (MMT CO_2 Eq.)

Source	1990	2005	2012	2013	2014	2015	2016
Unloading with Plunger Lifts	NO	3.0	3.9	2.9	1.9	1.5	1.5
Unloading without Plunger Lifts	9.5	6.1	2.3	2.6	3.1	2.3	1.8
Total Emissions	**9.5**	**9.1**	**6.3**	**5.5**	**5.1**	**3.8**	**3.3**
Previous Estimated Emissions	*8.8*	*7.5*	*5.4*	*5.4*	*5.4*	*5.2*	NA

NO (Not Occurring)

EPA developed new CO_2 emission factors for liquids unloading using the same GHGRP data sets and methodology used to calculate CH_4 emissions. CO_2 emissions from liquids unloading averaged 63.1 kt CO_2 over the time series, which is an average decrease across the time series of 93 kt CO_2, or 53 percent. Stakeholder feedback supported calculating emissions using a year-specific and basin-level approach. EPA analyzed approaches of calculating year-specific emissions at a basin level and at the national level and found that calculated results from the two approaches were very similar. See the *2018 Year-Specific Revisions Memo* for additional discussion.

Table 3-73: Liquids Unloading National CO_2 Emissions (kt CO_2)

Source	1990	2005	2012	2013	2014	2015	2016
Unloading with Plunger Lifts	NO	10	23	5	3	2	3
Unloading without Plunger Lifts	85	55	32	7	7	5	3
Total Emissions	**85**	**65**	**55**	**12**	**11**	**7**	**6**
Previous Estimated Emissions	*236*	*179*	*40*	*40*	*39*	*39*	NA

NO (Not Occurring)
NA (Not Applicable)

Activity Data Updates

Well Counts

EPA has used a more recent version of the DrillingInfo data set to update well counts data in the Inventory. There are not methodological changes to this source in the 2018 Inventory or major changes to the activity data, but because this is a key input, results are highlighted here.

Table 3-74: Producing Gas Well Count Data

Gas Well Count	1990		2005		2012	2013	2014	2015	2016
Number of Gas Wells	197,626		348,470		433,390	427,828	431,446	425,651	416,881
Previous Estimate	*202,628*		*355,234*		*438,672*	*431,926*	*433,941*	*421,893*	*NA*

NA (Not Applicable)

In December 2017, EIA released a 2000 through 2016 time series of national oil and gas well counts. EIA total (oil and gas) well counts for 2016 were 1,010,441. EPA's total well counts were 978,845. Over the 2000 through 2016 time series, EPA's well counts were on average 2 percent lower than EIA's. EIA's well counts include side tracks, completions, and recompletions, and therefore are expected to be higher than EPA's which include only producing wells. EPA and EIA use different thresholds for distinguishing between oil and gas (EIA uses 6 mcf/bbl, while EPA uses 100 mcf/bbl), which results in EIA having a lower fraction of oil wells and a higher fraction of gas wells than EPA. Across the 2000 through 2016 EIA time series, EIA estimates (which include multiple well categories, as noted above) on average 128,335 (or 31 percent) more gas wells in each year than EPA's gas well counts (which include only producing wells).

Equipment Counts

EPA recalculated activity factors of equipment per well using the GHGRP RY2015 data. This resulted in changes across the time series. For example, the number of heaters per well decreased by 20 percent over the time series, the number of chemical injection pumps per well decreased by 4 percent, and the number of dehydrators per well increased by 5 percent. The impact of the changes in equipment counts per well along with changes in well counts resulted in changes in methane emissions across the time series for heaters (-21 percent), chemical injection pumps (-6 percent), and dehydrators (+3 percent).

CO_2 Updates

EPA updated CO_2 emissions for a number of sources in the production segment. See the *2018 CO_2 Memo* for more details. The overall impact was an average decrease of 8.9 MMT CO_2 (or 74 percent) over the time series, which is partially due to the reallocation of CO_2 emissions from associated gas and miscellaneous onshore production flaring from natural gas systems to petroleum systems, which was not possible in the past because the previous data source aggregated flaring activity data from both petroleum and natural gas systems, but is now possible through use of the GHGRP data.

Sources with the largest impacts include miscellaneous production flaring (decrease of 10.2 MMT CO_2 on average over the time series), and tanks (increase of 0.5 MMT CO_2 over the time series). These sources are discussed in detail below. Other sources recalculated had increases or decreases of less than 0.5 MMT CO_2 (and certain CO_2 updates were already discussed above).

Miscellaneous Production Flaring

EPA developed new estimates for CO_2 and CH_4 emissions from miscellaneous production flaring using GHGRP subpart W data. Along with other updates to flaring emissions in both oil and gas production, this replaces the estimate for onshore flaring that was previously reported in the natural gas systems CO_2 emissions totals. EPA used a production-based scaling and basin-level aggregation approach to calculate emissions from this source. To implement the production-based scaling approach, EPA apportioned miscellaneous production flaring emissions reported to GHGRP (as "flare stacks" emissions) between natural gas and petroleum systems according to the reported counts of gas and oil wells at each facility, then calculated production type-specific emission factors as emissions per unit gas or unit oil production. To implement the basin-level approach, EPA evaluated basin-level miscellaneous production flaring data reported to GHGRP from 2011 to 2016; if a basin contributed at least 10 percent of total annual emissions (on a CO_2 Eq. basis) from flare stacks in any year, then basin-specific emission factors and activity data were developed. Three basins met this criteria: Gulf Coast, Williston, and Permian. Miscellaneous production flaring data in all other basins were combined, and emission factors and activity data developed for the other basins as a single group. For each basin or group, emission factors were calculated for 2015 and 2016, an emission factor of 0 was assumed for 1990 through 1992, and linear interpolation was applied to develop emission factors for 1993 through 2014. Stakeholder feedback supports this approach to calculating emission from miscellaneous production flaring.

Table 3-75: Miscellaneous Production Flaring National CO_2 Emissions (kt CO_2)

Source	1990	2005	2012	2013	2014	2015	2016
Miscellaneous Flaring-Gulf Coast Basin	NO	170	228	274	323	361	246
Miscellaneous Flaring-Williston Basin	NO	+	+	+	+	+	+
Miscellaneous Flaring-Permian Basin	NO	270	398	454	561	674	474
Miscellaneous Flaring-Other Basins	NO	132	312	329	357	380	409
Miscellaneous Flaring-National Total	NO	**572**	**938**	**1,057**	**1,241**	**1,415**	**1,129**
Previous Estimated emissions from flaring (natural gas and petroleum)[a]	*9,093*	*7,193*	*12,704*	*15,684*	*17,629*	*17,629*	*NA*

[a] The previous estimated emissions from flaring included emissions from multiple sources in the production and processing segments, and also included petroleum systems flaring emissions.

NO (Not Occurring)

NA (Not Applicable)

+ Does not exceed 0.5 kt CO_2.

Table 3-76: Miscellaneous Production Flaring National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2012	2013	2014	2015	2016
Miscellaneous Flaring-Gulf Coast Basin	NO	608	815	977	1,152	1,288	672
Miscellaneous Flaring-Williston Basin	NO	+	+	+	+	+	+
Miscellaneous Flaring-Permian Basin	NO	1,197	1,767	2,017	2,490	2,992	2,095
Miscellaneous Flaring-Other Basins	NO	569	1,345	1,418	1,540	1,639	1,895
Miscellaneous Flaring-National Total	NO	**2,374**	**3,926**	**4,411**	**5,182**	**5,918**	**4,662**
Previous Estimated emissions from flaring (natural gas and petroleum)[a]	*NE*	*NE*	*NE*	*NE*	*NE*	*NE*	*NA*

[a] Prior Inventories did not estimate methane emissions from a source similar to miscellaneous production flaring.

NO (Not Occurring)

NE (Not Estimated)

NA (Not Applicable)

+ Does not exceed 0.5 MT CH_4.

Tanks

EPA developed CO_2 emissions estimates for condensate tanks using GHGRP data and a throughput-based approach. This approach is identical to the methodology to calculate CH_4 emissions; for more information, please see the *2017 Production Memo*. The overall impact of the change is an average increase in calculated CO_2 emissions of 0.5 MMT CO_2 over the time series.

Table 3-77: National Condensate Tank Emissions by Category and National Emissions (kt CO_2)

CO_2 Emissions	1990	2005	2012	2013	2014	2015	2016
Large Tanks w/ Flares	287	363	819	985	1,030	1,041	1,172
Large Tanks w/ VRU	NO	1	2	3	3	3	3
Large Tanks w/o Control	1	+	+	1	1	1	1
Small Tanks w/ Flares	NO	9	27	33	35	35	35
Small Tanks w/o Flares	6	4	8	9	10	10	13
Malfunctioning Dump Valves	+	+	+	+	+	+	+
Total Emissions	**294**	**378**	**857**	**1,030**	**1,078**	**1,089**	**1,224**
Previous Estimated Emissions	*12*	*12*	*25*	*30*	*30*	*30*	*NA*

NA (Not Applicable)
NO (Not Occurring)
+ Does not exceed 0.5 kt CO_2.

Gas STAR Revisions

EPA updated the methodology to calculate Gas STAR reductions for the production segment. Most Gas STAR reductions in the production segment are not directly attributable to specific sources, and are therefore grouped together as “other” reductions. However, because most emission sources in the production segment use a net approach to calculate emissions, applying all of the “other” reductions is not warranted, since many reduction activities within this grouping likely pertain to sources that use a net calculation approach. Therefore, EPA calculates a scaling factor to apply to the "other" reductions for the production segment, so that only a fraction of such reductions is used in emission calculations. The “other” reductions scaling factor is calculated as one minus the sum of emissions from sources with net approaches, divided by the sum of all production segment emissions. This approach was updated this year to increase accuracy by including offshore platform emissions as a net source (previously it was not), and to include regulatory reductions in the denominator (they were previously excluded from the analysis). The GasSTAR reductions from 2013 were also applied directly to the following years, as year-specific Gas STAR reductions data have not been processed after year 2013. As a result of the update, Gas STAR reductions averaged 3.8 MMT CO_2 Eq. over the time series, which is an average decrease across the time series of 7 percent (or 0.5 MMT CO_2 Eq.).

Table 3-78: Production Segment Gas STAR Reductions (MMT CO_2 Eq.)

CH_4 reductions	1990	2005	2012	2013	2014	2015	2016
Gas STAR Reductions	NA	5.2	6.6	6.7	6.7	6.7	6.7
Previous Estimate	*NA*	*5.5*	*7.7*	*7.9*	*8.4*	*9.0*	*NA*

NA (Not Applicable)

Processing

There were no updates to the CH_4 emissions estimation methodology for the processing segment. Updates to activity data resulted in a minor decrease (less than 0.1 MMT CO_2 Eq., or 0.5 percent) in CH_4 emissions estimates for this segment across the time series. EPA updated CO_2 emissions for a number of sources in the processing segment to use emission factors directly calculated from subpart W data. See the *2018 CO_2 Memo* for more details. The overall impact was an average decrease of 1.7 MMT CO_2 (or 8 percent) over the time series, which is primarily due to the incorporation of GHGRP data for acid gas removal vents. Acid gas removal CO_2 emissions decreased by an average of 4.7 MMT CO_2, or 21 percent over the time series. Incorporation of GHGRP data for flaring in processing increased emissions by 3.0 MMT CO_2.

Table 3-79: Processing CO_2 Updates, National Emissions (kt CO_2)

Source	1990	2005	2012	2013	2014	2015	2016
Acid Gas Removal	28,282	15,320	13,579	14,565	14,946	14,946	16,565
Previous Acid Gas Removal	*27,708*	*21,694*	*21,404*	*21,690*	*23,643*	*23,643*	*NA*

Processing-flaring	*0*	*3,516*	5,502	5,902	6,056	6,056	5,404
Previous processing flaring [a]	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*

NA (Not Applicable)

[a] The previous estimated emissions from flaring included emissions from multiple sources in the natural gas and petroleum production segments, and natural gas processing segment. The previous estimate was presented as a single emission source in the natural gas systems production segment.

Transmission and Storage

Changes in the estimates for CH_4 from transmission and storage include the addition of flaring emissions, recalculations due to updated data (e.g., GHGRP station counts, the GHGRP split between dry and wet seal centrifugal compressors, and GHGRP pneumatic controller data), and adjustments to GasSTAR data. These changes resulted in an average increase in calculated methane emissions over the time series from this segment of 1.2 MMT CO_2 Eq., or 3 percent.

Additional information on inclusion of the Aliso Canyon emissions can be found in the Methodology section above and in the memorandum *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2015: Update to Storage Segment Emissions*[94] and not in the Recalculation Discussion section as it did not involve recalculation of a previous year of the Inventory.

Table 3-80: Transmission and Storage CH_4 Updates to Flaring, National Emissions (MT CH_4)

Source	1990	2005	2012	2013	2014	2015	2016
Transmission-flaring*	307	276	281	303	326	326	395
Storage-flaring*	235	223	231	232	232	227	198
Previous flaring (transmission and storage)	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*

NA (Not Applicable)

*Estimates are developed from GHGRP data, wherein compressor stations that service underground storage fields might be classified as transmission compression as the primary function. A significant fraction of the transmission station flaring emissions presented in this table likely occurs at stations that service storage facilities; such stations typically require flares, compared to a typical transmission compressor station used solely for mainline compression that does not require liquids separation, dehydration, and flaring.

EPA updated CO_2 emissions for pneumatic controllers and flares in the transmission and storage segment. See the *2018 CO_2 Memo* for more details. The overall impact was an average increase of 0.1 MMT CO_2 (or by a factor of 3) over the time series. The updated CO_2 data for pneumatic controllers increased estimated emissions from pneumatic controllers by less than 0.01 MMT CO_2, or 53 percent over the time series. The addition of an estimate for flares increased CO_2 emissions from transmission and storage by an average of 0.1 MMT CO_2 over the time series.

Table 3-81: Transmission and Storage CO_2 Updates, National Emissions (kt CO_2)

Source	1990	2005	2012	2013	2014	2015	2016
Transmission-pneumatic controllers	6.3	4.0	2.9	3.0	0.9	0.8	0.7
Previous transmission pneumatic controllers	*6.1*	*2.1*	*0.6*	*0.8*	*0.8*	*0.8*	*NA*
Storage-pneumatic controllers	1.3	1.2	1.0	1.0	0.9	0.6	1.0
Previous Storage pneumatic controllers	*1.3*	*1.0*	0.7	0.9	0.8	0.8	*NA*
Transmission-flaring*	78.8	71.0	72.2	78.0	83.7	83.9	88.4
Storage-flaring*	24.5	23.2	24.0	24.1	24.1	23.6	15.3
Previous flaring (transmission and storage)	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*

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[94] See <https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems-ghg-inventory-additional-information-1990-2015-ghg>.

NA (Not Applicable)
* Estimates are developed from GHGRP data, wherein compressor stations that service underground storage fields might be classified as transmission compression as the primary function. A significant fraction of the transmission station flaring emissions presented in this table likely occurs at stations that service storage facilities; such stations typically require flares, compared to a typical transmission compressor station used solely for mainline compression that does not require liquids separation, dehydration, and flaring.

Gas STAR Revisions

EPA reviewed the GasSTAR data reported for the transmission and storage segment and made the following revisions. EPA removed the transmission station fugitives reductions (as this source was previously updated to use a net emissions approach) and certain "other" reductions because the emissions are minimal, and most transmission and storage sources have net emissions approaches. The GasSTAR reductions from 2013 were also applied directly to the following years. As a result of the revisions, Gas STAR reductions averaged 5.4 MMT CO_2 Eq. over the time series, which is an average decrease across the time series of 19 percent (or 1.2 MMT CO_2 Eq.).

Table 3-82: Transmission and Storage Segment Gas STAR Reductions (MMT CO_2 Eq.)

CH_4 reductions	1990	2005	2012	2013	2014	2015	2016
Gas STAR reductions	NA	8.4	9.2	8.2	8.2	8.2	8.2
Previous Estimate	*NA*	*12.4*	9.4	8.3	8.4	8.5	*NA*

NA (Not Applicable)

Distribution

There were no methodological updates to the distribution segment, but there were GasSTAR revisions and recalculations due to updated data (e.g., GHGRP M&R station counts) that resulted in an average increase in calculated emissions over the time series from this segment of 1.2 MMT CO_2 Eq. CH_4 (or 6.3 percent) and less than 0.01 MMT CO_2 (or 1.9 percent).

Gas STAR revisions

EPA reviewed the GasSTAR data reported for the distribution segment and removed all GasSTAR reductions. EPA removed the mishaps/dig-ins and distribution main blowdown reductions, because in reviewing recent measurement data compared to current emission factors, it was determined it was inappropriate to apply the Gas STAR reduction data. EPA also removed the "other" GasSTAR reductions because most distribution segment sources have net emissions approaches (including the sources most likely related to the "other" reductions).

Table 3-83: Distribution Segment Gas STAR Reductions (MMT CO_2 Eq.)

CH_4 reductions	1990	2005	2012	2013	2014	2015	2016
Gas STAR reductions	NA	NA	NA	NA	NA	NA	NA
Previous Estimate	*NA*	*1.2*	*1.1*	*1.0*	*1.0*	*1.0*	*NA*

NA (Not Applicable)

Planned Improvements

EPA seeks stakeholder feedback on the improvements noted below for future Inventories.

Gathering and Boosting and Transmission Pipeline GHGRP Data

EPA will continue to review data available from its GHGRP, in particular new data on gathering and boosting stations, gathering pipelines, and transmission pipeline blowdowns and new well-specific information, available in

2017 (for reporting year 2016) for the first time. EPA will consider revising its methods to take into account the new GHGRP data.

Liquids Unloading

The emissions and activity data methodology used in the current Inventory rely exclusively on recently collected data (from 2011 or later). EPA is evaluating the liquids unloading data collected for the 1996 GRI/EPA study to determine if it better represents early time series years.

Year-Specific Emission Factors

EPA will continue to consider the development of year-specific emission factors, using GHGRP data, for sources with annual emissions currently calculated with data from one year or an average of a several years.

Well-Related Activity Data

As described in the Recalculations Discussion, EPA has updated the emission factors for several well-related emission sources, including testing, completions, and workovers. EPA will continue to assess available data, including data from the GHGRP and stakeholder feedback on considerations, to improve activity estimates for sources that rely on well-related activity data. For example, EPA will review GHGRP data regarding reported well workover rates; review DrillingInfo data to possibly estimate numbers of wells drilled in recent years (as the current EIA data source is not maintained after 2010); and seek information on other data sets that might inform estimates of non-hydraulically fractured oil well completions and workovers.

LNG Segment Emissions

The current Inventory estimates emissions from LNG storage stations and LNG import terminals in the transmission and storage segment of natural gas systems. The emission factors are based on the 1996 GRI/EPA study, which developed emission factors using underground natural gas storage and transmission compressor station data; specific emissions data for LNG storage stations and LNG import terminals were not available in the GRI/EPA study. EPA's GHGRP subpart W collects data from LNG storage and LNG import and export facilities that meet a reporting threshold of 25,000 metric tons of CO_2 equivalent (MT CO_2 Eq.) emissions. EPA is considering approaches and seeking stakeholder feedback on incorporating GHGRP data to improve LNG emissions estimates in the Inventory. Refer to the memorandum *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2016: Additional Revisions Under Consideration* (*2018 Other Updates Memo)*[95] for additional details. Incorporating GHGRP data would likely decrease emissions from this segment.

N_2O Emissions

N_2O emissions are currently not included in petroleum systems estimates, but EPA is considering developing a methodology to estimate N_2O emissions. The *2018 Other Updates Memo* provides discussion on this topic. EPA will consider options such as using GHGRP data directly for sources that already rely on GHGRP data for CH_4 or CO_2 estimates. GHGRP RY2015 and RY2016 reported N_2O flaring emissions specific to natural gas systems were 26 metric tons (or less than 0.01 MMT CO_2 Eq.) and 14 metric tons (or less than 0.01 MMT CO_2 Eq.), respectively. In addition, reported N_2O flaring emissions were 36 metric tons N_2O (or 0.01 MMT CO_2 Eq.) and 48 metric tons (or 0.01 MMT CO_2 Eq.) for GHGRP RY2015 and RY2016, respectively, for sources that fall within both natural gas and petroleum systems.

Offshore Platforms

EPA is considering updates to the offshore platform emissions calculation methodology, as discussed in the *2018 Other Updates Memo*. The current emission factors were based on data from the 2011 DOI/Bureau of Ocean Energy

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[95] See < https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems>

Management's (BOEM) Gulf Offshore Activity Data System (GOADS), and 2014 GOADS data is available. A different source for platform counts is also being considered.

Upcoming Data, and Additional Data that Could Inform the Inventory

EPA will assess new data received by the Methane Challenge Program on an ongoing basis, which may be used to confirm or improve existing estimates and assumptions.

EPA continues to track studies that contain data that may be used to update the Inventory. Key studies in progress include: DOE-funded work on vintage and new plastic pipelines (distribution segment), industrial meters (distribution segment), and sources within the gathering and storage segments[96]; an API field study on pneumatic controllers; and a Pipeline Research Council International (PRCI) project in which researchers are gathering and analyzing subpart W data on transmission compressor stations and underground storage facilities. EPA will also continue to assess studies that include and compare both top-down and bottom-up estimates, and which could lead to improved understanding of unassigned high emitters (e.g., identification of emission sources and information on frequency of high emitters) as recommended in stakeholder comments.

EPA also continues to seek new data that could be used to assess or update the estimates in the Inventory. For example, stakeholder comments have highlighted areas where additional data that could inform the Inventory are currently limited or unavailable:

- Tank malfunction and control efficiency data.
- Consider updating engine emission factors, including using subpart W data to the extent possible, and considering whether and how to represent differences between rich- and lean-burn engines.
- Activity data and emissions data for production facilities that do not report to GHGRP.
- Natural gas leaks at point of use estimates. A recent study (Lavoie et al. 2017) measured three natural gas power plants and found them to be large sources of natural gas leak emissions, and the stakeholder suggested that EPA evaluate the study and any additional information available on this source. At least one country, the United Kingdom, includes an emission estimate for residential and commercial customer natural gas use leaks (e.g., domestic heating boiler cycling and pre-ignition losses from domestic and commercial gas appliances) in its national greenhouse gas emissions inventory; the EPA seeks available data to estimate emissions from this source in the U.S. Stakeholder feedback (one stakeholder) supports use of data from Lavoie et al. or use of the U.K. approach to calculate emissions from this source.

One stakeholder suggested that the Inventory should be updated with site-level and basin-level data, noting EPA could first use basin-level data to assess the Inventory, and that future research could focus on collecting data in basins with the largest discrepancies.

EPA will continue to seek available data on these and other sources as part of the process to update the Inventory.

3.8 Abandoned Oil and Gas Wells (CRF Source Categories 1B2a and 1B2b)

The term "abandoned wells" encompasses various types of wells:

- Wells with no recent production, and not plugged. Common terms (such as those used in state databases) might include: inactive, temporarily abandoned, shut-in, dormant, and idle.
- Wells with no recent production and no responsible operator. Common terms might include: orphaned, deserted, long-term idle, and abandoned.
- Wells that have been plugged to prevent migration of gas or fluids.

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[96] See <https://www.energy.gov/under-secretary-science-and-energy/articles/doe-announces-13-million-quantify-and-mitigate-methane>.

The U.S. population of abandoned wells is around 3.1 million (with around 2.6 million abandoned oil wells and 0.6 million abandoned gas wells). Abandoned wells emit both CH_4 and CO_2. Wells that are plugged have much lower emissions than wells that are unplugged (less than 1 kg CH_4 per well per year, versus over 100 kg CH_4 per well per year). Around 30 percent of the abandoned well population in the United States is plugged. This fraction has increased over the time series (from around 19 percent in 1990) as more wells fall under regulations and programs requiring or promoting plugging of abandoned wells.

Abandoned oil wells. Abandoned oil wells emitted 230 kt CH_4 and 5 kt CO_2 in 2016. Emissions of both gases increased by 3 percent from 1990, as the total population of abandoned oil wells increased 25 percent. Emissions of both gases decreased by 1 percent between 2015 and 2016 as a result of well plugging activities.

Abandoned gas wells. Abandoned gas wells emitted 54 kt CH_4 in 2016 and 2 kt CO_2. Emissions of both gases increased by 51 percent from 1990, as the total population of abandoned gas wells increased 73 percent. Emissions of both gases decreased by 1 percent between 2015 and 2016 as a result of well plugging activities.

Table 3-84: CH_4 Emissions from Abandoned Oil and Gas Wells (MMT CO_2 Eq.)

Activity	1990	2005	2012	2013	2014	2015	2016
Abandoned Oil Wells	5.6	5.8	5.8	5.8	5.8	5.8	5.8
Abandoned Gas Wells	0.9	1.1	1.2	1.2	1.3	1.4	1.4
Total	**6.5**	**6.9**	**7.0**	**7.0**	**7.1**	**7.2**	**7.1**

Note: Totals may not sum due to independent rounding.

Table 3-85: CH_4 Emissions from Abandoned Oil and Gas Wells (kt)

Activity	1990	2005	2012	2013	2014	2015	2016
Abandoned Oil Wells	224	233	231	230	230	232	230
Abandoned Gas Wells	36	42	48	50	52	55	54
Total	**260**	**275**	**279**	**280**	**282**	**286**	**284**

Note: Totals may not sum due to independent rounding.

Table 3-86: CO_2 Emissions from Abandoned Oil and Gas Wells (MMT CO_2)

Activity	1990	2005	2012	2013	2014	2015	2016
Abandoned Oil Wells	+	+	+	+	+	+	+
Abandoned Gas Wells	+	+	+	+	+	+	+
Total	**+**	**+**	**+**	**+**	**+**	**+**	**+**

+ Does not exceed 0.05 MMT CO_2.

Table 3-87: CO_2 Emissions from Abandoned Oil and Gas Wells (kt)

Activity	1990	2005	2012	2013	2014	2015	2016
Abandoned Oil Wells	5	5	5	5	5	5	5
Abandoned Gas Wells	2	2	2	2	2	2	2
Total	**6**	**7**	**7**	**7**	**7**	**7**	**7**

Note: Totals may not sum due to independent rounding.

Methodology

EPA developed abandoned well CH_4 emission factors using data from Kang et al. (2016) and Townsend-Small et al. (2016). Plugged and unplugged abandoned well CH_4 emission factors were developed at the national-level (emission data from Townsend-Small et al.) and for the Appalachia region (using emission data from measurements in Pennsylvania and Ohio conducted by Kang et al. and Townsend-Small et al., respectively). The Appalachia region emissions factors were applied to abandoned wells in states in the Appalachian basin region, and the national-level emission factors were applied to all other abandoned wells.

EPA developed abandoned well CO_2 emission factors using the CH_4 emission factors and an assumed ratio of CO_2-to-CH_4 gas content, similar to the approach used to calculate CO_2 emissions for many sources in Petroleum Systems and Natural Gas Systems. For abandoned oil wells, EPA used the Petroleum Systems default production segment associated gas ratio of 0.020 MT CO_2/MT CH_4, which was derived through API TankCalc modeling runs. For abandoned gas wells, EPA used the Natural Gas Systems default production segment CH_4 and CO_2 gas content values (GRI/EPA 1996, GTI 2001) to develop a ratio of 0.044 MT CO_2/MT CH_4.

The total population of abandoned wells over the time series was estimated using historical data and DrillingInfo data. The abandoned well population was then split into plugged and unplugged wells by assuming that all abandoned wells were unplugged in 1950, 31 percent of abandoned wells were plugged in 2016 (based on an analysis of DrillingInfo data), and applying linear interpolation for intermediate years. See the memorandum *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2016: Abandoned Wells in Natural Gas and Petroleum Systems (2018 Abandoned Wells Memo)* for details.[97]

Abandoned Oil Wells

Table 3-88: Abandoned Oil Wells Activity Data, CH_4 and CO_2 Emissions (Metric Tons)

Source	1990	2005	2012	2013	2014	2015	2016
Plugged abandoned oil wells	382,446	610,884	719,901	736,830	754,118	776,450	788,396
Unplugged abandoned oil wells	1,666,399	1,769,214	1,768,266	1,769,425	1,770,862	1,783,308	1,771,362
Total Abandoned Oil Wells	2,048,846	2,380,098	2,488,167	2,506,255	2,524,980	2,559,758	2,559,758
Abandoned oil wells in Appalachia	26%	24%	24%	23%	23%	23%	23%
Abandoned oil wells outside of Appalachia	74%	76%	76%	77%	77%	77%	77%
CH_4 from plugged abandoned oil wells (MT)	314	471	539	549	560	574	582
CH_4 from unplugged abandoned oil wells (MT)	223,780	232,546	230,070	229,885	229,735	231,011	229,464
Total CH_4 from Abandoned oil wells (MT)	224,094	233,017	230,609	230,434	230,295	231,585	230,046
Total CO_2 from Abandoned oil wells (MT)	4,547	4,728	4,679	4,676	4,673	4,699	4,668

Abandoned Gas Wells

Table 3-89: Abandoned Gas Wells Activity Data, CH_4 and CO_2 Emissions (Metric Tons)

Source	1990	2005	2012	2013	2014	2015	2016
Plugged abandoned gas wells	59,480	103,379	138,537	146,187	156,144	167,011	169,580
Unplugged abandoned gas wells	259,166	299,402	340,284	351,053	366,666	383,580	381,011
Total Abandoned Gas Wells	318,645	402,781	478,821	497,239	522,810	550,591	550,591
Abandoned gas wells in Appalachia	28%	29%	30%	30%	30%	30%	30%
Abandoned gas wells outside of Appalachia	72%	71%	70%	70%	70%	70%	70%
CH_4 from plugged abandoned gas wells (MT)	53	96	131	139	149	159	162
CH_4 from unplugged abandoned gas wells (MT)	35,810	42,064	48,176	49,754	52,024	54,483	54,118
Total $CH_4$from abandoned gas wells (MT)	35,863	42,160	48,307	49,893	52,173	54,643	54,280

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[97] See <https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems>

Total CO_2 from abandoned gas wells (MT)	1,572		1,848		2,117	2,187	2,287	2,395	2,379

Uncertainty and Time-Series Consistency

To characterize uncertainty surrounding estimates of abandoned well emissions, EPA conducted a quantitative uncertainty analysis using the IPCC Approach 2 methodology (Monte Carlo simulation technique). See the *2018 Abandoned Wells Memo* for the uncertainty analysis details. EPA used Microsoft Excel's @RISK add-in tool to estimate the 95 percent confidence bound around total methane emissions from abandoned oil and gas wells, then applied the calculated bounds to both CH_4 and CO_2 emissions estimates for each population. The @RISK add-in provides for the specification of probability density functions (PDFs) for key variables within a computational structure that mirrors the calculation of the inventory estimate. EPA used measurement data from the Kang et al. (2016) and Townsend-Small et al. (2016) studies to characterize the CH_4 emission factor PDFs. For activity data inputs (e.g., total count of abandoned wells, split between plugged and unplugged), EPA assigned default uncertainty bounds of +/- 10 percent based on expert judgment.

The IPCC guidance notes that in using this method, "some uncertainties that are not addressed by statistical means may exist, including those arising from omissions or double counting, or other conceptual errors, or from incomplete understanding of the processes that may lead to inaccuracies in estimates developed from models." As a result, the understanding of the uncertainty of emission estimates for this category evolves and improves as the underlying methodologies and datasets improve. The uncertainty bounds reported below only reflect those uncertainties that EPA has been able to quantify and do not incorporate considerations such as modeling uncertainty, data representativeness, measurement errors, misreporting or misclassification.

The results presented below in Table 3-90 provide the 95 percent confidence bound within which actual emissions from abandoned oil and gas wells are likely to fall for the year 2016, using the recommended IPCC methodology. Abandoned oil well CH_4 emissions in 2016 were estimated to be between 1.0 and 18.1 MMT CO_2 Eq., while abandoned gas well CH_4 emissions were estimated to be between 0.2 and 4.3 MMT CO_2 Eq. at a 95 percent confidence level. Uncertainty bounds for other years of the time series have not been calculated, but uncertainty is expected to vary over the time series.

Table 3-90: Approach 2 Quantitative Uncertainty Estimates for CH_4 and CO_2 Emissions from Petroleum and Natural Gas Systems (MMT CO_2 Eq. and Percent)

Source	Gas	2016 Emission Estimate (MMT CO_2 Eq.)[b]	Uncertainty Range Relative to Emission Estimate[a]			
			(MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Abandoned Oil Wells	CH_4	5.8	1.0	18.1	-83%	+215%
Abandoned Gas Wells	CH_4	1.4	0.2	4.3	-83%	+215%
Abandoned Oil Wells	CO_2	0.005	0.001	0.015	-83%	+215%
Abandoned Gas Wells	CO_2	0.007	0.001	0.022	-83%	+215%

[a] Range of emission estimates estimated by applying the 95 percent confidence intervals obtained from the Monte Carlo Simulation analysis conducted for the year 2016 for total abandoned oil and gas well CH_4 emissions.

[b] All reported values are rounded after calculation. As a result, lower and upper bounds may not be duplicable from other rounded values as shown in table.

To calculate a time series of emissions for abandoned wells, EPA developed annual activity data for 1990 through 2016 by summing an estimate of total abandoned wells not included in recent databases, to an annual estimate of abandoned wells in the DrillingInfo data set. As discussed above, the abandoned well population was split into plugged and unplugged wells by assuming that all abandoned wells were unplugged in 1950, 31 percent of abandoned wells were plugged in 2016 (based on an analysis of DrillingInfo data), and applying linear interpolation for intermediate years. The same emission factors were applied to the corresponding categories for each year of the time series.

QA/QC and Verification Discussion

The emission estimates in the Inventory are continually being reviewed and assessed to determine whether emission factors and activity factors accurately reflect current industry practices. A QA/QC analysis was performed for data gathering and input, documentation, and calculation. QA/QC checks are consistently conducted to minimize human error in the model calculations.

As in previous years, EPA conducted early engagement and communication with stakeholders on updates prior to public review. EPA held stakeholder workshops on greenhouse gas data for oil and gas in June and October of 2017, and held webinars in April and August of 2017 and March of 2018. In advance of each workshop, EPA released memos detailing updates under consideration and requesting stakeholder feedback. Stakeholder feedback received through these processes is discussed in the Planned Improvements sections below.

Planned Improvements

Through EPA's stakeholder process on oil and gas in the Inventory, EPA received initial stakeholder feedback on the abandoned wells update to the Inventory. Stakeholders noted varying definitions regarding abandoned well populations and subpopulations and plugging status, and noted varying degrees of plugging, due to state-level programs to plug abandoned wells. A stakeholder noted limited coverage of abandoned wells studies in the U.S., and cautioned that it may be premature to develop national level estimates for this source, while another stakeholder supported the inclusion of this emission sources and noted that the update uses the best available data for this source.

EPA will also continue to assess new data and stakeholder feedback on considerations (such as the disaggregation of the well population into Appalachia and other regions) to improve the abandoned well count estimates and emission factors.

3.9 Energy Sources of Indirect Greenhouse Gas Emissions

In addition to the main greenhouse gases addressed above, many energy-related activities generate emissions of indirect greenhouse gases. Total emissions of nitrogen oxides (NO_x), carbon monoxide (CO), and non-CH_4 volatile organic compounds (NMVOCs) from energy-related activities from 1990 to 2016 are reported in Table 3-91.

Table 3-91: NO_x, CO, and NMVOC Emissions from Energy-Related Activities (kt)

Gas/Activity	1990	2005	2012	2013	2014	2015	2016
NO_x	**21,106**	**16,602**	**11,271**	**10,747**	**10,161**	**9,323**	**8,352**
Mobile Fossil Fuel Combustion	10,862	10,295	6,871	6,448	6,024	5,417	4,814
Stationary Fossil Fuel Combustion	10,023	5,858	3,655	3,504	3,291	3,061	2,692
Oil and Gas Activities	139	321	663	704	745	745	745
Waste Combustion	82	128	82	91	100	100	100
International Bunker Fuels[a]	*1,956*	*1,704*	*1,398*	*1,139*	*1,139*	*1,226*	*1,322*
CO	**125,640**	**64,985**	**42,164**	**40,239**	**38,315**	**36,348**	**34,401**
Mobile Fossil Fuel Combustion	119,360	58,615	36,153	34,000	31,848	29,881	27,934
Stationary Fossil Fuel Combustion	5,000	4,648	4,027	3,884	3,741	3,741	3,741
Waste Combustion	978	1,403	1,318	1,632	1,947	1,947	1,947
Oil and Gas Activities	302	318	666	723	780	780	780
International Bunker Fuels[a]	*103*	*133*	*133*	*129*	*135*	*141*	*146*
NMVOCs	**12,620**	**7,191**	**7,558**	**7,357**	**7,154**	**6,867**	**6,581**
Mobile Fossil Fuel Combustion	10,932	5,724	4,243	3,924	3,605	3,318	3,032
Oil and Gas Activities	554	510	2,651	2,786	2,921	2,921	2,921
Stationary Fossil Fuel Combustion	912	716	569	539	507	507	507
Waste Combustion	222	241	94	108	121	121	121
International Bunker Fuels[a]	*57*	*54*	*46*	*41*	*42*	*47*	*50*

[a] These values are presented for informational purposes only and are not included in totals.
Note: Totals may not sum due to independent rounding. The values for International Bunker Fuels in 2016 were updated on 4/16 to address an error.

Methodology

Emission estimates for 1990 through 2016 were obtained from data published on the National Emission Inventory (NEI) Air Pollutant Emission Trends web site (EPA 2016), and disaggregated based on EPA (2003). Emission estimates for 2012 and 2013 for non-electric generating units (EGU) were updated to the most recent available data in EPA (2016). Emission estimates for 2012 and 2013 for non-mobile sources are recalculated emissions by interpolation from 2016 in EPA (2016). Emissions were calculated either for individual categories or for many categories combined, using basic activity data (e.g., the amount of raw material processed) as an indicator of emissions. National activity data were collected for individual applications from various agencies.

Activity data were used in conjunction with emission factors, which together relate the quantity of emissions to the activity. Emission factors are generally available from the EPA's *Compilation of Air Pollutant Emission Factors, AP-42* (EPA 1997). The EPA currently derives the overall emission control efficiency of a source category from a variety of information sources, including published reports, the 1985 National Acid Precipitation and Assessment Program emissions inventory, and other EPA databases.

Uncertainty and Time-Series Consistency

Uncertainties in these estimates are partly due to the accuracy of the emission factors used and accurate estimates of activity data. A quantitative uncertainty analysis was not performed.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2016. Details on the emission trends through time are described in more detail in the Methodology section, above.

3.10 International Bunker Fuels (CRF Source Category 1: Memo Items)

Emissions resulting from the combustion of fuels used for international transport activities, termed international bunker fuels under the UNFCCC, are not included in national emission totals, but are reported separately based upon location of fuel sales. The decision to report emissions from international bunker fuels separately, instead of allocating them to a particular country, was made by the Intergovernmental Negotiating Committee in establishing the Framework Convention on Climate Change.[98] These decisions are reflected in the IPCC methodological guidance, including IPCC (2006), in which countries are requested to report emissions from ships or aircraft that depart from their ports with fuel purchased within national boundaries and are engaged in international transport separately from national totals (IPCC 2006).[99]

Two transport modes are addressed under the IPCC definition of international bunker fuels: aviation and marine.[100] Greenhouse gases emitted from the combustion of international bunker fuels, like other fossil fuels, include CO_2, CH_4 and N_2O for marine transport modes, and CO_2 and N_2O for aviation transport modes. Emissions from ground

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[98] See report of the Intergovernmental Negotiating Committee for a Framework Convention on Climate Change on the work of its ninth session, held at Geneva from 7 to 18 February 1994 (A/AC.237/55, annex I, para. 1c).

[99] Note that the definition of international bunker fuels used by the UNFCCC differs from that used by the International Civil Aviation Organization.

[100] Most emission related international aviation and marine regulations are under the rubric of the International Civil Aviation Organization (ICAO) or the International Maritime Organization (IMO), which develop international codes, recommendations, and conventions, such as the International Convention of the Prevention of Pollution from Ships (MARPOL).

transport activities—by road vehicles and trains—even when crossing international borders are allocated to the country where the fuel was loaded into the vehicle and, therefore, are not counted as bunker fuel emissions.

The *2006 IPCC Guidelines* distinguish between different modes of air traffic. Civil aviation comprises aircraft used for the commercial transport of passengers and freight, military aviation comprises aircraft under the control of national armed forces, and general aviation applies to recreational and small corporate aircraft. The *2006 IPCC Guidelines* further define international bunker fuel use from civil aviation as the fuel combusted for civil (e.g., commercial) aviation purposes by aircraft arriving or departing on international flight segments. However, as mentioned above, and in keeping with the *2006 IPCC Guidelines*, only the fuel purchased in the United States and used by aircraft taking-off (i.e., departing) from the United States are reported here. The standard fuel used for civil aviation is kerosene-type jet fuel, while the typical fuel used for general aviation is aviation gasoline.[101]

Emissions of CO_2 from aircraft are essentially a function of fuel use. Nitrous oxide emissions also depend upon engine characteristics, flight conditions, and flight phase (i.e., take-off, climb, cruise, decent, and landing). Recent data suggest that little or no CH_4 is emitted by modern engines (Anderson et al. 2011), and as a result, CH_4 emissions from this category are considered zero. In jet engines, N_2O is primarily produced by the oxidation of atmospheric nitrogen, and the majority of emissions occur during the cruise phase. International marine bunkers comprise emissions from fuels burned by ocean-going ships of all flags that are engaged in international transport. Ocean-going ships are generally classified as cargo and passenger carrying, military (i.e., U.S. Navy), fishing, and miscellaneous support ships (e.g., tugboats). For the purpose of estimating greenhouse gas emissions, international bunker fuels are solely related to cargo and passenger carrying vessels, which is the largest of the four categories, and military vessels. Two main types of fuels are used on sea-going vessels: distillate diesel fuel and residual fuel oil. Carbon dioxide is the primary greenhouse gas emitted from marine shipping.

Overall, aggregate greenhouse gas emissions in 2016 from the combustion of international bunker fuels from both aviation and marine activities were 117.7 MMT CO_2 Eq., or 12.6 percent above emissions in 1990 (see Table 3-92 and Table 3-93). Emissions from international flights and international shipping voyages departing from the United States have increased by 94.7 percent and decreased by 35.1 percent, respectively, since 1990. The majority of these emissions were in the form of CO_2; however, small amounts of CH_4 (from marine transport modes) and N_2O were also emitted.

Table 3-92: CO_2, CH_4, and N_2O Emissions from International Bunker Fuels (MMT CO_2 Eq.)

Gas/Mode	1990	2005	2012	2013	2014	2015	2016
CO_2	**103.5**	**113.1**	**105.8**	**99.8**	**103.4**	**110.9**	**116.6**
Aviation	38.0	60.1	64.5	65.7	69.6	71.9	74.1
Commercial	*30.0*	*55.6*	*61.4*	*62.8*	*66.3*	*68.6*	*70.8*
Military	*8.1*	*4.5*	*3.1*	*2.9*	*3.3*	*3.3*	*3.3*
Marine	65.4	53.0	41.3	34.1	33.8	38.9	42.5
CH_4	**0.2**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Aviation[a]	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Marine	0.2	0.1	0.1	0.1	0.1	0.1	0.1
N_2O	**0.9**	**1.0**	**0.9**	**0.9**	**0.9**	**0.9**	**1.0**
Aviation	0.4	0.6	0.6	0.6	0.7	0.7	0.7
Marine	0.5	0.4	0.3	0.2	0.2	0.3	0.3
Total	**104.5**	**114.2**	**106.8**	**100.7**	**104.4**	**111.9**	**117.7**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] CH_4 emissions from aviation are estimated to be zero.

Notes: Totals may not sum due to independent rounding. Includes aircraft cruise altitude emissions.

Table 3-93: CO_2, CH_4, and N_2O Emissions from International Bunker Fuels (kt)

Gas/Mode	1990	2005	2012	2013	2014	2015	2016
CO_2	**103,463**	**113,139**	**105,805**	**99,763**	**103,400**	**110,887**	**116,594**
Aviation	38,034	60,125	64,524	65,664	69,609	71,942	74,059

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[101] Naphtha-type jet fuel was used in the past by the military in turbojet and turboprop aircraft engines.

Marine	65,429	53,014	41,281	34,099	33,791	38,946	42,535
CH_4	**7**	**5**	**4**	**3**	**3**	**3**	**4**
Aviation[a]	0	0	0	0	0	0	0
Marine	7	5	4	3	3	3	4
N_2O	**3**	**3**	**3**	**3**	**3**	**3**	**3**
Aviation	1	2	2	2	2	2	2
Marine	2	1	1	1	1	1	1

[a] CH_4 emissions from aviation are estimated to be zero.

Notes: Totals may not sum due to independent rounding. Includes aircraft cruise altitude emissions.

Methodology

Emissions of CO_2 were estimated by applying C content and fraction oxidized factors to fuel consumption activity data. This approach is analogous to that described under Section 3.1 – CO_2 from Fossil Fuel Combustion. Carbon content and fraction oxidized factors for jet fuel, distillate fuel oil, and residual fuel oil were taken directly from EIA and are presented in Annex 2.1, Annex 2.2, and Annex 3.8 of this Inventory. Density conversions were taken from Chevron (2000), ASTM (1989), and USAF (1998). Heat content for distillate fuel oil and residual fuel oil were taken from EIA (2018) and USAF (1998), and heat content for jet fuel was taken from EIA (2018). A complete description of the methodology and a listing of the various factors employed can be found in Annex 2.1. See Annex 3.8 for a specific discussion on the methodology used for estimating emissions from international bunker fuel use by the U.S. military.

Emission estimates for CH_4 and N_2O were calculated by multiplying emission factors by measures of fuel consumption by fuel type and mode. Emission factors used in the calculations of CH_4 and N_2O emissions were obtained from the *2006 IPCC Guidelines* (IPCC 2006). For aircraft emissions, the following value, in units of grams of pollutant per kilogram of fuel consumed (g/kg), was employed: 0.1 for N_2O (IPCC 2006). For marine vessels consuming either distillate diesel or residual fuel oil the following values (g/MJ), were employed: 0.32 for CH_4 and 0.08 for N_2O. Activity data for aviation included solely jet fuel consumption statistics, while the marine mode included both distillate diesel and residual fuel oil.

Activity data on domestic and international aircraft fuel consumption were developed by the U.S. Federal Aviation Administration (FAA) using radar-informed data from the FAA Enhanced Traffic Management System (ETMS) for 1990, 2000 through 2016 as modeled with the Aviation Environmental Design Tool (AEDT). This bottom-up approach is built from modeling dynamic aircraft performance for each flight occurring within an individual calendar year. The analysis incorporates data on the aircraft type, date, flight identifier, departure time, arrival time, departure airport, arrival airport, ground delay at each airport, and real-world flight trajectories. To generate results for a given flight within AEDT, the radar-informed aircraft data is correlated with engine and aircraft performance data to calculate fuel burn and exhaust emissions. Information on exhaust emissions for in-production aircraft engines comes from the International Civil Aviation Organization (ICAO) Aircraft Engine Emissions Databank (EDB). This bottom-up approach is in accordance with the Tier 3B method from the *2006 IPCC Guidelines* (IPCC 2006).

International aviation CO_2 estimates for 1990 and 2000 through 2016 are obtained from FAA's AEDT model (FAA 2017). The radar-informed method that was used to estimate CO_2 emissions for commercial aircraft for 1990, and 2000 through 2016 is not possible for 1991 through 1999 because the radar data set is not available for years prior to 2000. FAA developed OAG schedule-informed inventories modeled with AEDT and great circle trajectories for 1990, 2000 and 2010. Because fuel consumption and CO_2 emission estimates for years 1991 through 1999 are unavailable, consumption estimates for these years were calculated using fuel consumption estimates from the Bureau of Transportation Statistics (DOT 1991 through 2013), adjusted based on 2000 through 2005 data.

Data on U.S. Department of Defense (DoD) aviation bunker fuels and total jet fuel consumed by the U.S. military was supplied by the Office of the Under Secretary of Defense (Installations and Environment), DoD. Estimates of the percentage of each Service's total operations that were international operations were developed by DoD. Military aviation bunkers included international operations, operations conducted from naval vessels at sea, and operations conducted from U.S. installations principally over international water in direct support of military operations at sea. Military aviation bunker fuel emissions were estimated using military fuel and operations data synthesized from unpublished data from DoD's Defense Logistics Agency Energy (DLA Energy 2017). Together, the data allow the quantity of fuel used in military international operations to be estimated. Densities for each jet fuel type were obtained from a report from the U.S. Air Force (USAF 1998). Final jet fuel consumption estimates are presented in Table 3-94. See Annex 3.8 for additional discussion of military data.

Activity data on distillate diesel and residual fuel oil consumption by cargo or passenger carrying marine vessels departing from U.S. ports were taken from unpublished data collected by the Foreign Trade Division of the U.S. Department of Commerce's Bureau of the Census (DOC 2017) for 1990 through 2001, 2007 through 2016, and the Department of Homeland Security's *Bunker Report* for 2003 through 2006 (DHS 2008). Fuel consumption data for 2002 was interpolated due to inconsistencies in reported fuel consumption data. Activity data on distillate diesel consumption by military vessels departing from U.S. ports were provided by DLA Energy (2017). The total amount of fuel provided to naval vessels was reduced by 21 percent to account for fuel used while the vessels were not-underway (i.e., in port). Data on the percentage of steaming hours underway versus not-underway were provided by the U.S. Navy. These fuel consumption estimates are presented in Table 3-95.

Table 3-94: Aviation Jet Fuel Consumption for International Transport (Million Gallons)

Nationality	1990		2005		2012	2013	2014	2015	2016
U.S. and Foreign Carriers	3,222		5,983		6,604	6,748	7,126	7,383	7,610
U.S. Military	862		462		321	294	339	341	333
Total	**4,084**		**6,445**		**6,925**	**7,042**	**7,465**	**7,725**	**7,943**

Table 3-95: Marine Fuel Consumption for International Transport (Million Gallons)

Fuel Type	1990		2005		2012	2013	2014	2015	2016
Residual Fuel Oil	4,781		3,881		3,069	2,537	2,466	2,718	3,011
Distillate Diesel Fuel & Other	617		444		280	235	261	492	534
U.S. Military Naval Fuels	522		471		381	308	331	326	314
Total	**5,920**		**4,796**		**3,730**	**3,081**	**3,058**	**3,536**	**3,858**

Note: Totals may not sum due to independent rounding.

Uncertainty and Time-Series Consistency

Emission estimates related to the consumption of international bunker fuels are subject to the same uncertainties as those from domestic aviation and marine mobile combustion emissions; however, additional uncertainties result from the difficulty in collecting accurate fuel consumption activity data for international transport activities separate from domestic transport activities.[102] For example, smaller aircraft on shorter routes often carry sufficient fuel to complete several flight segments without refueling in order to minimize time spent at the airport gate or take advantage of lower fuel prices at particular airports. This practice, called tankering, when done on international flights, complicates the use of fuel sales data for estimating bunker fuel emissions. Tankering is less common with the type of large, long-range aircraft that make many international flights from the United States, however. Similar practices occur in the marine shipping industry where fuel costs represent a significant portion of overall operating costs and fuel prices vary from port to port, leading to some tankering from ports with low fuel costs.

Uncertainties exist with regard to the total fuel used by military aircraft and ships, and in the activity data on military operations and training that were used to estimate percentages of total fuel use reported as bunker fuel emissions. Total aircraft and ship fuel use estimates were developed from DoD records, which document fuel sold to the Navy and Air Force from the Defense Logistics Agency. These data may slightly over or under estimate actual total fuel use in aircraft and ships because each Service may have procured fuel from, and/or may have sold to, traded with, and/or given fuel to other ships, aircraft, governments, or other entities. There are uncertainties in aircraft operations and training activity data. Estimates for the quantity of fuel actually used in Navy and Air Force flying activities

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[102] See uncertainty discussions under Carbon Dioxide Emissions from Fossil Fuel Combustion.

reported as bunker fuel emissions had to be estimated based on a combination of available data and expert judgment. Estimates of marine bunker fuel emissions were based on Navy vessel steaming hour data, which reports fuel used while underway and fuel used while not underway. This approach does not capture some voyages that would be classified as domestic for a commercial vessel. Conversely, emissions from fuel used while not underway preceding an international voyage are reported as domestic rather than international as would be done for a commercial vessel. There is uncertainty associated with ground fuel estimates for 1997 through 2001. Small fuel quantities may have been used in vehicles or equipment other than that which was assumed for each fuel type.

There are also uncertainties in fuel end-uses by fuel type, emissions factors, fuel densities, diesel fuel sulfur content, aircraft and vessel engine characteristics and fuel efficiencies, and the methodology used to back-calculate the data set to 1990 using the original set from 1995. The data were adjusted for trends in fuel use based on a closely correlating, but not matching, data set. All assumptions used to develop the estimate were based on process knowledge, Department and military Service data, and expert judgments. The magnitude of the potential errors related to the various uncertainties has not been calculated, but is believed to be small. The uncertainties associated with future military bunker fuel emission estimates could be reduced through additional data collection.

Although aggregate fuel consumption data have been used to estimate emissions from aviation, the recommended method for estimating emissions of gases other than CO_2 in the *2006 IPCC Guidelines* (IPCC 2006) is to use data by specific aircraft type, number of individual flights and, ideally, movement data to better differentiate between domestic and international aviation and to facilitate estimating the effects of changes in technologies. The IPCC also recommends that cruise altitude emissions be estimated separately using fuel consumption data, while landing and take-off (LTO) cycle data be used to estimate near-ground level emissions of gases other than CO_2.[103]

There is also concern regarding the reliability of the existing DOC (2017) data on marine vessel fuel consumption reported at U.S. customs stations due to the significant degree of inter-annual variation.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2016. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

A source-specific QA/QC plan for international bunker fuels was developed and implemented. This effort included a general analysis, as well as portions of a category specific analysis. The category specific procedures that were implemented involved checks specifically focusing on the activity data and emission factor sources and methodology used for estimating CO_2, CH_4, and N_2O from international bunker fuels in the United States. Emission totals for the different sectors and fuels were compared and trends were investigated. No corrective actions were necessary.

Planned Improvements

The feasibility of including data from a broader range of domestic and international sources for bunker fuels, including data from studies such as the *Third IMO GHG Study 2014* (IMO 2014), is being considered.

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[103] U.S. aviation emission estimates for CO, NO_x, and NMVOCs are reported by EPA's National Emission Inventory (NEI) Air Pollutant Emission Trends website, and reported under the Mobile Combustion section. It should be noted that these estimates are based solely upon LTO cycles and consequently only capture near ground-level emissions, which are more relevant for air quality evaluations. These estimates also include both domestic and international flights. Therefore, estimates reported under the Mobile Combustion section overestimate IPCC-defined domestic CO, NO_x, and NMVOC emissions by including landing and take-off (LTO) cycles by aircraft on international flights, but underestimate because they do not include emissions from aircraft on domestic flight segments at cruising altitudes. The estimates in Mobile Combustion are also likely to include emissions from ocean-going vessels departing from U.S. ports on international voyages.

3.11 Wood Biomass and Biofuels Consumption (CRF Source Category 1A)

The combustion of biomass fuels such as wood, charcoal, and wood waste and biomass-based fuels such as ethanol, biogas, and biodiesel generates CO_2 in addition to CH_4 and N_2O already covered in this chapter. In line with the reporting requirements for inventories submitted under the UNFCCC, CO_2 emissions from biomass combustion have been estimated separately from fossil fuel CO_2 emissions and are not directly included in the energy sector contributions to U.S. totals. In accordance with IPCC methodological guidelines, any such emissions are calculated by accounting for net carbon (C) fluxes from changes in biogenic C reservoirs in wooded or crop lands. For a more complete description of this methodological approach, see the Land Use, Land-Use Change, and Forestry chapter (Chapter 6), which accounts for the contribution of any resulting CO_2 emissions to U.S. totals within the Land Use, Land-Use Change, and Forestry sector's approach.

Therefore, CO_2 emissions from wood biomass and biofuel consumption are not included specifically in summing energy sector totals and are instead included in net carbon fluxes from changes in biogenic carbon reservoirs in the estimates for Land Use, Land-Use Change, and Forestry. However, they are presented here for informational purposes and to provide detail on wood biomass and biofuels consumption.

In 2016, total CO_2 emissions from the burning of woody biomass in the industrial, residential, commercial, and electric power sectors were approximately 208.4 MMT CO_2 Eq. (208,354 kt) (see Table 3-96 and Table 3-97). As the largest consumer of woody biomass, the industrial sector was responsible for 66.4 percent of the CO_2 emissions from this source. The residential sector was the second largest emitter, constituting 18.4 percent of the total, while the commercial and electric power sectors accounted for the remainder.

Table 3-96: CO_2 Emissions from Wood Consumption by End-Use Sector (MMT CO_2 Eq.)

End-Use Sector	1990	2005	2012	2013	2014	2015	2016
Industrial	135.3	136.3	137.3	139.8	140.3	138.5	138.3
Residential	59.8	44.3	43.3	59.8	60.9	45.4	38.4
Commercial	6.8	7.2	6.3	7.2	7.8	8.4	8.5
Electric Power	13.3	19.1	19.6	21.4	25.9	25.1	23.1
Total	**215.2**	**206.9**	**206.4**	**228.2**	**234.9**	**217.4**	**208.4**

Note: Totals may not sum due to independent rounding.

Table 3-97: CO_2 Emissions from Wood Consumption by End-Use Sector (kt)

End-Use Sector	1990	2005	2012	2013	2014	2015	2016
Industrial	135,348	136,269	137,256	139,769	140,331	138,537	138,339
Residential	59,808	44,340	43,309	59,808	60,884	45,359	38,419
Commercial	6,779	7,218	6,257	7,235	7,760	8,377	8,457
Electric Power	13,252	19,074	19,612	21,389	25,908	25,146	23,140
Total	**215,186**	**206,901**	**206,434**	**228,200**	**234,884**	**217,418**	**208,354**

Note: Totals may not sum due to independent rounding.

The transportation sector is responsible for most of the fuel ethanol consumption in the United States. Ethanol used for fuel is currently produced primarily from corn grown in the Midwest, but it can be produced from a variety of biomass feedstocks. Most ethanol for transportation use is blended with gasoline to create a 90 percent gasoline, 10 percent by volume ethanol blend known as E-10 or gasohol.

In 2016, the United States transportation sector consumed an estimated 1,143.0 trillion Btu of ethanol, and as a result, produced approximately 78.2 MMT CO_2 Eq. (78,249 kt) (see Table 3-98 and Table 3-99) of CO_2 emissions. Ethanol fuel production and consumption has grown significantly since 1990 due to the favorable economics of blending ethanol into gasoline and federal policies that have encouraged use of renewable fuels.

Table 3-98: CO_2 Emissions from Ethanol Consumption (MMT CO_2 Eq.)

End-Use Sector	1990	2005	2012	2013	2014	2015	2016
Transportation[a]	4.1	22.4	71.5	73.4	74.9	76.0	78.2
Industrial	0.1	0.5	1.1	1.2	1.0	1.2	1.2
Commercial	+	0.1	0.2	0.2	0.2	1.8	1.8
Total	**4.2**	**22.9**	**72.8**	**74.7**	**76.1**	**78.9**	**81.2**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] See Annex 3.2, Table A-95 for additional information on transportation consumption of these fuels.

Note: Totals may not sum due to independent rounding.

Table 3-99: CO_2 Emissions from Ethanol Consumption (kt)

End-Use Sector	1990	2005	2012	2013	2014	2015	2016
Transportation[a]	4,136	22,414	71,510	73,359	74,857	75,981	78,249
Industrial	56	468	1,142	1,202	970	1,201	1,235
Commercial	34	60	175	183	249	1,752	1,766
Total	**4,227**	**22,943**	**72,827**	**74,743**	**76,075**	**78,934**	**81,250**

[a] See Annex 3.2, Table A-95 for additional information on transportation consumption of these fuels.

Note: Totals may not sum due to independent rounding.

The transportation sector is assumed to be responsible for all of the biodiesel consumption in the United States (EIA 2018a). Biodiesel is currently produced primarily from soybean oil, but it can be produced from a variety of biomass feedstocks including waste oils, fats and greases. Biodiesel for transportation use appears in low-level blends (less than 5 percent) with diesel fuel, high-level blends (between 6 and 20 percent) with diesel fuel, and 100 percent biodiesel (EIA 2018b).

In 2016, the United States consumed an estimated 266.1 trillion Btu of biodiesel, and as a result, produced approximately 19.6 MMT CO_2 Eq. (19,648 kt) (see Table 3-100 and Table 3-101) of CO_2 emissions. Biodiesel production and consumption has grown significantly since 2001 due to the favorable economics of blending biodiesel into diesel and federal policies that have encouraged use of renewable fuels (EIA 2018b). There was no measured biodiesel consumption prior to 2001 EIA (2018a).

Table 3-100: CO_2 Emissions from Biodiesel Consumption (MMT CO_2 Eq.)

End-Use Sector	1990	2005	2012	2013	2014	2015	2016
Transportation[a]	0.0	0.9	8.5	13.5	13.3	14.1	19.6
Total	**0.0**	**0.9**	**8.5**	**13.5**	**13.3**	**14.1**	**19.6**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] See Annex 3.2, Table A-95 for additional information on transportation consumption of these fuels.

Note: Totals may not sum due to independent rounding.

Table 3-101: CO_2 Emissions from Biodiesel Consumption (kt)

End-Use Sector	1990	2005	2012	2013	2014	2015	2016
Transportation[a]	0	856	8,470	13,462	13,349	14,077	19,648
Total	**0**	**856**	**8,470**	**13,462**	**13,349**	**14,077**	**19,648**

[a] See Annex 3.2, Table A-95 for additional information on transportation consumption of these fuels.

Note: Totals may not sum due to independent rounding.

Methodology

Woody biomass emissions were estimated by applying two EIA gross heat contents (Lindstrom 2006) to U.S. consumption data (EIA 2018a) (see Table 3-102), provided in energy units for the industrial, residential, commercial, and electric generation sectors. One heat content (16.95 MMBtu/MT wood and wood waste) was applied to the industrial sector's consumption, while the other heat content (15.43 MMBtu/MT wood and wood waste) was applied to the consumption data for the other sectors. An EIA emission factor of 0.434 MT C/MT wood (Lindstrom 2006) was then applied to the resulting quantities of woody biomass to obtain CO_2 emission estimates. It was assumed that the woody biomass contains black liquor and other wood wastes, has a moisture content of 12 percent, and is converted into CO_2 with 100 percent efficiency. The emissions from ethanol consumption were calculated by applying an emission factor of 18.7 MMT C/QBtu (EPA 2010) to U.S. ethanol consumption estimates that were provided in energy units (EIA 2018a) (see Table 3-103). The emissions from biodiesel consumption were calculated by applying an emission factor of 20.1 MMT C/QBtu (EPA 2010) to U.S. biodiesel consumption estimates that were provided in energy units (EIA 2018a) (see Table 3-104).

Table 3-102: Woody Biomass Consumption by Sector (Trillion Btu)

End-Use Sector	1990	2005	2012	2013	2014	2015	2016
Industrial	1,441.9	1,451.7	1,462.2	1,489.0	1,495.0	1,475.9	1,473.8
Residential	580.0	430.0	420.0	580.0	590.4	439.9	372.6
Commercial	65.7	70.0	60.7	70.2	75.3	81.2	82.0
Electric Power	128.5	185.0	190.2	207.4	251.3	243.9	224.4
Total	**2,216.2**	**2,136.7**	**2,133.1**	**2,346.6**	**2,412.0**	**2,240.9**	**2,152.8**

Note: Totals may not sum due to independent rounding.

Table 3-103: Ethanol Consumption by Sector (Trillion Btu)

End-Use Sector	1990	2005	2012	2013	2014	2015	2016
Transportation	60.4	327.4	1,044.6	1,071.6	1,093.5	1,109.9	1,143.0
Industrial	0.8	6.8	16.7	17.6	14.2	17.6	18.0
Commercial	0.5	0.9	2.6	2.7	3.6	25.6	25.8
Total	**61.7**	**335.1**	**1,063.8**	**1,091.8**	**1,111.3**	**1,153.1**	**1,186.9**

Note: Totals may not sum due to independent rounding.

Table 3-104: Biodiesel Consumption by Sector (Trillion Btu)

End-Use Sector	1990	2005	2012	2013	2014	2015	2016
Transportation	0.0	11.6	114.7	182.3	180.8	190.6	266.1
Total	**0.0**	**11.6**	**114.7**	**182.3**	**180.8**	**190.6**	**266.1**

Note: Totals may not sum due to independent rounding.

Uncertainty and Time-Series Consistency

It is assumed that the combustion efficiency for woody biomass is 100 percent, which is believed to be an overestimate of the efficiency of wood combustion processes in the United States. Decreasing the combustion efficiency would decrease emission estimates for CO_2. Additionally, the heat content applied to the consumption of woody biomass in the residential, commercial, and electric power sectors is unlikely to be a completely accurate representation of the heat content for all the different types of woody biomass consumed within these sectors. Emission estimates from ethanol and biodiesel production are more certain than estimates from woody biomass consumption due to better activity data collection methods and uniform combustion techniques.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2016. Details on the emission trends through time are described in more detail in the Methodology section, above.

Recalculations Discussion

EIA updated wood biomass and biofuels consumption statistics across the time series relative to the previous Inventory (EIA 2018a). EIA revised 2010 through 2015 wood energy consumption in the industrial sector, and 2014 through 2015 wood energy consumption in the residential and commercial sectors. Additionally, EIA revised sector allocations of ethanol in 2015, resulting in a shift of ethanol consumption from the industrial and commercial sectors to the transportation sector. Revisions to wood energy consumption resulted in an average annual increase of 3.4 MMT CO_2 Eq. (1.7 percent) in CO_2 emissions from wood consumption for the period 1990 through 2015, relative to the previous Inventory.

Planned Improvements

Future research will look into the availability of data on woody biomass heat contents and carbon emission factors the see if there are newer, improved data sources available for these factors.

The availability of facility-level combustion emissions through EPA's GHGRP will be examined to help better characterize the industrial sector's energy consumption in the United States, and further classify woody biomass consumption by business establishments according to industrial economic activity type. Most methodologies used in EPA's GHGRP are consistent with IPCC, though for EPA's GHGRP, facilities collect detailed information specific to their operations according to detailed measurement standards, which may differ with the more aggregated data collected for the Inventory to estimate total, national U.S. emissions. In addition, and unlike the reporting requirements for this chapter under the UNFCCC reporting guidelines, some facility-level fuel combustion emissions reported under EPA's GHGRP may also include industrial process emissions.[104] In line with UNFCCC reporting guidelines, fuel combustion emissions are included in this chapter, while process emissions are included in the Industrial Processes and Product Use chapter of this report. In examining data from EPA's GHGRP that would be useful to improve the emission estimates for the CO_2 from biomass combustion category, particular attention will also be made to ensure time series consistency, as the facility-level reporting data from EPA's GHGRP are not available for all inventory years as reported in this Inventory. Additionally, analyses will focus on aligning reported facility-level fuel types and IPCC fuel types per the national energy statistics, ensuring CO_2 emissions from biomass are separated in the facility-level reported data, and maintaining consistency with national energy statistics provided by EIA. In implementing improvements and integration of data from EPA's GHGRP, the latest guidance from the IPCC on the use of facility-level data in national inventories will be relied upon.[105]

Currently emission estimates from biomass and biomass-based fuels included in this inventory are limited to woody biomass, ethanol, and biodiesel. Other forms of biomass-based fuel consumption include biogas. An effort will be made to examine sources of data for biogas including data from EIA for possible inclusion. EIA (2018a) natural gas data already deducts biogas used in the natural gas supply so no adjustments are needed to the natural gas fuel consumption data to account for biogas.

As per discussion in Section 3.1, an additional planned improvement is to evaluate and potentially update EPA's method for allocating motor gasoline consumption across the Transportation, Industrial and Commercial sectors to improve accuracy and create a more consistent time series. Further research will be conducted to determine if changes also need to be made to ethanol allocation between these sectors to match gasoline's sectoral distribution.

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[104] See <https://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf#page=2>.

[105] See <http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf>.

4. Industrial Processes and Product Use

The Industrial Processes and Product Use (IPPU) chapter includes greenhouse gas emissions occurring from industrial processes and from the use of greenhouse gases in products. The industrial processes and product use categories included in this chapter are presented in Figure 4-1. Greenhouse gas emissions from industrial processes can occur in two different ways. First, they may be generated and emitted as the byproducts of various non-energy-related industrial activities. Second, they may be emitted due to their use in manufacturing processes or by end-consumers.

In the case of byproduct emissions, the emissions are generated by an industrial process itself, and are not directly a result of energy consumed during the process. For example, raw materials can be chemically or physically transformed from one state to another. This transformation can result in the release of greenhouse gases such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and fluorinated greenhouse gases (e.g., HFC-23). The greenhouse gas byproduct generating processes included in this chapter include iron and steel production and metallurgical coke production, cement production, lime production, other process uses of carbonates (e.g., flux stone, flue gas desulfurization, and glass manufacturing), ammonia production and urea consumption, petrochemical production, aluminum production, HCFC-22 production, soda ash production and use, titanium dioxide production, ferroalloy production, glass production, zinc production, phosphoric acid production, lead production, silicon carbide production and consumption, nitric acid production, adipic acid production, and caprolactam production.

Greenhouse gases that are used in manufacturing processes or by end-consumers include man-made compounds such as hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6), and nitrogen trifluoride (NF_3). The present contribution of HFCs, PFCs, SF_6, and NF_3 gases to the radiative forcing effect of all anthropogenic greenhouse gases is small; however, because of their extremely long lifetimes, many of them will continue to accumulate in the atmosphere as long as emissions continue. In addition, many of these gases have high global warming potentials; SF_6 is the most potent greenhouse gas the Intergovernmental Panel on Climate Change (IPCC) has evaluated. Use of HFCs is growing rapidly since they are the primary substitutes for ozone depleting substances (ODS), which are being phased-out under the Montreal Protocol on Substances that Deplete the Ozone Layer. Hydrofluorocarbons, PFCs, SF_6, and NF_3 are employed and emitted by a number of other industrial sources in the United States, such as semiconductor manufacture, electric power transmission and distribution, and magnesium metal production and processing. Carbon dioxide is also consumed and emitted through various end-use applications. In addition, nitrous oxide is used in and emitted by semiconductor manufacturing and anesthetic and aerosol applications.

In 2016, IPPU generated emissions of 362.1 million metric tons of CO_2 equivalent (MMT CO_2 Eq.), or 5.6 percent of total U.S. greenhouse gas emissions.[1] Carbon dioxide emissions from all industrial processes were 164.7 MMT CO_2 Eq. (164,686 kt CO_2) in 2016, or 3.1 percent of total U.S. CO_2 emissions. Methane emissions from industrial processes resulted in emissions of approximately 0.3 MMT CO_2 Eq. (11 kt CH_4) in 2016, which was less than 1 percent of U.S. CH_4 emissions. Nitrous oxide emissions from IPPU were 23.6 MMT CO_2 Eq. (79 kt N_2O) in 2016, or 6.4 percent of total U.S. N_2O emissions. In 2016 combined emissions of HFCs, PFCs, SF_6, and NF_3 totaled 173.5

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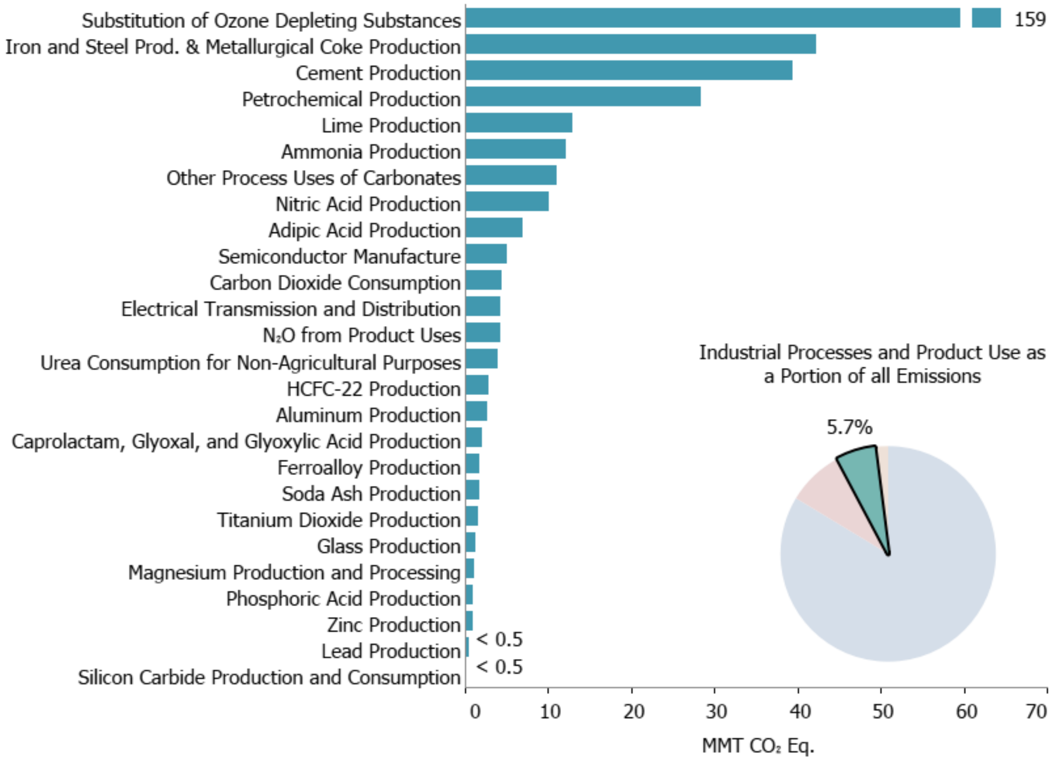
[1] Emissions reported in the IPPU Chapter include those from all 50 states, including Hawaii and Alaska, as well as from U.S. Territories to the extent of which industries are occurring.

$MMT CO_2$ Eq. Total emissions from IPPU in 2016 were 5.9 percent more than 1990 emissions. Indirect greenhouse gas emissions also result from IPPU, and are presented in Table 4-112 in kilotons (kt).

Figure 4-1: 2016 Industrial Processes and Product Use Chapter Greenhouse Gas Sources ($MMT CO_2$ Eq.)



The increase in overall IPPU emissions since 1990 reflects a range of emission trends among the emission sources. Emissions resulting from most types of metal production have declined significantly since 1990, largely due to production shifting to other countries, but also due to transitions to less-emissive methods of production (in the case of iron and steel) and to improved practices (in the case of PFC emissions from aluminum production). Similarly, CO_2 and CH_4 emissions from many chemical production sources have either decreased or not changed significantly since 1990, with the exception of petrochemical production which has steadily increased. Emissions from mineral sources have either increased (e.g., cement manufacturing) or not changed significantly (e.g., glass and lime manufacturing) since 1990 but largely follow economic cycles. Hydrofluorocarbon emissions from the substitution of ODS have increased drastically since 1990, while the emissions of HFCs, PFCs, SF_6, and NF_3 from other sources have generally declined. Nitrous oxide emissions from the production of adipic and nitric acid have decreased, while N_2O emissions from product uses have remained nearly constant over time. Trends are explained further within each emission source category throughout the chapter.

Table 4-1 summarizes emissions for the IPPU chapter in $MMT CO_2$ Eq. using *IPCC Fourth Assessment Report* (AR4) GWP values, following the requirements of the current United Nations Framework Convention on Climate Change (UNFCCC) reporting guidelines for national inventories (IPCC 2007).[2] Unweighted native gas emissions in kt are also provided in Table 4-2. The source descriptions that follow in the chapter are presented in the order as reported to the UNFCCC in the Common Reporting Format (CRF) tables, corresponding generally to: mineral products, chemical production, metal production, and emissions from the uses of HFCs, PFCs, SF_6, and NF_3.

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[2] See <http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf>.

Table 4-1: Emissions from Industrial Processes and Product Use (MMT CO_2 Eq.)

Gas/Source	1990	2005	2012	2013	2014	2015	2016
CO_2	**208.8**	**191.6**	**171.1**	**173.1**	**179.2**	**172.9**	**164.7**
Iron and Steel Production & Metallurgical Coke Production	101.6	68.2	55.6	53.5	58.4	47.8	42.3
Iron and Steel Production	*99.1*	*66.2*	*55.1*	*51.6*	*56.3*	*45.0*	*41.0*
Metallurgical Coke Production	*2.5*	*2.1*	*0.5*	*1.8*	*2.0*	*2.8*	*1.3*
Cement Production	33.5	46.2	35.3	36.4	39.4	39.9	39.4
Petrochemical Production	21.2	26.8	26.5	26.4	26.5	28.1	28.1
Lime Production	11.7	14.6	13.8	14.0	14.2	13.3	12.9
Ammonia Production	13.0	9.2	9.4	10.0	9.6	10.9	12.2
Other Process Uses of Carbonates	6.3	7.6	9.1	11.5	13.0	12.3	11.0
Carbon Dioxide Consumption	1.5	1.4	4.0	4.2	4.5	4.5	4.5
Urea Consumption for Non-Agricultural Purposes	3.8	3.7	4.4	4.1	1.5	4.2	4.0
Ferroalloy Production	2.2	1.4	1.9	1.8	1.9	2.0	1.8
Soda Ash Production	1.4	1.7	1.7	1.7	1.7	1.7	1.7
Titanium Dioxide Production	1.2	1.8	1.5	1.7	1.7	1.6	1.6
Aluminum Production	6.8	4.1	3.4	3.3	2.8	2.8	1.3
Glass Production	1.5	1.9	1.2	1.3	1.3	1.3	1.2
Phosphoric Acid Production	1.5	1.3	1.1	1.1	1.0	1.0	1.0
Zinc Production	0.6	1.0	1.5	1.4	1.0	0.9	0.9
Lead Production	0.5	0.6	0.5	0.5	0.5	0.5	0.5
Silicon Carbide Production and Consumption	0.4	0.2	0.2	0.2	0.2	0.2	0.2
Magnesium Production and Processing	+	+	+	+	+	+	+
CH_4	**0.3**	**0.1**	**0.1**	**0.1**	**0.2**	**0.2**	**0.3**
Petrochemical Production	0.2	0.1	0.1	0.1	0.1	0.2	0.2
Ferroalloy Production	+	+	+	+	+	+	+
Silicon Carbide Production and Consumption	+	+	+	+	+	+	+
Iron and Steel Production & Metallurgical Coke Production	+	+	+	+	+	+	+
Iron and Steel Production	+	+	+	+	+	+	+
Metallurgical Coke Production	0.0	0.0	0.0	0.0	0.0	0.0	0.0
N_2O	**33.3**	**24.9**	**22.4**	**21.0**	**22.8**	**22.3**	**23.6**
Nitric Acid Production	12.1	11.3	10.5	10.7	10.9	11.6	10.2
Adipic Acid Production	15.2	7.1	5.5	3.9	5.4	4.3	7.0
N_2O from Product Uses	4.2	4.2	4.2	4.2	4.2	4.2	4.2
Caprolactam, Glyoxal, and Glyoxylic Acid Production	1.7	2.1	2.0	2.0	2.0	2.0	2.0
Semiconductor Manufacturing	+	0.1	0.2	0.2	0.2	0.2	0.2
HFCs	**46.6**	**123.0**	**150.5**	**151.1**	**156.7**	**160.8**	**162.3**
Substitution of Ozone Depleting Substances[a]	0.3	102.7	144.8	146.8	151.3	156.1	159.1
HCFC-22 Production	46.1	20.0	5.5	4.1	5.0	4.3	2.8
Semiconductor Manufacturing	0.2	0.2	0.2	0.2	0.3	0.3	0.3
Magnesium Production and Processing	0.0	0.0	+	0.1	0.1	0.1	0.1
PFCs	**24.3**	**6.7**	**5.9**	**5.8**	**5.6**	**5.1**	**4.3**
Semiconductor Manufacturing	2.8	3.3	3.0	2.8	3.1	3.1	3.0
Aluminum Production	21.5	3.4	2.9	3.0	2.5	2.0	1.4
Substitution of Ozone Depleting Substances	0.0	+	+	+	+	+	+
SF_6	**28.8**	**11.8**	**6.7**	**6.3**	**6.4**	**5.9**	**6.2**
Electrical Transmission and Distribution	23.1	8.3	4.7	4.5	4.7	4.3	4.3

Magnesium Production and Processing	5.2	2.7	1.6	1.5	1.0	0.9	1.0
Semiconductor Manufacturing	0.5	0.7	0.3	0.4	0.7	0.7	0.8
NF_3	**+**	**0.5**	**0.6**	**0.6**	**0.5**	**0.6**	**0.6**
Semiconductor Manufacturing	+	0.5	0.6	0.6	0.5	0.6	0.6
Total	**342.0**	**358.6**	**357.4**	**357.9**	**371.4**	**367.8**	**362.1**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Small amounts of PFC emissions also result from this source.

Note: Totals may not sum due to independent rounding.

Table 4-2: Emissions from Industrial Processes and Product Use (kt)

Gas/Source	1990	2005	2012	2013	2014	2015	2016
CO_2	**208,814**	**191,638**	**171,136**	**173,073**	**179,168**	**172,933**	**164,686**
Iron and Steel Production & Metallurgical Coke Production	101,630	68,210	55,600	53,471	58,353	47,825	42,306
Iron and Steel Production	*99,126*	*66,160*	*55,050*	*51,641*	*56,332*	*44,981*	*40,979*
Metallurgical Coke Production	*2,504*	*2,050*	*550*	*1,830*	*2,020*	*2,843*	*1,327*
Cement Production	33,484	46,194	35,270	36,369	39,439	39,907	39,439
Petrochemical Production	21,203	26,794	26,501	26,395	26,496	28,062	28,110
Lime Production	11,700	14,552	13,785	14,028	14,210	13,342	12,942
Ammonia Production	13,047	9,196	9,377	9,962	9,619	10,883	12,194
Other Process Uses of Carbonates	6,297	7,644	9,119	11,524	12,954	12,312	10,986
Carbon Dioxide Consumption	1,472	1,375	4,019	4,188	4,471	4,471	4,471
Urea Consumption for Non-Agricultural Purposes	3,784	3,653	4,392	4,074	1,541	4,169	3,959
Ferroalloy Production	2,152	1,392	1,903	1,785	1,914	1,960	1,796
Soda Ash Production	1,431	1,655	1,665	1,694	1,685	1,714	1,723
Titanium Dioxide Production	1,195	1,755	1,528	1,715	1,688	1,635	1,608
Aluminum Production	6,831	4,142	3,439	3,255	2,833	2,767	1,334
Glass Production	1,535	1,928	1,248	1,317	1,336	1,299	1,243
Phosphoric Acid Production	1,529	1,342	1,118	1,149	1,038	999	992
Zinc Production	632	1,030	1,486	1,429	956	933	925
Lead Production	516	553	527	546	459	473	482
Silicon Carbide Production and Consumption	375	219	158	169	173	180	174
Magnesium Production and Processing	1	3	2	2	2	3	3
CH_4	**12**	**4**	**4**	**4**	**6**	**9**	**11**
Petrochemical Production	9	3	3	3	5	7	10
Ferroalloy Production	1	+	1	+	1	1	1
Silicon Carbide Production and Consumption	1	+	+	+	+	+	+
Iron and Steel Production & Metallurgical Coke Production	1	1	+	+	+	+	+
Iron and Steel Production	*1*	*1*	+	+	+	+	+
Metallurgical Coke Production	*0*	*0*	*0*	*0*	*0*	*0*	*0*
N_2O	**112**	**84**	**75**	**71**	**77**	**75**	**79**
Nitric Acid Production	41	38	35	36	37	39	34
Adipic Acid Production	51	24	19	13	18	14	23
N_2O from Product Uses	14	14	14	14	14	14	14
Caprolactam, Glyoxal, and Glyoxylic Acid Production	6	7	7	7	7	7	7
Semiconductor Manufacturing	+	+	1	1	1	1	1
HFCs	**M**	**M**	**M**	**M**	**M**	**M**	**M**
Substitution of Ozone Depleting Substances[a]	M	M	M	M	M	M	M
HCFC-22 Production	3	1	+	+	+	+	+

Semiconductor Manufacturing	M	M	M	M	M	M	M
Magnesium Production and Processing	0	0	+	+	+	+	+
PFCs	**M**	**M**	**M**	**M**	**M**	**M**	**M**
Semiconductor Manufacturing	M	M	M	M	M	M	M
Aluminum Production	M	M	M	M	M	M	M
Substitution of Ozone Depleting Substances	0	+	+	+	+	+	+
SF$_6$	**1**	**1**	**+**	**+**	**+**	**+**	**+**
Electrical Transmission and Distribution	1	+	+	+	+	+	+
Magnesium Production and Processing	+	+	+	+	+	+	+
Semiconductor Manufacturing	+	+	+	+	+	+	+
NF$_3$	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Semiconductor Manufacturing	+	+	+	+	+	+	+

+ Does not exceed 0.5 kt.

M (Mixture of gases)

[a] Small amounts of PFC emissions also result from this source.

Note: Totals may not sum due to independent rounding.

The UNFCCC incorporated the *2006 IPCC Guidelines for National Greenhouse Gas Inventories (2006 IPCC Guidelines)* as the standard for Annex I countries at the Nineteenth Conference of the Parties (Warsaw, November 11-23, 2013). This chapter presents emission estimates calculated in accordance with the methodological guidance provided in these guidelines. For additional detail on IPPU sources that are not estimated in this Inventory report, please review Annex 5, Assessment of the Sources and Sinks of Greenhouse Gas Emissions Not Included. These sources are not estimated due to various national circumstances, such as that emissions from a source may not currently occur in the United States, data are not currently available for those emission sources (e.g., ceramics, non-metallurgical magnesium production), emissions are included elsewhere within the Inventory report, or data suggest that emissions are not significant. Information on planned improvements for specific IPPU source categories can be found in the Planned Improvements section of the individual source category.

In addition, as mentioned in the Energy chapter of this report (Box 3-6), fossil fuels consumed for non-energy uses for primary purposes other than combustion for energy (including lubricants, paraffin waxes, bitumen asphalt, and solvents) are reported in the Energy chapter. According to the *2006 IPCC Guidelines*, these non-energy uses of fossil fuels are to be reported under IPPU, rather than Energy; however, due to national circumstances regarding the allocation of energy statistics and carbon (C) balance data, the United States reports non-energy uses in the Energy chapter of this Inventory. Reporting these non-energy use emissions under IPPU would involve making artificial adjustments to the non-energy use C balance. These artificial adjustments would also result in the C emissions for lubricants, waxes, and asphalt and road oil being reported under IPPU, while the C storage for lubricants, waxes, and asphalt and road oil would be reported under Energy. To avoid presenting an incomplete C balance, double-counting, and adopting a less transparent approach, the entire calculation of C storage and C emissions is therefore conducted in the Non-Energy Uses of Fossil Fuels category calculation methodology and reported under the Energy sector. For more information, see the Methodology section for CO$_2$ from Fossil Fuel Combustion and Section 3.2, Carbon Emitted from Non-Energy Uses of Fossil Fuels.

Finally, as stated in the Energy chapter, portions of the fuel consumption data for seven fuel categories—coking coal, distillate fuel, industrial other coal, petroleum coke, natural gas, residual fuel oil, and other oil—are reallocated to the IPPU chapter, as they are consumed during non-energy related industrial process activity. Emissions from uses of fossil fuels as feedstocks or reducing agents (e.g., petrochemical production, aluminum production, titanium dioxide and zinc production) are reported in the IPPU chapter, unless otherwise noted due to specific national circumstances. More information on the methodology to adjust for these emissions within the Energy chapter is described in the Methodology section of CO$_2$ from Fossil Fuel Combustion (3.1 Fossil Fuel Combustion (CRF Source Category 1A)) and Annex 2.1, Methodology for Estimating Emissions of CO$_2$ from Fossil Fuel Combustion.

QA/QC and Verification Procedures

For IPPU sources, a detailed QA/QC plan was developed and implemented for specific categories. This plan was based on the overall *Quality Assurance/Quality Control and Uncertainty Management Plan for the U.S. Greenhouse Gas Inventory* (QA/QC Management Plan), but was tailored to include specific procedures recommended for these sources. Two types of checks were performed using this plan: (1) general (Tier 1) procedures consistent with Volume 1, Chapter 6 of the *2006 IPCC Guidelines* that focus on annual procedures and checks to be used when gathering, maintaining, handling, documenting, checking, and archiving the data, supporting documents, and files; and (2) source category specific (Tier 2) procedures that focus on checks and comparisons of the emission factors, activity data, and methodologies used for estimating emissions from the relevant industrial process and product use sources. Examples of these procedures include: checks to ensure that activity data and emission estimates are consistent with historical trends to identify significant changes; that, where possible, consistent and reputable data sources are used and specified across sources; that interpolation or extrapolation techniques are consistent across sources; and that common datasets, units, and conversion factors are used where applicable. The IPPU QA/QC plan also checked for transcription errors in data inputs required for emission calculations, including activity data and emission factors; and confirmed that estimates were calculated and reported for all applicable and able portions of the source categories for all years.

General or Tier 1 QA/QC procedures and calculation-related QC (category-specific, Tier 2) have been performed for all IPPU sources. Consistent with the *2006 IPCC Guidelines*, additional category-specific QC procedures were performed for more significant emission categories (such as the comparison of reported consumption with modeled consumption using EPA's Greenhouse Gas Reporting Program (GHGRP) data within Substitution of Ozone Depleting Substances) or sources where significant methodological and data updates have taken place. The QA/QC implementation did not reveal any significant inaccuracies, and all errors identified were documented and corrected. Application of these procedures, specifically category-specific QC procedures and updates/improvements as a result of QA processes (expert, public, and UNFCCC technical expert reviews), are described further within respective source categories, in the Recalculations and Planned Improvement sections.

For most IPPU categories, activity data are obtained via aggregation of facility-level data from EPA's GHGRP, national commodity surveys conducted by U.S. Geologic Survey National Minerals Information Center, U.S. Department of Energy (DOE), U.S. Census Bureau, industry associations such as Air-Conditioning, Heating, and Refrigeration Institute (AHRI), American Chemistry Council (ACC), and American Iron and Steel Institute (AISI) (specified within each source category). The emission factors used include those derived from the EPA's GHGRP and application of IPCC default factors. Descriptions of uncertainties and assumptions for activity data and emission factors are included within the uncertainty discussion sections for each IPPU source category.

The uncertainty analysis performed to quantify uncertainties associated with the 2016 emission estimates from IPPU continues a multi-year process for developing credible quantitative uncertainty estimates for these source categories using the IPCC Tier 2 approach. As the process continues, the type and the characteristics of the actual probability density functions underlying the input variables are identified and better characterized (resulting in development of more reliable inputs for the model, including accurate characterization of correlation between variables), based primarily on expert judgment. Accordingly, the quantitative uncertainty estimates reported in this section should be considered illustrative and as iterations of ongoing efforts to produce accurate uncertainty estimates. The correlation among data used for estimating emissions for different sources can influence the uncertainty analysis of each individual source. While the uncertainty analysis recognizes very significant connections among sources, a more comprehensive approach that accounts for all linkages will be identified as the uncertainty analysis moves forward.

Box 4-1: Methodological Approach for Estimating and Reporting U.S. Emissions and Removals

In following the United Nations Framework Convention on Climate Change (UNFCCC) requirement under Article 4.1 to develop and submit national greenhouse gas emission inventories, the emissions and removals presented in this report and this chapter, are organized by source and sink categories and calculated using internationally-accepted methods provided by the Intergovernmental Panel on Climate Change (IPCC) in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories (2006 IPCC Guidelines)*. Additionally, the calculated emissions and removals in a given year for the United States are presented in a common manner in line with the UNFCCC reporting guidelines for the reporting of inventories under this international agreement. The use of consistent methods to calculate emissions and removals by all nations providing their inventories to the UNFCCC ensures that these reports are comparable. The presentation of emissions and removals provided in this Inventory do not preclude alternative examinations, but rather, this Inventory presents emissions and removals in a common format consistent with how countries are to report Inventories under the UNFCCC. The report itself, and this chapter, follows this standardized format, and provides an explanation of the application of methods used to calculate emissions and removals.

Box 4-2: Industrial Processes Data from EPA's Greenhouse Gas Reporting Program

On October 30, 2009, the U.S. EPA published a rule requiring annual reporting of greenhouse gas data from large greenhouse gas emission sources in the United States. Implementation of the rule, codified at 40 CFR Part 98, is referred to as EPA's GHGRP. The rule applies to direct greenhouse gas emitters, fossil fuel suppliers, industrial gas suppliers, and facilities that inject CO_2 underground for sequestration or other reasons and requires reporting by sources or suppliers in 41 industrial categories ("Subparts"). Annual reporting is at the facility level, except for certain suppliers of fossil fuels and industrial greenhouse gases. In general, the threshold for reporting is 25,000 metric tons or more of CO_2 Eq. per year, but reporting is required for all facilities in some industries. Calendar year 2010 was the first year for which data were reported for facilities subject to 40 CFR Part 98, though some source categories first reported data for calendar year 2011.

EPA's GHGRP dataset and the data presented in this Inventory are complementary. The GHGRP dataset continues to be an important resource for the Inventory, providing not only annual emissions information, but also other annual information such as activity data and emission factors that can improve and refine national emission estimates and trends over time. GHGRP data also allow EPA to disaggregate national inventory estimates in new ways that can highlight differences across regions and sub-categories of emissions, along with enhancing application of QA/QC procedures and assessment of uncertainties. EPA uses annual GHGRP data in a number of categories to improve the national estimates presented in this Inventory consistent with IPCC guidelines. While many methodologies used in EPA's GHGRP are consistent with IPCC, it should be noted that the definitions for source categories in EPA's GHGRP may differ from those used in this Inventory in meeting the UNFCCC reporting guidelines (IPCC 2011). In line with the UNFCCC reporting guidelines, the Inventory is a comprehensive accounting of all emissions from source categories identified in the *2006 IPCC Guidelines*. Further information on the reporting categorizations in EPA's GHGRP and specific data caveats associated with monitoring methods in EPA's GHGRP has been provided on the GHGRP website.[3]

For certain source categories in this Inventory (e.g., nitric acid production, cement production and petrochemical production), EPA has also integrated data values that have been calculated by aggregating GHGRP data that are considered confidential business information (CBI) at the facility level. EPA, with industry engagement, has put forth criteria to confirm that a given data aggregation shields underlying CBI from public disclosure. EPA is only publishing data values that meet these aggregation criteria.[4] Specific uses of aggregated facility-level data are described in the respective methodological sections. For other source categories in this chapter, as indicated in the respective planned improvements sections, EPA is continuing to analyze how facility-level GHGRP data may be used to improve the national estimates presented in this Inventory, giving particular consideration to ensuring time-series consistency and completeness. As stated previously in the Introduction chapter, this year EPA has integrated GHGRP information for various Industrial Processes and Product Use categories[5] and also identified places where EPA plans to integrate additional GHGRP data in additional categories[6] (see those categories' Planned Improvements sections for details). EPA has paid particular attention to ensuring time-series consistency for major recalculations that have occurred from the incorporation of GHGRP data into these categories, consistent with *2006*

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[3] See <http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf>.

[4] U.S. EPA Greenhouse Gas Reporting Program. Developments on Publication of Aggregated Greenhouse Gas Data, November 25, 2014. See <http://www.epa.gov/ghgreporting/confidential-business-information-ghg-reporting>.

[5] Adipic Acid Production, Aluminum Production, Carbon Dioxide Consumption, Cement Production, Electrical Transmission and Distribution, HCFC-22 Production, Lime Production, Magnesium Production and Processing, Substitution of Ozone Depleting Substances, Nitric Acid Production, Petrochemical Production, and Semiconductor Manufacture.

[6] Ammonia Production, Glass Production and Other fluorinated gas production.

IPCC Guidelines and *IPCC Technical Bulletin on Use of Facility-Specific Data in National GHG Inventories*.[7] EPA verifies annual facility-level reports through a multi-step process to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent.[8] The GHGRP dataset is a particularly important annual resource and will continue to be important for improving emissions estimates from IPPU in future Inventory reports. Additionally, EPA's GHGRP has and will continue to enhance QA/QC procedures and assessment of uncertainties within the IPPU categories (see those categories for specific QA/QC details regarding the use of GHGRP data).

4.1 Cement Production (CRF Source Category 2A1)

Cement production is an energy- and raw material-intensive process that results in the generation of carbon dioxide (CO_2) from both the energy consumed in making the cement and the chemical process itself. Emissions from fuels consumed for energy purposes during the production of cement are accounted for in the Energy chapter.

During the cement production process, calcium carbonate ($CaCO_3$) is heated in a cement kiln at a temperature range of about 700 to 1000 degrees Celsius (1,292 to 1,832 degrees Fahrenheit) to form lime (i.e., calcium oxide or CaO) and CO_2 in a process known as calcination or calcining. The quantity of CO_2 emitted during cement production is directly proportional to the lime content of the clinker. During calcination, each mole of limestone ($CaCO_3$) heated in the clinker kiln forms one mole of lime (CaO) and one mole of CO_2:

$$CaCO_3 + heat \rightarrow CaO + CO_2$$

Next, the lime is combined with silica-containing materials to produce clinker (an intermediate product), with the earlier byproduct CO_2 being released to the atmosphere. The clinker is then rapidly cooled to maintain quality, mixed with a small amount of gypsum and potentially other materials (e.g., slag, etc.), and used to make Portland cement.[9]

Carbon dioxide emitted from the chemical process of cement production is the second largest source of industrial CO_2 emissions in the United States. Cement is produced in 34 states and Puerto Rico. Texas, California, Missouri, Florida, and Alabama were the leading cement-producing states in 2016 and accounted for almost 50 percent of total U.S. production (USGS 2017). Clinker production in 2016 decreased approximately 1 percent from 2015 levels as cement sales increased significantly in 2016, with much of the increase accounted for by imports. In 2016, U.S. clinker production totaled 75,800 kilotons (EPA 2017). The resulting CO_2 emissions were estimated to be 39.4 MMT CO_2 Eq. (39,439 kt) (see Table 4-3).

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[7] See <http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf>.

[8] See <https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf>.

[9] Approximately three percent of total clinker production is used to produce masonry cement, which is produced using plasticizers (e.g., ground limestone, lime, etc.) and Portland cement (USGS 2011). Carbon dioxide emissions that result from the production of lime used to create masonry cement are included in the Lime Manufacture source category.

Table 4-3: CO_2 Emissions from Cement Production (MMT CO_2 Eq. and kt)

Year	MMT CO_2 Eq.	kt
1990	33.5	33,484
2005	46.2	46,194
2012	35.3	35,270
2013	36.4	36,369
2014	39.4	39,439
2015	39.9	39,907
2016	39.4	39,439

Greenhouse gas emissions from cement production increased every year from 1991 through 2006 (with the exception of a slight decrease in 1997), but decreased in the following years until 2009. Emissions from cement production were at their lowest levels in 2009 (2009 emissions are approximately 28 percent lower than 2008 emissions and 12 percent lower than 1990). Since 2010, emissions have increased by roughly 25 percent. In 2016, emissions from cement production decreased by 1 percent from 2015 levels.

Emissions since 1990 have increased by 18 percent. Emissions decreased significantly between 2008 and 2009, due to the economic recession and associated decrease in demand for construction materials. Emissions increased slightly from 2009 levels in 2010, and continued to gradually increase during the 2011 through 2015 time period due to increasing consumption. Emissions in 2016 decreased slightly from 2015 levels. Cement continues to be a critical component of the construction industry; therefore, the availability of public and private construction funding, as well as overall economic conditions, have considerable impact on the level of cement production.

Methodology

Carbon dioxide emissions were estimated using the Tier 2 methodology from the *2006 IPCC Guidelines*. The Tier 2 methodology was used because detailed and complete data (including weights and composition) for carbonate(s) consumed in clinker production are not available, and thus a rigorous Tier 3 approach is impractical. Tier 2 specifies the use of aggregated plant or national clinker production data and an emission factor, which is the product of the average lime fraction for clinker of 65 percent and a constant reflecting the mass of CO_2 released per unit of lime. The U.S. Geological Survey (USGS) mineral commodity expert for cement has confirmed that this is a reasonable assumption for the United States (Van Oss 2013a). This calculation yields an emission factor of 0.510 tons of CO_2 per ton of clinker produced, which was determined as follows:

$$\mathrm{EF_{clinker}} = 0.650\ \mathrm{CaO} \times [(44.01\ \mathrm{g/mole\ CO_2}) \div (56.08\ \mathrm{g/mole\ CaO})] = 0.510\ \mathrm{tons\ CO_2/ton\ clinker}$$

During clinker production, some of the clinker precursor materials remain in the kiln as non-calcinated, partially calcinated, or fully calcinated cement kiln dust (CKD). The emissions attributable to the calcinated portion of the CKD are not accounted for by the clinker emission factor. The IPCC recommends that these additional CKD CO_2 emissions should be estimated as two percent of the CO_2 emissions calculated from clinker production (when data on CKD generation are not available). Total cement production emissions were calculated by adding the emissions from clinker production to the emissions assigned to CKD (IPCC 2006).

Furthermore, small amounts of impurities (i.e., not calcium carbonate) may exist in the raw limestone used to produce clinker. The proportion of these impurities is generally minimal, although a small amount (1 to 2 percent) of magnesium oxide (MgO) may be desirable as a flux. Per the IPCC Tier 2 methodology, a correction for MgO is not used, since the amount of MgO from carbonate is likely very small and the assumption of a 100 percent carbonate source of CaO already yields an overestimation of emissions (IPCC 2006).

The 1990 through 2012 activity data for clinker production (see Table 4-4) were obtained from USGS (Van Oss 2013a, Van Oss 2013b). Clinker production data for 2013 were also obtained from USGS (USGS 2014). The data were compiled by USGS (to the nearest ton) through questionnaires sent to domestic clinker and cement manufacturing plants, including the facilities in Puerto Rico. During the 1990 through 2015 Inventory report cycle, EPA began incorporating clinker production data from EPA's GHGRP to estimate emissions in these respective years. Clinker production values in the current Inventory report utilize GHGRP data for the years 2014, 2015 and 2016 (EPA 2017). More details on how this change compares to USGS reported data can be found in the section on Uncertainty and Time-Series Consistency.

Table 4-4: Clinker Production (kt)

Year	Clinker
1990	64,355
2005	88,783
2012	67,788
2013	69,900
2014	75,800
2015	76,700
2016	75,800

Notes: Clinker production from 1990 through 2016 includes Puerto Rico.

Uncertainty and Time-Series Consistency

The uncertainties contained in these estimates are primarily due to uncertainties in the lime content of clinker and in the percentage of CKD recycled inside the cement kiln. Uncertainty is also associated with the assumption that all calcium-containing raw materials are $CaCO_3$, when a small percentage likely consists of other carbonate and non-carbonate raw materials. The lime content of clinker varies from 60 to 67 percent; 65 percent is used as a representative value (Van Oss 2013a). CKD loss can range from 1.5 to 8 percent depending upon plant specifications. Additionally, some amount of CO_2 is reabsorbed when the cement is used for construction. As cement reacts with water, alkaline substances such as calcium hydroxide are formed. During this curing process, these compounds may react with CO_2 in the atmosphere to create calcium carbonate. This reaction only occurs in roughly the outer 0.2 inches of surface area. Because the amount of CO_2 reabsorbed is thought to be minimal, it was not estimated. However, see Planned Improvements described below to reassess this assumption by conducting a review to identify recent studies that may provide information or data on reabsorption rates of cement products.

Total U.S. clinker production is assumed to have low uncertainty. USGS takes a number of manual steps to review clinker production reported through their voluntary surveys. EPA continues to assess the accuracy of reported clinker production data required by GHGRP Subpart H facilities for current and future Inventory reports. EPA verifies annual facility-level reports through a multi-step process (e.g., combination of electronic checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent. Based on the results of the verification process, the EPA follows up with facilities to resolve mistakes that may have occurred.[10] Facilities are also required to monitor and maintain records of monthly clinker production.

EPA relied upon the latest guidance from the IPCC on the use of facility-level data in national inventories and applied a category-specific QC process to compare activity data from GHGRP with existing data from USGS. This was to ensure time-series consistency of the emission estimates presented in the Inventory. For the year 2014, USGS and GHGRP clinker production data showed a difference of approximately 2 percent, while in 2015 and in 2016 that difference decreased to less than 1 percent between the two sets of activity data. This difference resulted in an increase of emissions compared to USGS data (USGS 2016a) by 0.7 MMT CO_2 Eq. in 2014 and less than 0.1 MMT CO_2 Eq. in 2015 and in 2016.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-5. Based on the uncertainties associated with total U.S. clinker production, the CO_2 emission factor for clinker production, and the emission factor for additional CO_2 emissions from CKD, 2016 CO_2 emissions from cement production were

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[10] See <https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf>.

estimated to be between 37.1 and 41.8 MMT CO_2 Eq. at the 95 percent confidence level. This confidence level indicates a range of approximately 6 percent below and 6 percent above the emission estimate of 39.4 MMT CO_2 Eq.

Table 4-5: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Cement Production (MMT CO_2 Eq. and Percent)

Source	Gas	2016 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Cement Production	CO_2	39.4	37.1	41.8	-6%	+6%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological approaches were applied to the entire time series to ensure time-series consistency from 1990 through 2016. Details on the emission trends through time are described in more detail in the Methodology section, above. More information on the consistency in clinker production data and emissions across the time series with the use of GHGRP clinker data for 2014 through 2016 can be found in the Uncertainty and Time-Series Consistency section.

For more information on the general QA/QC process applied to this source category, consistent with Volume 1, Chapter 6 of the *2006 IPCC Guidelines*, see QA/QC and Verification Procedures section in the introduction of the IPPU chapter.

Planned Improvements

In response to comments from the Portland Cement Association (PCA) and UNFCCC expert technical reviews, EPA is continuing to evaluate and analyze data reported under EPA's GHGRP that would be useful to improve the emission estimates for the Cement Production source category. EPA held a technical meeting with PCA in August 2016 to review Inventory methods and available data from the GHGRP data set. Most cement production facilities reporting under EPA's GHGRP use Continuous Emission Monitoring Systems (CEMS) to monitor and report CO_2 emissions, thus reporting combined process and combustion emissions from kilns. In implementing further improvements and integration of data from EPA's GHGRP, the latest guidance from the IPCC on the use of facility-level data in national inventories will be relied upon, in addition to category-specific QC methods recommended by the *2006 IPCC Guidelines*.[11] EPA's long-term improvement plan includes continued assessment of the feasibility of using additional GHGRP information, in particular disaggregating aggregated GHGRP emissions consistent with IPCC and UNFCCC guidelines to present both national process and combustion emissions streams. This long-term planned analysis is still in development and has not been updated for this current Inventory.

Finally, in response to feedback from PCA during the Public Review comment period of the previous Inventory in March 2017, EPA plans to meet with PCA to discuss additional long-term improvements to review methods and data used to estimate CO_2 emissions from cement production to account for both organic material and magnesium carbonate in the raw material, and to discuss the carbonation that occurs later in the cement product lifecycle. EPA will work with PCA to identify data and studies on the average MgO content of clinker produced in the United States, the average carbon content for organic materials in kiln feed in the United States, and CO_2 reabsorption rates via carbonation for various cement products.

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[11] See <http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf>.

4.2 Lime Production (CRF Source Category 2A2)

Lime is an important manufactured product with many industrial, chemical, and environmental applications. Lime production involves three main processes: stone preparation, calcination, and hydration. Carbon dioxide (CO_2) is generated during the calcination stage, when limestone—mostly calcium carbonate ($CaCO_3$)—is roasted at high temperatures in a kiln to produce calcium oxide (CaO) and CO_2. The CO_2 is given off as a gas and is normally emitted to the atmosphere.

$$CaCO_3 \rightarrow CaO + CO_2$$

Some of the CO_2 generated during the production process, however, is recovered at some facilities for use in sugar refining and precipitated calcium carbonate (PCC) production.[12] Emissions from fuels consumed for energy purposes during the production of lime are accounted for in the Energy chapter.

For U.S. operations, the term “lime” actually refers to a variety of chemical compounds. These include CaO, or high-calcium quicklime; calcium hydroxide ($Ca(OH)_2$), or hydrated lime; dolomitic quicklime ([CaO•MgO]); and dolomitic hydrate ([$Ca(OH)_2$•MgO] or [$Ca(OH)_2$•$Mg(OH)_2$]).

The current lime market is approximately distributed across five end-use categories as follows: metallurgical uses, 37 percent; environmental uses, 31 percent; chemical and industrial uses, 22 percent; construction uses, 9 percent; and refractory dolomite, 1 percent (USGS 2016b). The major uses are in steel making, flue gas desulfurization systems at coal-fired electric power plants, construction, and water treatment, as well as uses in mining, pulp and paper and precipitated calcium carbonate manufacturing. Lime is also used as a CO_2 scrubber, and there has been experimentation on the use of lime to capture CO_2 from electric power plants.

Lime production in the United States—including Puerto Rico—was reported to be 17,700 kilotons in 2016 (USGS 2018). At year-end 2016, there were 77 operating primary lime plants in the United States, including Puerto Rico.[13] Principal lime producing states are Missouri, Alabama, Kentucky, Ohio, Texas (USGS 2017).

U.S. lime production resulted in estimated net CO_2 emissions of 12.9 MMT CO_2 Eq. (12,942 kt) (see Table 4-6 and Table 4-7). The trends in CO_2 emissions from lime production are directly proportional to trends in production, which are described below.

Table 4-6: CO_2 Emissions from Lime Production (MMT CO_2 Eq. and kt)

Year	MMT CO_2 Eq.	kt
1990	11.7	11,700
2005	14.6	14,552
2012	13.8	13,785
2013	14.0	14,028
2014	14.2	14,210
2015	13.3	13,342
2016	12.9	12,942

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[12] PCC is obtained from the reaction of CO_2 with calcium hydroxide. It is used as a filler and/or coating in the paper, food, and plastic industries.

[13] In 2016, 75 operating primary lime facilities in the United States reported to the EPA Greenhouse Gas Reporting Program.

Table 4-7: Potential, Recovered, and Net CO_2 Emissions from Lime Production (kt)

Year	Potential	Recovered[a]	Net Emissions
1990	11,959	259	11,700
2005	15,074	522	14,552
2012	14,258	473	13,785
2013	14,495	467	14,028
2014	14,715	505	14,210
2015	13,764	422	13,342
2016	13,312	370	12,942

[a] For sugar refining and PCC production.
Note: Totals may not sum due to independent rounding.

In 2016, lime production decreased compared to 2015 levels (decrease of about 3 percent) at 17,700 kilotons, owing to lesser amounts of lime needed for the desulfurization of flue gases in coal-fired utility power plants (USGS 2018; USGS 2017).

Methodology

To calculate emissions, the amounts of high-calcium and dolomitic lime produced were multiplied by their respective emission factors using the Tier 2 approach from the *2006 IPCC Guidelines*. The emission factor is the product of the stoichiometric ratio between CO_2 and CaO, and the average CaO and MgO content for lime. The CaO and MgO content for lime is assumed to be 95 percent for both high-calcium and dolomitic lime (IPCC 2006). The emission factors were calculated as follows:

For high-calcium lime:

$$[(44.01\ \mathrm{g/mole\ CO_2}) \div (56.08\ \mathrm{g/mole\ CaO})] \times (0.9500\ \mathrm{CaO/lime}) = 0.7455\ \mathrm{g\ CO_2/g\ lime}$$

For dolomitic lime:

$$[(88.02\ \mathrm{g/mole\ CO_2}) \div (96.39\ \mathrm{g/mole\ CaO})] \times (0.9500\ \mathrm{CaO/lime}) = 0.8675\ \mathrm{g\ CO_2/g\ lime}$$

Production was adjusted to remove the mass of chemically combined water found in hydrated lime, determined according to the molecular weight ratios of H_2O to ($Ca(OH)_2$ and [$Ca(OH)_2{\bullet}Mg(OH)_2$]) (IPCC 2006). These factors set the chemically combined water content to 24.3 percent for high-calcium hydrated lime, and 27.2 percent for dolomitic hydrated lime.

The *2006 IPCC Guidelines* (Tier 2 method) also recommends accounting for emissions from lime kiln dust (LKD) through application of a correction factor. LKD is a byproduct of the lime manufacturing process typically not recycled back to kilns. LKD is a very fine-grained material and is especially useful for applications requiring very small particle size. Most common LKD applications include soil reclamation and agriculture. Currently, data on annual LKD production is not readily available to develop a country-specific correction factor. Lime emission estimates were multiplied by a factor of 1.02 to account for emissions from LKD (IPCC 2006). See the Planned Improvements section associated with efforts to improve uncertainty analysis and emission estimates associated with LKD.

Lime emission estimates were further adjusted to account for the amount of CO_2 captured for use in on-site processes. All the domestic lime facilities are required to report these data to EPA under its GHGRP. The total national-level annual amount of CO_2 captured for on-site process use was obtained from EPA's GHGRP (EPA 2017) based on reported facility level data for years 2010 through 2016. The amount of CO_2 captured/recovered for on-site process use is deducted from the total potential emissions (i.e., from lime production and LKD). The net lime emissions are presented in Table 4-6 and Table 4-7. GHGRP data on CO_2 removals (i.e., CO_2 captured/recovered) was available only for 2010 through 2016. Since GHGRP data are not available for 1990 through 2009, IPCC "splicing" techniques were used as per the *2006 IPCC Guidelines* on time-series consistency (IPCC 2006, Volume 1, Chapter 5).

Lime production data (by type, high-calcium- and dolomitic-quicklime, high-calcium- and dolomitic-hydrated, and dead-burned dolomite) for 1990 through 2016 (see Table 4-8) were obtained from the U.S. Geological Survey (USGS) (USGS 2017 and 2018) annual reports and are compiled by USGS to the nearest ton. The high-calcium quicklime and dolomitic quicklime values were estimated using the ratio of the 2015 quicklime values to the 2016 total values. The 2015 values for high-calcium hydrated, dolomitic hydrated, and dead-burned dolomite were used since there is less fluctuation in their production from year to year. Natural hydraulic lime, which is produced from CaO and hydraulic calcium silicates, is not manufactured in the United States (USGS 2011). Total lime production was adjusted to account for the water content of hydrated lime by converting hydrate to oxide equivalent based on recommendations from the IPCC, and is presented in Table 4-9 (IPCC 2006). The CaO and CaO•MgO contents of lime were obtained from the IPCC (IPCC 2006). Since data for the individual lime types (high calcium and dolomitic) were not provided prior to 1997, total lime production for 1990 through 1996 was calculated according to the three-year distribution from 1997 to 1999.

Table 4-8: High-Calcium- and Dolomitic-Quicklime, High-Calcium- and Dolomitic-Hydrated, and Dead-Burned-Dolomite Lime Production (kt)

Year	High-Calcium Quicklime	Dolomitic Quicklime	High-Calcium Hydrated	Dolomitic Hydrated	Dead-Burned Dolomite
1990	11,166	2,234	1,781	319	342
2005	14,100	2,990	2,220	474	200
2012	13,600	2,790	2,000	253	200
2013	13,800	2,850	2,050	260	200
2014	14,100	2,740	2,190	279	200
2015	13,100	2,550	2,150	279	200
2016	12,615	2,456	2,150	279	200

Table 4-9: Adjusted Lime Production (kt)

Year	High-Calcium	Dolomitic
1990	12,466	2,800
2005	15,721	3,522
2012	15,060	3,167
2013	15,297	3,252
2014	15,699	3,135
2015	14,670	2,945
2016	14,185	2,851

Note: Minus water content of hydrated lime.

Uncertainty and Time-Series Consistency

The uncertainties contained in these estimates can be attributed to slight differences in the chemical composition of lime products and CO_2 recovery rates for on-site process use over the time series. Although the methodology accounts for various formulations of lime, it does not account for the trace impurities found in lime, such as iron oxide, alumina, and silica. Due to differences in the limestone used as a raw material, a rigid specification of lime material is impossible. As a result, few plants produce lime with exactly the same properties.

In addition, a portion of the CO_2 emitted during lime production will actually be reabsorbed when the lime is consumed, especially at captive lime production facilities. As noted above, lime has many different chemical, industrial, environmental, and construction applications. In many processes, CO_2 reacts with the lime to create calcium carbonate (e.g., water softening). Carbon dioxide reabsorption rates vary, however, depending on the application. For example, 100 percent of the lime used to produce precipitated calcium carbonate reacts with CO_2; whereas most of the lime used in steel making reacts with impurities such as silica, sulfur, and aluminum compounds. Quantifying the amount of CO_2 that is reabsorbed would require a detailed accounting of lime use in the United States and additional information about the associated processes where both the lime and byproduct CO_2 are "reused" are required to quantify the amount of CO_2 that is reabsorbed. Research conducted thus far has not yielded the necessary information to quantify CO_2 reabsorption rates.[14] However, some additional information on the amount of CO_2 consumed on site at lime facilities has been obtained from EPA's GHGRP.

In some cases, lime is generated from calcium carbonate byproducts at pulp mills and water treatment plants.[15] The lime generated by these processes is included in the USGS data for commercial lime consumption. In the pulping industry, mostly using the Kraft (sulfate) pulping process, lime is consumed in order to causticize a process liquor (green liquor) composed of sodium carbonate and sodium sulfide. The green liquor results from the dilution of the smelt created by combustion of the black liquor where biogenic carbon (C) is present from the wood. Kraft mills recover the calcium carbonate "mud" after the causticizing operation and calcine it back into lime—thereby generating CO_2—for reuse in the pulping process. Although this re-generation of lime could be considered a lime manufacturing process, the CO_2 emitted during this process is mostly biogenic in origin, and therefore is not included in the industrial processes totals (Miner and Upton 2002). In accordance with IPCC methodological guidelines, any such emissions are calculated by accounting for net C fluxes from changes in biogenic C reservoirs in wooded or crop lands (see the Land Use, Land-Use Change, and Forestry chapter).

In the case of water treatment plants, lime is used in the softening process. Some large water treatment plants may recover their waste calcium carbonate and calcine it into quicklime for reuse in the softening process. Further research is necessary to determine the degree to which lime recycling is practiced by water treatment plants in the United States.

Another uncertainty is the assumption that calcination emissions for LKD are around 2 percent. The National Lime Association (NLA) has commented that the estimates of emissions from LKD in the United States could be closer to 6 percent. They also note that additional emissions (approximately 2 percent) may also be generated through production of other byproducts/wastes (off-spec lime that is not recycled, scrubber sludge) at lime plants (Seeger 2013). Publicly available data on LKD generation rates, total quantities not used in cement production, and types of other byproducts/wastes produced at lime facilities are limited. EPA initiated a dialogue with NLA to discuss data needs to generate a country-specific LKD factor and is reviewing the information provided by NLA. NLA compiled and shared historical emissions information and quantities for some waste products reported by member facilities associated with generation of total calcined byproducts and LKD, as well as methodology and calculation worksheets that member facilities complete when reporting. There is uncertainty regarding the availability of data across the time series needed to generate a representative country-specific LKD factor. Uncertainty of the activity data is also a function of the reliability and completeness of voluntarily reported plant-level production data. Further research and data is needed to improve understanding of additional calcination emissions to consider revising the current assumptions that are based on IPCC guidelines. More information can be found in the Planned Improvements section below.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-10. Lime CO_2 emissions for 2016 were estimated to be between 12.7 and 13.2 MMT CO_2 Eq. at the 95 percent confidence level. This confidence level indicates a range of approximately 2 percent below and 2 percent above the emission estimate of 12.9 MMT CO_2 Eq.

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[14] Representatives of the National Lime Association estimate that CO_2 reabsorption that occurs from the use of lime may offset as much as a quarter of the CO_2 emissions from calcination (Males 2003).

[15] Some carbide producers may also regenerate lime from their calcium hydroxide byproducts, which does not result in emissions of CO_2. In making calcium carbide, quicklime is mixed with coke and heated in electric furnaces. The regeneration of lime in this process is done using a waste calcium hydroxide (hydrated lime) [$CaC_2 + 2H_2O \rightarrow C_2H_2 + Ca(OH)_2$], not calcium carbonate [$CaCO_3$]. Thus, the calcium hydroxide is heated in the kiln to simply expel the water [$Ca(OH)_2 + heat \rightarrow CaO + H_2O$] and no CO_2 is released.

Table 4-10: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Lime Production (MMT CO_2 Eq. and Percent)

Source	Gas	2016 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Lime Production	CO_2	12.9	12.7	13.2	-2%	+2%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2016. Details on the emission trends through time are described in more detail in the Methodology section, above.

For more information on the general QA/QC process applied to this source category, consistent with Volume 1, Chapter 6 of the *2006 IPCC Guidelines*, see the QA/QC and Verification Procedures section in the introduction of the IPPU chapter.

Planned Improvements

Future improvements involve finishing a review of data to improve current assumptions associated with emissions from production of LKD and other byproducts/wastes as discussed in the Uncertainty and Time-Series Consistency section per comments from the NLA provided during the Public Review comment period of the previous (1990 to 2015) Inventory. In response to comments, EPA met with NLA on April 7, 2015 to outline specific information required to apply IPCC methods to develop a country-specific correction factor to more accurately estimate emissions from production of LKD. In response to this technical meeting, in January and February 2016, NLA compiled and shared historical emissions information reported by member facilities on an annual basis under voluntary reporting initiatives over 2002 through 2011 associated with generation of total calcined byproducts and LKD (LKD reporting only differentiated starting in 2010). This emissions information was reported on a voluntary basis consistent with NLA's facility-level reporting protocol also recently provided. EPA needs additional time to review the information provided by NLA and plans to work with them to address needs for EPA's analysis, as there is limited information across the time series. Due to limited resources and need for additional QA of information, this planned improvement is still in process and has not been incorporated into this current Inventory report. As an interim step, EPA has updated the qualitative description of uncertainty to reflect the information provided by NLA.

In addition, EPA plans to review GHGRP emissions and activity data reported to EPA under Subpart S, and in particular, aggregated activity data on lime production by type. Particular attention will be made to also ensuring time-series consistency of the emissions estimates presented in future Inventory reports, consistent with IPCC and UNFCCC guidelines. This is required as the facility-level reporting data from EPA's GHGRP, with the program's initial requirements for reporting of emissions in calendar year 2010, are not available for all inventory years (i.e., 1990 through 2009) as required for this Inventory. In implementing improvements and integration of data from EPA's GHGRP, the latest guidance from the IPCC on the use of facility-level data in national inventories will be relied upon.[16]

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[16] See <http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf>.

4.3 Glass Production (CRF Source Category 2A3)

Glass production is an energy and raw-material intensive process that results in the generation of carbon dioxide (CO_2) from both the energy consumed in making glass and the glass process itself. Emissions from fuels consumed for energy purposes during the production of glass are accounted for in the Energy sector.

Glass production employs a variety of raw materials in a glass-batch. These include formers, fluxes, stabilizers, and sometimes colorants. The major raw materials (i.e., fluxes and stabilizers) which emit process-related CO_2 emissions during the glass melting process are limestone, dolomite, and soda ash. The main former in all types of glass is silica (SiO_2). Other major formers in glass include feldspar and boric acid (i.e., borax). Fluxes are added to lower the temperature at which the batch melts. Most commonly used flux materials are soda ash (sodium carbonate, Na_2CO_3) and potash (potassium carbonate, K_2O). Stabilizers are used to make glass more chemically stable and to keep the finished glass from dissolving and/or falling apart. Commonly used stabilizing agents in glass production are limestone ($CaCO_3$), dolomite ($CaCO_3MgCO_3$), alumina (Al_2O_3), magnesia (MgO), barium carbonate ($BaCO_3$), strontium carbonate ($SrCO_3$), lithium carbonate (Li_2CO_3), and zirconia (ZrO_2) (OIT 2002). Glass makers also use a certain amount of recycled scrap glass (cullet), which comes from in-house return of glassware broken in the process or other glass spillage or retention such as recycling or cullet broker services.

The raw materials (primarily limestone, dolomite and soda ash) release CO_2 emissions in a complex high-temperature chemical reaction during the glass melting process. This process is not directly comparable to the calcination process used in lime manufacturing, cement manufacturing, and process uses of carbonates (i.e., limestone/dolomite use), but has the same net effect in terms of CO_2 emissions (IPCC 2006). The U.S. glass industry can be divided into four main categories: containers, flat (window) glass, fiber glass, and specialty glass. The majority of commercial glass produced is container and flat glass (EPA 2009). The United States is one of the major global exporters of glass. Domestically, demand comes mainly from the construction, auto, bottling, and container industries. There are over 1,500 companies that manufacture glass in the United States, with the largest being Corning, Guardian Industries, Owens-Illinois, and PPG Industries.[17]

In 2016, 458 kilotons of limestone and 2,510 kilotons of soda ash were consumed for glass production (USGS 2015b; Willett 2018). Dolomite consumption data for glass manufacturing was reported to be zero for 2016. Use of limestone and soda ash in glass production resulted in aggregate CO_2 emissions of 1.2 MMT CO_2 Eq. (1,243 kt) (see Table 4-11). Overall, emissions have decreased 19 percent from 1990 through 2016.

Emissions in 2016 decreased approximately 4 percent from 2015 levels while, in general, emissions from glass production have remained relatively constant over the time series with some fluctuations since 1990. In general, these fluctuations were related to the behavior of the export market and the U.S. economy. Specifically, the extended downturn in residential and commercial construction and automotive industries between 2008 and 2010 resulted in reduced consumption of glass products, causing a drop in global demand for limestone/dolomite and soda ash, and a corresponding decrease in emissions. Furthermore, the glass container sector is one of the leading soda ash consuming sectors in the United States. Some commercial food and beverage package manufacturers are shifting from glass containers towards lighter and more cost effective polyethylene terephthalate (PET) based containers, putting downward pressure on domestic consumption of soda ash (USGS 1995 through 2015b).

Table 4-11: CO_2 Emissions from Glass Production (MMT CO_2 Eq. and kt)

Year	MMT CO_2 Eq.	kt
1990	1.5	1,535
2005	1.9	1,928

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[17] Excerpt from Glass & Glass Product Manufacturing Industry Profile, First Research. Available online at: <http://www.firstresearch.com/Industry-Research/Glass-and-Glass-Product-Manufacturing.html>.

2012	1.2	1,248
2013	1.3	1,317
2014	1.3	1,336
2015	1.3	1,299
2016	1.2	1,243

Note: Totals may not sum due to independent rounding

Methodology

Carbon dioxide emissions were calculated based on the *2006 IPCC Guidelines* Tier 3 method by multiplying the quantity of input carbonates (limestone, dolomite, and soda ash) by the carbonate-based emission factor (in metric tons CO_2/metric ton carbonate): limestone, 0.43971; dolomite, 0.47732; and soda ash, 0.41492.

Consumption data for 1990 through 2016 of limestone, dolomite, and soda ash used for glass manufacturing were obtained from the U.S. Geological Survey (USGS) *Minerals Yearbook: Crushed Stone Annual Report* (1995 through 2015a), 2016 preliminary data from the USGS Crushed Stone Commodity Expert (Willett 2018), the *USGS Minerals Yearbook: Soda Ash Annual Report* (1995 through 2015) (USGS 1995 through 2015b), USGS Mineral Industry Surveys for Soda Ash in January 2017 (USGS 2017) and the U.S. Bureau of Mines (1991 and 1993a), which are reported to the nearest ton. During 1990 and 1992, the USGS did not conduct a detailed survey of limestone and dolomite consumption by end-use. Consumption for 1990 was estimated by applying the 1991 percentages of total limestone and dolomite use constituted by the individual limestone and dolomite uses to 1990 total use. Similarly, the 1992 consumption figures were approximated by applying an average of the 1991 and 1993 percentages of total limestone and dolomite use constituted by the individual limestone and dolomite uses to the 1992 total.

Additionally, each year the USGS withholds data on certain limestone and dolomite end-uses due to confidentiality agreements regarding company proprietary data. For the purposes of this analysis, emissive end-uses that contained withheld data were estimated using one of the following techniques: (1) the value for all the withheld data points for limestone or dolomite use was distributed evenly to all withheld end-uses; or (2) the average percent of total limestone or dolomite for the withheld end-use in the preceding and succeeding years.

There is a large quantity of limestone and dolomite reported to the USGS under the categories "unspecified–reported" and "unspecified–estimated." A portion of this consumption is believed to be limestone or dolomite used for glass manufacturing. The quantities listed under the "unspecified" categories were, therefore, allocated to glass manufacturing according to the percent limestone or dolomite consumption for glass manufacturing end use for that year.[18]

Based on the 2016 reported data, the estimated distribution of soda ash consumption for glass production compared to total domestic soda ash consumption is 48 percent (USGS 1995 through 2015b).

Table 4-12: Limestone, Dolomite, and Soda Ash Consumption Used in Glass Production (kt)

Activity	**1990**	**2005**	**2012**	**2013**	**2014**	**2015**	**2016**
Limestone	430	920	555	693	765	699	458
Dolomite	59	541	0	0	0	0	0
Soda Ash	3,177	3,050	2,420	2,440	2,410	2,390	2,510
Total	**3,666**	**4,511**	**2,975**	**3,133**	**3,175**	**3,089**	**2,968**

Uncertainty and Time-Series Consistency

The uncertainty levels presented in this section arise in part due to variations in the chemical composition of limestone used in glass production. In addition to calcium carbonate, limestone may contain smaller amounts of

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[18] This approach was recommended by USGS.

magnesia, silica, and sulfur, among other minerals (potassium carbonate, strontium carbonate and barium carbonate, and dead burned dolomite). Similarly, the quality of the limestone (and mix of carbonates) used for glass manufacturing will depend on the type of glass being manufactured.

The estimates below also account for uncertainty associated with activity data. Large fluctuations in reported consumption exist, reflecting year-to-year changes in the number of survey responders. The uncertainty resulting from a shifting survey population is exacerbated by the gaps in the time series of reports. The accuracy of distribution by end use is also uncertain because this value is reported by the manufacturer of the input carbonates (limestone, dolomite and soda ash) and not the end user. For 2016, there has been no reported consumption of dolomite for glass manufacturing. These data have been reported to USGS by dolomite manufacturers and not end-users (i.e., glass manufacturers). There is a high uncertainty associated with this estimate, as dolomite is a major raw material consumed in glass production. Additionally, there is significant inherent uncertainty associated with estimating withheld data points for specific end uses of limestone and dolomite. The uncertainty of the estimates for limestone and dolomite used in glass making is especially high. Lastly, much of the limestone consumed in the United States is reported as "other unspecified uses;" therefore, it is difficult to accurately allocate this unspecified quantity to the correct end-uses. Further research is needed into alternate and more complete sources of data on carbonate-based raw material consumption by the glass industry. This year, EPA reinitiated dialogue with the USGS National Minerals Information Center Crushed Stone commodity expert to assess the current uncertainty ranges associated with quantities of carbonates consumed for glass production compiled and published in USGS reports.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-13. In 2016, glass production CO_2 emissions were estimated to be between 1.2 and 1.3 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 4 percent below and 4 percent above the emission estimate of 1.2 MMT CO_2 Eq.

Table 4-13: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Glass Production (MMT CO_2 Eq. and Percent)

Source	Gas	2016 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	**Upper Bound**	**Lower Bound**	**Upper Bound**
Glass Production	CO_2	1.2	1.2	1.3	-4%	+4%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2016. Details on the emission trends through time are described in more detail in the Methodology section, above.

For more information on the general QA/QC process applied to this source category, consistent with Volume 1, Chapter 6 of the *2006 IPCC Guidelines*, see the QA/QC and Verification Procedures section in the introduction of the IPPU chapter.

Planned Improvements

As noted in the previous reports, current publicly available activity data shows consumption of only limestone and soda ash for glass manufacturing. While limestone and soda ash are the predominant carbonates used in glass manufacturing, there are other carbonates that are also consumed for glass manufacturing, although in smaller quantities. EPA has initiated review of available activity data on carbonate consumption by type in the glass industry from EPA's Greenhouse Gas Reporting Program (GHGRP) reported annually since 2010, as well as USGS publications.

EPA has initiated review of this activity data and anticipates to finalize assessment for future integration of data reported under EPA's GHGRP in the spring of 2017 to improve the completeness of emission estimates and facilitate category-specific QC per Volume 1 of the *2006 IPCC Guidelines* for the Glass Production source category. EPA's GHGRP has an emission threshold for reporting, so the assessment will consider the completeness of carbonate consumption data for glass production in the United States. Particular attention will also be made to also ensuring time-series consistency of the emissions estimates presented in future Inventory reports, consistent with

IPCC and UNFCCC guidelines. This is required as the facility-level reporting data from EPA's GHGRP, with the program's initial requirements for reporting of emissions in calendar year 2010, are not available for all inventory years (i.e., 1990 through 2009) as required for this Inventory. In implementing improvements and integration of data from EPA's GHGRP, the latest guidance from the IPCC on the use of facility-level data in national inventories will be relied upon.[19] These planned improvements are ongoing and EPA may also initiate research into other sources of activity data for carbonate consumption by the glass industry.

4.4 Other Process Uses of Carbonates (CRF Source Category 2A4)

Limestone ($CaCO_3$), dolomite ($CaCO_3MgCO_3$),[20] and other carbonates such as soda ash, magnesite, and siderite are basic materials used by a wide variety of industries, including construction, agriculture, chemical, metallurgy, glass production, and environmental pollution control. This section addresses only limestone and dolomite use. For industrial applications, carbonates such as limestone and dolomite are heated sufficiently enough to calcine the material and generate CO_2 as a byproduct.

$$CaCO_3 \rightarrow CaO + CO_2$$

$$MgCO_3 \rightarrow MgO + CO_2$$

Examples of such applications include limestone used as a flux or purifier in metallurgical furnaces, as a sorbent in flue gas desulfurization (FGD) systems for utility and industrial plants, and as a raw material for the production of glass, lime, and cement. Emissions from limestone and dolomite used in other process sectors such as cement, lime, glass production, and iron and steel, are excluded from this section and reported under their respective source categories (e.g., Section 4.3, Glass Production). Emissions from soda ash consumption associated with glass manufacturing are reported under Section 4.3 Glass Production (CRF Source Category 2A3). Emissions from fuels consumed for energy purposes during these processes are accounted for in the Energy chapter.

Limestone is widely distributed throughout the world in deposits of varying sizes and degrees of purity. Large deposits of limestone occur in nearly every state in the United States, and significant quantities are extracted for industrial applications. In 2015, the leading limestone producing states were Texas, Missouri, Florida, Ohio, and Kentucky, which contributed 44 percent of the total U.S. output (USGS 1995a through 2017). Similarly, dolomite deposits are also widespread throughout the world. Dolomite deposits are found in the United States, Canada, Mexico, Europe, Africa, and Brazil. In the United States, the leading dolomite producing states are Illinois, Pennsylvania, and New York, which currently contribute more than half of the total U.S. output (USGS 1995a through 2017).

In 2016, 20,864 kt of limestone, 2,816 kt of dolomite, and 2,608 kt of soda ash were consumed for these emissive applications, excluding glass manufacturing (Willett 2018). Usage of limestone, dolomite and soda ash resulted in aggregate CO_2 emissions of 11.0 MMT CO_2 Eq. (10,986 kt) (see Table 4-14 and Table 4-15). While 2016 emissions have decreased 11 percent compared to 2015, overall emissions have increased 75 percent from 1990 through 2016.

Table 4-14: CO_2 Emissions from Other Process Uses of Carbonates (MMT CO_2 Eq.)

Year	Flux Stone	FGD	Magnesium Production	Soda Ash Consumption[a]	Other Miscellaneous Uses[b]	Total
1990	2.6	1.4	0.1	1.4	0.8	6.3
2005	2.6	3.0	0.0	1.3	0.7	7.6

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[19] See <http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf>.

[20] Limestone and dolomite are collectively referred to as limestone by the industry, and intermediate varieties are seldom distinguished.

2012	1.1	5.8	0.0	1.1	1.1	9.1
2013	2.3	6.3	0.0	1.1	1.8	11.5
2014	2.9	7.1	0.0	1.1	1.8	13.0
2015	3.0	7.3	0.0	1.1	0.9	12.3
2016	2.1	6.2	0.0	1.1	1.6	11.0

[a] Soda ash consumption not associated with glass manufacturing.
[b] "Other miscellaneous uses" include chemical stone, mine dusting or acid water treatment, acid neutralization, and sugar refining.
Note: Totals may not sum due to independent rounding.

Table 4-15: CO_2 Emissions from Other Process Uses of Carbonates (kt)

Year	Flux Stone	FGD	Magnesium Production	Soda Ash Consumption[a]	Other Miscellaneous Uses[b]	Total
1990	2,592	1,432	64	1,390	819	6,297
2005	2,649	2,973	0	1,305	718	7,644
2012	1,077	5,797	0	1,097	1,148	9,110
2013	2,307	6,309	0	1,109	1,798	11,524
2014	2,911	7,111	0	1,143	1,790	12,954
2015	3,031	7,335	0	1,075	871	12,312
2016	2,058	6,207	0	1,082	1,638	10,986

[a] Soda ash consumption not associated with glass manufacturing.
[b] "Other miscellaneous uses" include chemical stone, mine dusting or acid water treatment, acid neutralization, and sugar refining.
Note: Totals may not sum due to independent rounding.

Methodology

Carbon dioxide emissions were calculated based on the *2006 IPCC Guidelines* Tier 2 method by multiplying the quantity of limestone or dolomite consumed by the emission factor for limestone or dolomite calcination, respectively – limestone: 0.43971 metric ton CO_2/metric ton carbonate, and dolomite: 0.47732 metric ton CO_2/metric ton carbonate.[21] This methodology was used for flux stone, flue gas desulfurization systems, chemical stone, mine dusting or acid water treatment, acid neutralization, and sugar refining. Flux stone used during the production of iron and steel was deducted from the Other Process Uses of Carbonates source category estimate and attributed to the Iron and Steel Production source category estimate. Similarly, limestone and dolomite consumption for glass manufacturing, cement, and lime manufacturing are excluded from this category and attributed to their respective categories.

Historically, the production of magnesium metal was the only other significant use of limestone and dolomite that produced CO_2 emissions. At the end of 2001, the sole magnesium production plant operating in the United States that produced magnesium metal using a dolomitic process that resulted in the release of CO_2 emissions ceased its operations (USGS 1995b through 2012; USGS 2013).

Consumption data for 1990 through 2016 of limestone and dolomite used for flux stone, flue gas desulfurization systems, chemical stone, mine dusting or acid water treatment, acid neutralization, and sugar refining (see Table 4-16) were obtained from the U.S. Geological Survey (USGS) *Minerals Yearbook: Crushed Stone Annual Report* (1995a through 2017), preliminary data for 2016 from USGS Crushed Stone Commodity Expert (Willett 2018), American Iron and Steel Institute limestone and dolomite consumption data (AISI 2017), and the U.S. Bureau of Mines (1991 and 1993a), which are reported to the nearest ton. The production capacity data for 1990 through 2016 of dolomitic magnesium metal also came from the USGS (1995b through 2012; USGS 2013) and the U.S. Bureau of Mines (1990 through 1993b). During 1990 and 1992, the USGS did not conduct a detailed survey of limestone and

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[21] *2006 IPCC Guidelines*, Volume 3: Chapter 2, Table 2.1.

dolomite consumption by end-use. Consumption for 1990 was estimated by applying the 1991 percentages of total limestone and dolomite use constituted by the individual limestone and dolomite uses to 1990 total use. Similarly, the 1992 consumption figures were approximated by applying an average of the 1991 and 1993 percentages of total limestone and dolomite use constituted by the individual limestone and dolomite uses to the 1992 total.

Additionally, each year the USGS withholds data on certain limestone and dolomite end-uses due to confidentiality agreements regarding company proprietary data. For the purposes of this analysis, emissive end-uses that contained withheld data were estimated using one of the following techniques: (1) the value for all the withheld data points for limestone or dolomite use was distributed evenly to all withheld end-uses; (2) the average percent of total limestone or dolomite for the withheld end-use in the preceding and succeeding years; or (3) the average fraction of total limestone or dolomite for the end-use over the entire time period.

There is a large quantity of crushed stone reported to the USGS under the category “unspecified uses.” A portion of this consumption is believed to be limestone or dolomite used for emissive end uses. The quantity listed for “unspecified uses” was, therefore, allocated to each reported end-use according to each end-use’s fraction of total consumption in that year.[22]

Table 4-16: Limestone and Dolomite Consumption (kt)

Activity	1990	2005	2012	2013	2014	2015	2016
Flux Stone	6,737	7,022	3,666	6,345	7,599	7,834	5,658
Limestone	5,804	3,165	3,108	4,380	4,243	4,590	2,842
Dolomite	933	3,857	559	1,965	3,356	3,244	2,816
FGD	3,258	6,761	13,185	14,347	16,171	16,680	14,116
Other Miscellaneous Uses	1,835	1,632	2,610	3,973	4,069	1,982	3,726
Total	**11,830**	**15,415**	**19,461**	**24,665**	**27,839**	**26,496**	**23,500**

Once produced, most soda ash is consumed in chemical production, with minor amounts in soap production, pulp and paper, flue gas desulfurization, and water treatment (excluding soda ash consumption for glass manufacturing). As soda ash is consumed for these purposes, additional CO_2 is usually emitted. In these applications, it is assumed that one mole of carbon is released for every mole of soda ash used. Thus, approximately 0.113 metric tons of carbon (or 0.415 metric tons of CO_2) are released for every metric ton of soda ash consumed. The activity data for soda ash consumption (see Table 4-17) for 1990 to 2016 were obtained from the U.S. Geological Survey (USGS) *Minerals Yearbook for Soda Ash* (1994 through 2015b) and USGS *Mineral Industry Surveys for Soda Ash* (USGS 2017a). Soda ash consumption data[23] were collected by the USGS from voluntary surveys of the U.S. soda ash industry.

Table 4-17: Soda Ash Consumption Not Associated with Glass Manufacturing (kt)

Activity	1990	2005	2012	2013	2014	2015	2016
Soda Ash[a]	3,351	3,144	2,645	2,674	2,754	2,592	2,608
Total	**3,351**	**3,144**	**2,645**	**2,674**	**2,754**	**2,592**	**2,608**

[a] Soda ash consumption is sales reported by producers which exclude imports. Historically, imported soda ash is less than 1 percent of the total U.S. consumption (Kostick 2012).

Uncertainty and Time-Series Consistency

The uncertainty levels presented in this section account for uncertainty associated with activity data. Data on limestone and dolomite consumption are collected by USGS through voluntary national surveys. USGS contacts the mines (i.e., producers of various types of crushed stone) for annual sales data. Data on other carbonate consumption are not readily available. The producers report the annual quantity sold to various end-users and industry types.

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[22] This approach was recommended by USGS, the data collection agency.

[23] EPA has assessed feasibility of using emissions information (including activity data) from EPA’s GHGRP program; however, at this time, the aggregated information associated with production of soda ash did not meet criteria to shield underlying confidential business information (CBI) from public disclosure.

USGS estimates the historical response rate for the crushed stone survey to be approximately 70 percent, and the rest is estimated by USGS. Large fluctuations in reported consumption exist, reflecting year-to-year changes in the number of survey responders. The uncertainty resulting from a shifting survey population is exacerbated by the gaps in the time series of reports. The accuracy of distribution by end use is also uncertain because this value is reported by the producer/mines and not the end user. Additionally, there is significant inherent uncertainty associated with estimating withheld data points for specific end uses of limestone and dolomite. Lastly, much of the limestone consumed in the United States is reported as "other unspecified uses;" therefore, it is difficult to accurately allocate this unspecified quantity to the correct end-uses. This year, EPA reinitiated dialogue with the USGS National Minerals Information Center Crushed Stone commodity expert to assess the current uncertainty ranges associated with the limestone and dolomite consumption data compiled and published by USGS. During this discussion, the expert confirmed that EPA's range of uncertainty was still reasonable (Willett 2017b).

Uncertainty in the estimates also arises in part due to variations in the chemical composition of limestone. In addition to calcium carbonate, limestone may contain smaller amounts of magnesia, silica, and sulfur, among other minerals. The exact specifications for limestone or dolomite used as flux stone vary with the pyrometallurgical process and the kind of ore processed.

For emissions from soda ash consumption, the primary source of uncertainty results from the fact that these emissions are dependent upon the type of processing employed by each end-use. Specific emission factors for each end-use are not available, so a Tier 1 default emission factor is used for all end uses. Therefore, there is uncertainty surrounding the emission factors from the consumption of soda ash. Additional uncertainty comes from the reported consumption and allocation of consumption within sectors that is collected on a quarterly basis by the USGS. Efforts have been made to categorize company sales within the correct end-use sector.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-18. Carbon dioxide emissions from other process uses of carbonates in 2016 were estimated to be between 9.8 and 12.7 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 12 percent below and 15 percent above the emission estimate of 11.0 MMT CO_2 Eq.

Table 4-18: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Other Process Uses of Carbonates (MMT CO_2 Eq. and Percent)

Source	Gas	2016 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Other Process Uses of Carbonates	CO_2	11.0	9.8	12.7	-12%	+15%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2016. Details on the emission trends through time are described in more detail in the Methodology section, above.

For more information on the general QA/QC process applied to this source category, consistent with Volume 1, Chapter 6 of the *2006 IPCC Guidelines*, see the QA/QC and Verification Procedures section in the introduction of the IPPU chapter.

Recalculations Discussion

Emissions from soda ash consumption in chemical production processes were removed from Section 4.12 Soda Ash Production (CRF Category 2B7) and are now reported in this section to be consistent with *2006 IPCC Guidelines*. This revision resulted in an increase in emissions associated with the other process uses of carbonates source category ranging from approximately 10 percent to 35 percent across the time series of 1990 through 2015 compared to the previous Inventory (i.e., 1990 through 2015 report).

Planned Improvements

EPA plans to continue the dialogue with USGS to assess uncertainty ranges for activity data used to estimate emissions from other process use of carbonates.

4.5 Ammonia Production (CRF Source Category 2B1)

Emissions of carbon dioxide (CO_2) occur during the production of synthetic ammonia, primarily through the use of natural gas, petroleum coke, or naphtha as a feedstock. The natural gas-, naphtha-, and petroleum coke-based processes produce CO_2 and hydrogen (H_2), the latter of which is used in the production of ammonia. The brine electrolysis process for production of ammonia does not lead to process-based CO_2 emissions. Due to national circumstances, emissions from fuels consumed for energy purposes during the production of ammonia are accounted for in the Energy chapter. More information on this approach can be found in the Methodology section, below.

In the United States, the majority of ammonia is produced using a natural gas feedstock; however, one synthetic ammonia production plant located in Kansas is producing ammonia from petroleum coke feedstock. In some U.S. plants, some of the CO_2 produced by the process is captured and used to produce urea rather than being emitted to the atmosphere. There are approximately 13 companies operating 26 ammonia producing facilities in 17 states. More than 55 percent of domestic ammonia production capacity is concentrated in the states of Louisiana (29 percent), Oklahoma (20 percent), and Texas (6 percent) (USGS 2017).

There are five principal process steps in synthetic ammonia production from natural gas feedstock. The primary reforming step converts methane (CH_4) to CO_2, carbon monoxide (CO), and H_2 in the presence of a catalyst. Only 30 to 40 percent of the CH_4 feedstock to the primary reformer is converted to CO and CO_2 in this step of the process. The secondary reforming step converts the remaining CH_4 feedstock to CO and CO_2. The CO in the process gas from the secondary reforming step (representing approximately 15 percent of the process gas) is converted to CO_2 in the presence of a catalyst, water, and air in the shift conversion step. Carbon dioxide is removed from the process gas by the shift conversion process, and the hydrogen gas is combined with the nitrogen (N_2) gas in the process gas during the ammonia synthesis step to produce ammonia. The CO_2 is included in a waste gas stream with other process impurities and is absorbed by a scrubber solution. In regenerating the scrubber solution, CO_2 is released from the solution.

The conversion process for conventional steam reforming of CH_4, including the primary and secondary reforming and the shift conversion processes, is approximately as follows:

$$0.88CH_4 + 1.26Air + 1.24H_2O \rightarrow 0.88CO_2 + N_2 + 3H_2$$

$$N_2 + 3H_2 \rightarrow 2NH_3$$

To produce synthetic ammonia from petroleum coke, the petroleum coke is gasified and converted to CO_2 and H_2. These gases are separated, and the H_2 is used as a feedstock to the ammonia production process, where it is reacted with N_2 to form ammonia.

Not all of the CO_2 produced during the production of ammonia is emitted directly to the atmosphere. Some of the ammonia and some of the CO_2 produced by the synthetic ammonia process are used as raw materials in the production of urea [$CO(NH_2)_2$], which has a variety of agricultural and industrial applications.

The chemical reaction that produces urea is:

$$2NH_3 + CO_2 \rightarrow NH_2COONH_4 \rightarrow CO(NH_2)_2 + H_2O$$

Only the CO_2 emitted directly to the atmosphere from the synthetic ammonia production process is accounted for in determining emissions from ammonia production. The CO_2 that is captured during the ammonia production process and used to produce urea does not contribute to the CO_2 emission estimates for ammonia production presented in this section. Instead, CO_2 emissions resulting from the consumption of urea are attributed to the urea consumption or urea application source category (under the assumption that the carbon stored in the urea during its manufacture is released into the environment during its consumption or application). Emissions of CO_2 resulting from agricultural applications of urea are accounted for in the Agriculture chapter. Previously, these emission estimates from the agricultural application of urea were accounted for in the *Cropland Remaining Cropland* section of the Land Use, Land Use Change, and Forestry chapter. Emissions of CO_2 resulting from non-agricultural applications of urea (e.g., use as a feedstock in chemical production processes) are accounted for in Section 4.6 Urea Consumption for Non-Agricultural Purposes of this chapter.

Total emissions of CO_2 from ammonia production in 2016 were 12.2 MMT CO_2 Eq. (12,194 kt), and are summarized in Table 4-19 and Table 4-20. Ammonia production relies on natural gas as both a feedstock and a fuel, and as such, market fluctuations and volatility in natural gas prices affect the production of ammonia. Since 1990, emissions from ammonia production have decreased by 6 percent. Emissions in 2016 have increased by approximately 12 percent from the 2015 levels.

Table 4-19: CO_2 Emissions from Ammonia Production (MMT CO_2 Eq.)

Source	1990	2005	2012	2013	2014	2015	2016
Ammonia Production	13.0	9.2	9.4	10.0	9.6	10.9	12.2
Total	**13.0**	**9.2**	**9.4**	**10.0**	**9.6**	**10.9**	**12.2**

Table 4-20: CO_2 Emissions from Ammonia Production (kt)

Source	1990	2005	2012	2013	2014	2015	2016
Ammonia Production	13,047	9,196	9,377	9,962	9,619	10,883	12,194
Total	**13,047**	**9,196**	**9,377**	**9,962**	**9,619**	**10,883**	**12,194**

Methodology

For the U.S. Inventory, CO_2 emissions from the production of synthetic ammonia from natural gas feedstock are estimated using a country-specific approach modified from the *2006 IPCC Guidelines* (IPCC 2006) Tier 1 and 2 methods. In the country-specific approach, emissions are not based on total fuel requirement per the *2006 IPCC Guidelines* due to data disaggregation limitations of energy statistics provided by the Energy Information Administration (EIA). A country-specific emission factor is developed and applied to national ammonia production to estimate emissions. The method uses a CO_2 emission factor published by the European Fertilizer Manufacturers Association (EFMA) that is based on natural gas-based ammonia production technologies that are similar to those employed in the United States. This CO_2 emission factor of 1.2 metric tons CO_2/metric ton NH_3 (EFMA 2000a) is applied to the percent of total annual domestic ammonia production from natural gas feedstock.

Emissions of CO_2 from ammonia production are then adjusted to account for the use of some of the CO_2 produced from ammonia production as a raw material in the production of urea. The CO_2 emissions reported for ammonia production are reduced by a factor of 0.733 multiplied by total annual domestic urea production. This corresponds to a stoichiometric CO_2/urea factor of 44/60, assuming complete conversion of ammonia (NH_3) and CO_2 to urea (IPCC 2006; EFMA 2000b).

All synthetic ammonia production and subsequent urea production are assumed to be from the same process—conventional catalytic reforming of natural gas feedstock, with the exception of ammonia production from petroleum coke feedstock at one plant located in Kansas. Annual ammonia and urea production are shown in Table 4-21. The CO_2 emission factor for production of ammonia from petroleum coke is based on plant-specific data, wherein all carbon contained in the petroleum coke feedstock that is not used for urea production is assumed to be emitted to the atmosphere as CO_2 (Bark 2004). Ammonia and urea are assumed to be manufactured in the same manufacturing complex, as both the raw materials needed for urea production are produced by the ammonia production process. The CO_2 emission factor of 3.57 metric tons CO_2/metric ton NH_3 for the petroleum coke feedstock process (Bark 2004) is applied to the percent of total annual domestic ammonia production from petroleum coke feedstock.

The emission factor of 1.2 metric ton CO_2/metric ton NH_3 for production of ammonia from natural gas feedstock was taken from the EFMA Best Available Techniques publication, Production of Ammonia (EFMA 2000a). The EFMA reported an emission factor range of 1.15 to 1.30 metric ton CO_2/metric ton NH_3, with 1.2 metric ton CO_2/metric ton NH_3 as a typical value (EFMA 2000a). Technologies (e.g., catalytic reforming process, etc.) associated with this factor are found to closely resemble those employed in the United States for use of natural gas as a feedstock. The EFMA reference also indicates that more than 99 percent of the CH_4 feedstock to the catalytic reforming process is ultimately converted to CO_2.

The consumption of natural gas and petroleum coke as fossil fuel feedstocks for NH_3 production are adjusted for within the Energy chapter as these fuels were consumed during non-energy related activities. More information on this methodology is described in Annex 2.1, Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion. See the Planned Improvements section on improvements of reporting fuel and feedstock CO_2 emissions utilizing EPA's GHGRP data to improve consistency with *2006 IPCC Guidelines*.

The total ammonia production data for 2011 through 2016 were obtained from American Chemistry Council (2017). For years before 2011, ammonia production data (see Table 4-21) were obtained from Coffeyville Resources (Coffeyville 2005, 2006, 2007a, 2007b, 2009, 2010, 2011, and 2012) and the Census Bureau of the U.S. Department of Commerce (U.S. Census Bureau 1991 through 1994, 1998 through 2011) as reported in Current Industrial Reports Fertilizer Materials and Related Products annual and quarterly reports. Urea-ammonia nitrate production from petroleum coke for years through 2011 was obtained from Coffeyville Resources (Coffeyville 2005, 2006, 2007a, 2007b, 2009, 2010, 2011, and 2012), and from *CVR Energy, Inc. Annual Report* (CVR 2012, 2014, 2015, 2016, and 2017) for 2012 through 2016. Urea production data for 1990 through 2008 were obtained from the *Minerals Yearbook: Nitrogen* (USGS 1994 through 2009). Urea production data for 2009 through 2010 were obtained from the U.S. Census Bureau (U.S. Census Bureau 2010 and 2011). The U.S. Census Bureau ceased collection of urea production statistics, and urea production data for 2011 through 2015 were obtained from the *Minerals Yearbook: Nitrogen* (USGS 2015, 2016, 2017). USGS urea production data for 2016 were not yet published and so 2015 data were used as a proxy.

Table 4-21: Ammonia Production and Urea Production (kt)

Year	Ammonia Production	Urea Production
1990	15,425	7,450
2005	10,143	5,270
2012	10,305	5,220
2013	10,930	5,480
2014	10,515	5,230
2015	11,765	5,540
2016	12,305	5,540

Uncertainty and Time-Series Consistency

The uncertainties presented in this section are primarily due to how accurately the emission factor used represents an average across all ammonia plants using natural gas feedstock. Uncertainties are also associated with ammonia production estimates and the assumption that all ammonia production and subsequent urea production was from the same process—conventional catalytic reforming of natural gas feedstock, with the exception of one ammonia production plant located in Kansas that is manufacturing ammonia from petroleum coke feedstock. Uncertainty is also associated with the representativeness of the emission factor used for the petroleum coke-based ammonia process. It is also assumed that ammonia and urea are produced at collocated plants from the same natural gas raw material. The uncertainty of the total urea production activity data, based on USGS *Minerals Yearbook: Nitrogen* data, is a function of the reliability of reported production data and is influenced by the completeness of the survey responses. In addition, due to the fact that 2016 nitrogen data has yet to be published, 2015 is used as a proxy which may result in greater uncertainty.

Recovery of CO_2 from ammonia production plants for purposes other than urea production (e.g., commercial sale, etc.) has not been considered in estimating the CO_2 emissions from ammonia production, as data concerning the disposition of recovered CO_2 are not available. Such recovery may or may not affect the overall estimate of CO_2 emissions depending upon the end use to which the recovered CO_2 is applied. Further research is required to determine whether byproduct CO_2 is being recovered from other ammonia production plants for application to end uses that are not accounted for elsewhere.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-22. Carbon dioxide emissions from ammonia production in 2016 were estimated to be between 11.3 and 13.1 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 7 percent below and 7 percent above the emission estimate of 12.2 MMT CO_2 Eq.

Table 4-22: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Ammonia Production (MMT CO_2 Eq. and Percent)

Source	Gas	2016 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Ammonia Production	CO_2	12.2	11.3	13.1	-7%	+7%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2016. Details on the emission trends through time are described in more detail in the Methodology section, above.

For more information on the general QA/QC process applied to this source category, consistent with Volume 1, Chapter 6 of the *2006 IPCC Guidelines*, see the QA/QC and Verification Procedures section in the introduction of the IPPU chapter.

Recalculations Discussion

For the previous Inventory (i.e., 1990 through 2015 report), 2015 urea production data were not published and so 2014 activity data were used as a proxy. Production estimates for urea production for 2015 were updated relative to the previous Inventory using information obtained from the recent *2015 Minerals Yearbook: Nitrogen* (USGS 2017). This update resulted in a slight increase of emissions by approximately 6 percent for 2015 relative to the previous Inventory.

Planned Improvements

Future improvements involve continuing to evaluate and analyze data reported under EPA's GHGRP to improve the emission estimates for the Ammonia Production source category, in particular new data from updated reporting requirements finalized in October of 2014 (79 FR 63750) and December 2016 (81 FR 89188),[24] that include facility-level ammonia production data and feedstock consumption. This data will first be reported by facilities in 2018 and available post-verification to assess in early 2019 for use in future Inventories (e.g., 2020 Inventory report) if the data meets GHGRP CBI aggregation criteria. Particular attention will be made to ensure time-series consistency of the emission estimates presented in future Inventory reports, along with application of appropriate category-specific QC procedures consistent with IPCC and UNFCCC guidelines. For example, data reported in 2018 will reflect activity in 2017 and may not be representative of activity in prior years of the time series. This assessment is required as the new facility-level reporting data from EPA's GHGRP associated with new requirements are only applicable starting with reporting of emissions in calendar year 2017, and thus are not available for all inventory years (i.e., 1990 through 2016) as required for this Inventory.

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[24] See <https://www.epa.gov/ghgreporting/historical-rulemakings>.

In implementing improvements and integration of data from EPA's GHGRP, the latest guidance from the IPCC on the use of facility-level data in national inventories will be relied upon.[25] Specifically, the planned improvements include assessing the anticipated new data to update the emission factors to include both fuel and feedstock CO_2 emissions to improve consistency with *2006 IPCC Guidelines,* in addition to reflecting CO_2 capture and storage practices (beyond use of CO_2 for urea production). Methodologies will also be updated if additional ammonia production plants are found to use hydrocarbons other than natural gas for ammonia production. Due to limited resources and ongoing data collection efforts, this planned improvement is still in development and so is not incorporated into this Inventory.

4.6 Urea Consumption for Non-Agricultural Purposes

Urea is produced using ammonia and carbon dioxide (CO_2) as raw materials. All urea produced in the United States is assumed to be produced at ammonia production facilities where both ammonia and CO_2 are generated. There were 31 plants producing ammonia in the United States during 2016, with two additional plants sitting idle for the entire year (USGS 2017b).

The chemical reaction that produces urea is:

$$2NH_3 + CO_2 \rightarrow NH_2COONH_4 \rightarrow CO(NH_2)_2 + H_2O$$

This section accounts for CO_2 emissions associated with urea consumed exclusively for non-agricultural purposes. Carbon dioxide emissions associated with urea consumed for fertilizer are accounted for in the Agriculture chapter.

Urea is used as a nitrogenous fertilizer for agricultural applications and also in a variety of industrial applications. The industrial applications of urea include its use in adhesives, binders, sealants, resins, fillers, analytical reagents, catalysts, intermediates, solvents, dyestuffs, fragrances, deodorizers, flavoring agents, humectants and dehydrating agents, formulation components, monomers, paint and coating additives, photosensitive agents, and surface treatments agents. In addition, urea is used for abating nitrogen oxide (NO_x) emissions from coal-fired power plants and diesel transportation motors.

Emissions of CO_2 from urea consumed for non-agricultural purposes in 2016 were estimated to be 4.0 MMT CO_2 Eq. (3,959 kt), and are summarized in Table 4-23 and Table 4-24. Net CO_2 emissions from urea consumption for non-agricultural purposes in 2016 have increased by approximately 5 percent from 1990 and decreased by approximately 5 percent from 2015. The significant decrease in emissions during 2014 can be attributed to a decrease in the amount of urea imported by the United States during that year.

Table 4-23: CO_2 Emissions from Urea Consumption for Non-Agricultural Purposes (MMT CO_2 Eq.)

Source	1990		2005		2012	2013	2014	2015	2016
Urea Consumption	3.8		3.7		4.4	4.1	1.5	4.2	4.0
Total	**3.8**		**3.7**		**4.4**	**4.1**	**1.5**	**4.2**	**4.0**

Table 4-24: CO_2 Emissions from Urea Consumption for Non-Agricultural Purposes (kt)

Source	1990		2005		2012	2013	2014	2015	2016
Urea Consumption	3,784		3,653		4,392	4,074	1,541	4,169	3,959
Total	**3,784**		**3,653**		**4,392**	**4,074**	**1,541**	**4,169**	**3,959**

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[25] See <http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf>.

Methodology

Emissions of CO_2 resulting from urea consumption for non-agricultural purposes are estimated by multiplying the amount of urea consumed in the United States for non-agricultural purposes by a factor representing the amount of CO_2 used as a raw material to produce the urea. This method is based on the assumption that all of the carbon in urea is released into the environment as CO_2 during use, and consistent with the *2006 IPCC Guidelines*.

The amount of urea consumed for non-agricultural purposes in the United States is estimated by deducting the quantity of urea fertilizer applied to agricultural lands, which is obtained directly from the Agriculture chapter (see Table 5-25) and is reported in Table 4-25, from the total domestic supply of urea. In previous Inventory reports, the quantity of urea fertilizer applied to agricultural lands was obtained directly from the *Cropland Remaining Cropland* section of the Land Use, Land Use Change, and Forestry chapter. The domestic supply of urea is estimated based on the amount of urea produced plus the sum of net urea imports and exports. A factor of 0.733 tons of CO_2 per ton of urea consumed is then applied to the resulting supply of urea for non-agricultural purposes to estimate CO_2 emissions from the amount of urea consumed for non-agricultural purposes. The 0.733 tons of CO_2 per ton of urea emission factor is based on the stoichiometry of producing urea from ammonia and CO_2. This corresponds to a stoichiometric CO_2/urea factor of 44/60, assuming complete conversion of NH_3 and CO_2 to urea (IPCC 2006; EFMA 2000).

Urea production data for 1990 through 2008 were obtained from the *Minerals Yearbook: Nitrogen* (USGS 1994 through 2009). Urea production data for 2009 through 2010 were obtained from the U.S. Census Bureau (2011). The U.S. Census Bureau ceased collection of urea production statistics in 2011, therefore, urea production data from 2011 to 2015 were obtained from the *Minerals Yearbook: Nitrogen* (USGS 2014 through 2017a). Urea production data for 2016 are not yet publicly available and so 2015 data (USGS 2015) have been used as proxy.

Urea import data for 2016 are not yet publicly available and so 2015 data have been used as proxy. Urea import data for 2013 to 2015 were obtained from the *Minerals Yearbook: Nitrogen* (USGS 2016; USGS 2017a). Urea import data for 2011 and 2012 were taken from U.S. Fertilizer Import/Exports from the United States Department of Agriculture (USDA) Economic Research Service Data Sets (U.S. Department of Agriculture 2012). USDA suspended updates to this data after 2012. Urea import data for the previous years were obtained from the U.S. Census Bureau *Current Industrial Reports Fertilizer Materials and Related Products* annual and quarterly reports for 1997 through 2010 (U.S. Census Bureau 2001 through 2011), The Fertilizer Institute (TFI 2002) for 1993 through 1996, and the United States International Trade Commission Interactive Tariff and Trade DataWeb (U.S. ITC 2002) for 1990 through 1992 (see Table 4-25).

Urea export data for 2016 are not yet publicly available and so 2015 data have been used as proxy. Urea export data for 2013 to 2015 were obtained from the *Minerals Yearbook: Nitrogen* (USGS 2016; USGS 2017a). Urea export data for 1990 through 2012 were taken from U.S. Fertilizer Import/Exports from USDA Economic Research Service Data Sets (U.S. Department of Agriculture 2012). USDA suspended updates to this data after 2012.

Table 4-25: Urea Production, Urea Applied as Fertilizer, Urea Imports, and Urea Exports (kt)

Year	Urea Production	Urea Applied as Fertilizer	Urea Imports	Urea Exports
1990	7,450	3,296	1,860	854
2005	5,270	4,779	5,026	536
2012	5,220	5,838	6,944	336
2013	5,480	6,059	6,470	335
2014	5,230	6,188	3,510	451
2015	5,540	6,665	7,190	380
2016	5,540	6,952	7,190	380

Uncertainty and Time-Series Consistency

There is limited publicly-available data on the quantities of urea produced and consumed for non-agricultural purposes. Therefore, the amount of urea used for non-agricultural purposes is estimated based on a balance that relies on estimates of urea production, urea imports, urea exports, and the amount of urea used as fertilizer. The primary uncertainties associated with this source category are associated with the accuracy of these estimates as well as the fact that each estimate is obtained from a different data source. Because urea production estimates are no longer available from the USGS, there is additional uncertainty associated with urea produced beginning in 2011. There is also uncertainty associated with the assumption that all of the carbon in urea is released into the environment as CO_2 during use.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-26. Carbon dioxide emissions associated with urea consumption for non-agricultural purposes were estimated to be between 3.5 and 4.4 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 12 percent below and 12 percent above the emission estimate of 4.0 MMT CO_2 Eq.

Table 4-26: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Urea Consumption for Non-Agricultural Purposes (MMT CO_2 Eq. and Percent)

Source	Gas	2016 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Urea Consumption for Non-Agricultural Purposes	CO_2	4.0	3.5	4.4	-12%	+12%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2016. Details on the emission trends through time are described in more detail in the Methodology section, above.

For more information on the general QA/QC process applied to this source category, consistent with Volume 1, Chapter 6 of the *2006 IPCC Guidelines*, see the QA/QC and Verification Procedures section in the introduction of the IPPU chapter.

Recalculations Discussion

The amount of urea consumed for agricultural purposes (used for calculating urea consumption for non-agricultural purposes) in the United States for the years 1990 through 2016 was revised based on updated urea application estimates obtained from the Agriculture chapter (see Table 5-25). These updates resulted in the following changes to the emission estimates relative to the previous Inventory: a decrease of less than 1 percent in 2012, an increase of 1.5 percent in 2013, an increase of 12 percent in 2014, and an increase of 270 percent in 2015. As stated previously in the Methodology section, in previous Inventories the quantity of urea fertilizer applied to agricultural lands was obtained directly from the *Cropland Remaining Cropland* section of the Land Use, Land-Use Change, and Forestry chapter; urea consumption is reported in the Agriculture chapter for the current report.

4.7 Nitric Acid Production (CRF Source Category 2B2)

Nitrous oxide (N_2O) is emitted during the production of nitric acid (HNO_3), an inorganic compound used primarily to make synthetic commercial fertilizers. It is also a major component in the production of adipic acid—a feedstock for nylon—and explosives. Virtually all of the nitric acid produced in the United States is manufactured by the high-temperature catalytic oxidation of ammonia (EPA 1998). There are two different nitric acid production methods: weak nitric acid and high-strength nitric acid. The first method utilizes oxidation, condensation, and absorption to produce nitric acid at concentrations between 30 and 70 percent nitric acid. High-strength acid (90 percent or greater nitric acid) can be produced from dehydrating, bleaching, condensing, and absorption of the weak nitric acid. The basic process technology for producing nitric acid has not changed significantly over time. Most U.S. plants were built between 1960 and 2000. As of 2016, there were 35 active weak nitric acid production plants, including one high-strength nitric acid production plant in the United States (EPA 2010; EPA 2017).

During this reaction, N_2O is formed as a byproduct and is released from reactor vents into the atmosphere. Emissions from fuels consumed for energy purposes during the production of nitric acid are accounted for in the Energy chapter.

Nitric acid is made from the reaction of ammonia (NH_3) with oxygen (O_2) in two stages. The overall reaction is:

$$4NH_3 + 8O_2 \rightarrow 4HNO_3 + 4H_2O$$

Currently, the nitric acid industry controls emissions of NO and NO_2 (i.e., NO_x). As such, the industry in the United States uses a combination of non-selective catalytic reduction (NSCR) and selective catalytic reduction (SCR) technologies. In the process of destroying NO_x, NSCR systems are also very effective at destroying N_2O. However, NSCR units are generally not preferred in modern plants because of high energy costs and associated high gas temperatures. NSCR systems were installed in nitric plants built between 1971 and 1977 with NSCRs installed at approximately one-third of the weak acid production plants. U.S. facilities are using both tertiary (i.e., NSCR) and secondary controls (i.e., alternate catalysts).

Nitrous oxide emissions from this source were estimated to be 10.2 MMT CO_2 Eq. (34 kt of N_2O) in 2016 (see Table 4-27). Emissions from nitric acid production have decreased by 16 percent since 1990, with the trend in the time series closely tracking the changes in production. Emissions have decreased by 30 percent since 1997, the highest year of production in the time series.

Table 4-27: N_2O Emissions from Nitric Acid Production (MMT CO_2 Eq. and kt N_2O)

Year	MMT CO_2 Eq.	kt N_2O
1990	12.1	41
2005	11.3	38
2012	10.5	35
2013	10.7	36
2014	10.9	37
2015	11.6	39
2016	10.2	34

Methodology

Emissions of N_2O were calculated using the estimation methods provided by the *2006 IPCC Guidelines* and country-specific methods from EPA's GHGRP. The *2006 IPCC Guidelines* Tier 2 method was used to estimate emissions from nitric acid production for 1990 through 2009, and a country-specific approach similar to the IPCC Tier 3 method was used to estimate N_2O emissions for 2010 through 2016.

2010 through 2016

Process N_2O emissions and nitric acid production data were obtained directly from EPA's GHGRP for 2010 through 2016 by aggregating reported facility-level data (EPA 2017). In the United States, all nitric acid facilities producing weak nitric acid (30 to 70 percent in strength) are required to report annual greenhouse gas emissions data to EPA as per the requirements of its GHGRP. As of 2016, there were 35 facilities that reported to EPA, including the known single high-strength nitric acid production facility in the United States (EPA 2017). All nitric acid (weak acid) facilities are required to calculate process emissions using a site-specific emission factor developed through annual performance testing under typical operating conditions or by directly measuring N_2O emissions using monitoring equipment.[26] The high-strength nitric acid facility also reports N_2O emissions associated with weak acid production and this may capture all relevant emissions, pending additional further EPA research. More details on the calculation, monitoring and QA/QC methods applicable to nitric acid facilities can be found under Subpart V: Nitric Acid Production of the regulation, Part 98.[27] EPA verifies annual facility-level GHGRP reports through a multi-step process (e.g., combination of electronic checks and manual reviews) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent. Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred.[28]

To calculate emissions from 2010 through 2016, the GHGRP nitric acid production data are utilized to develop weighted country-specific emission factors used to calculate emissions estimates. Based on aggregated nitric acid production data by abatement type (i.e., with, without) provided by EPA's GHGRP, the percent of production values and associated emissions of nitric acid with and without abatement technologies are calculated. These percentages are the basis for developing the country-specific weighted emission factors which vary from year to year based on the amount of nitric acid production with and without abatement technologies.

1990 through 2009

Using GHGRP data for 2010,[29] country-specific N_2O emission factors were calculated for nitric acid production with abatement and without abatement (i.e., controlled and uncontrolled emission factors), as previously stated. The following 2010 emission factors were derived for production with abatement and without abatement: 3.3 kg N_2O/metric ton HNO_3 produced at plants using abatement technologies (e.g., tertiary systems such as NSCR systems) and 5.99 kg N_2O/metric ton HNO_3 produced at plants not equipped with abatement technology. Country-specific weighted emission factors were derived by weighting these emission factors by percent production with abatement and without abatement over time periods 1990 through 2008 and 2009. These weighted emission factors were used to estimate N_2O emissions from nitric acid production for years prior to the availability of GHGRP data (i.e., 1990 through 2008 and 2009). A separate weighted factor is included for 2009 due to data availability for that year. At that time, EPA had initiated compilation of a nitric acid database to improve estimation of emissions from this industry and obtained updated information on application of controls via review of permits and outreach with facilities and trade associations. The research indicated recent installation of abatement technologies at additional facilities.

Based on the available data, it was assumed that emission factors for 2010 would be more representative of operating conditions in 1990 through 2009 than more recent years. Initial review of historical data indicates that percent production with and without abatement can change over time and also year over year due to changes in application of facility-level abatement technologies, maintenance of abatement technologies, and also due to plant closures and start-ups (EPA 2012, 2013; Desai 2012; CAR 2013). The installation dates of N_2O abatement technologies are not known at most facilities, but it is assumed that facilities reporting abatement technology use

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[26] Facilities must use standard methods, either EPA Method 320 or ASTM D6348-03 and must follow associated QA/QC procedures consistent during these performance test consistent with category-specific QC of direct emission measurements.

[27] See <http://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title40/40cfr98_main_02.tpl>.

[28] See <https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf>.

[29] National N_2O process emissions, national production, and national share of nitric acid production with abatement and without abatement technology was aggregated from the GHGRP facility-level data for 2010 to 2016 (i.e., percent production with and without abatement).

have had this technology installed and operational for the duration of the time series considered in this report (especially NSCRs).

The country-specific weighted N_2O emission factors were used in conjunction with annual production to estimate N_2O emissions for 1990 through 2009, using the following equations:

$$E_i = P_i \times EF_{weighted,i}$$

$$EF_{weighted,i} = \left[\left(\%P_{C,i} \times EF_c\right) + \left(\%P_{unc,i} \times EF_{unc}\right)\right]$$

where,

E_i = Annual N_2O Emissions for year i (kg/yr)
P_i = Annual nitric acid production for year i (metric tons HNO_3)
$EF_{weighted,i}$ = Weighted N_2O emission factor for year i (kg N_2O/metric ton HNO_3)
$\%P_{c,i}$ = Percent national production of HNO_3 with N_2O abatement technology (%)
EF_c = N_2O emission factor, with abatement technology (kg N_2O/metric ton HNO_3)
$\%P_{unc,i}$ = Percent national production of HNO_3 without N_2O abatement technology (%)
EF_{unc} = N_2O emission factor, without abatement technology (kg N_2O/metric ton HNO_3)
i = year from 1990 through 2009

- For 2009: Weighted N_2O emission factor = 5.46 kg N_2O/metric ton HNO_3.
- For 1990 through 2008: Weighted N_2O emission factor = 5.66 kg N_2O/metric ton HNO_3.

Nitric acid production data for the United States for 1990 through 2009 were obtained from the U.S. Census Bureau (U.S. Census Bureau 2008, 2009, 2010a, 2010b) (see Table 4-28). Publicly-available information on plant-level abatement technologies was used to estimate the shares of nitric acid production with and without abatement for 2008 and 2009 (EPA 2012, 2013; Desai 2012; CAR 2013). EPA has previously conducted a review of operating permits to obtain more current information due to the lack of publicly-available data on use of abatement technologies for 1990 through 2007, as stated previously; therefore, the share of national production with and without abatement for 2008 was assumed to be constant for 1990 through 2007.

Table 4-28: Nitric Acid Production (kt)

Year	kt
1990	7,200
2005	6,710
2012	7,460
2013	7,580
2014	7,660
2015	7,210
2016	7,810

Uncertainty and Time-Series Consistency

Uncertainty associated with the parameters used to estimate N_2O emissions includes the share of U.S. nitric acid production attributable to each emission abatement technology over the time series (especially prior to 2010), and the associated emission factors applied to each abatement technology type. While some information has been obtained through outreach with industry associations, limited information is available over the time series (especially prior to 2010) for a variety of facility level variables, including plant-specific production levels, plant production technology (e.g., low, high pressure, etc.), and abatement technology type, installation date of abatement technology, and accurate destruction and removal efficiency rates. Production data prior to 2010 were obtained from National Census Bureau, which does not provide uncertainty estimates with their data. Facilities reporting to EPA's GHGRP must measure production using equipment and practices used for accounting purposes. At this time EPA does not estimate uncertainty of the aggregated facility-level information. As noted in the Methodology section, EPA verifies annual facility-level reports through a multi-step process (e.g., combination of electronic checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent. The annual production reported by each nitric acid facility under EPA's GHGRP and then aggregated to estimate national N_2O emissions is assumed to have low uncertainty.

The results of this Approach 2 quantitative uncertainty analysis are summarized in Table 4-29. Nitrous oxide emissions from nitric acid production were estimated to be between 9.6 and 10.7 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 5 percent below to 5 percent above the 2016 emissions estimate of 10.2 MMT CO_2 Eq.

Table 4-29: Approach 2 Quantitative Uncertainty Estimates for N_2O Emissions from Nitric Acid Production (MMT CO_2 Eq. and Percent)

Source	Gas	2016 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Nitric Acid Production	N_2O	10.2	9.6	10.7	-5%	+5%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2016. To maintain consistency across the time series and with the rounding approaches taken by other data sets, a new rounding approach was performed for the GHGRP Subpart V: Nitric Acid data. This resulted in production data changes across the time series of 2010 to 2016, in which EPA's GHGRP data have been utilized. The results of this update have had an insignificant impact on the emission estimates across the 2010 to 2016 time series. Details on the emission trends through time are described in more detail in the Methodology section, above.

For more information on the general QA/QC process applied to this source category, consistent with Volume 1, Chapter 6 of the *2006 IPCC Guidelines*, see the QA/QC and Verification Procedures section in the introduction of the IPPU chapter.

Planned Improvements

Pending resources, EPA is considering both near-term and long-term improvement to estimates and associated characterization of uncertainty. In the short-term, with 7 years of EPA's GHGRP data, EPA anticipates completing updates of category-specific QC procedures to potentially also improve both qualitative and quantitative uncertainty estimates. Longer term, in 2020, EPA anticipates having information from EPA's GHGRP facilities on the installation date of any N_2O abatement equipment, per recent revisions finalized in December 2016 to EPA's GHGRP. This information will enable more accurate estimation of N_2O emissions from nitric acid production over the time series.

4.8 Adipic Acid Production (CRF Source Category 2B3)

Adipic acid is produced through a two-stage process during which nitrous oxide (N_2O) is generated in the second stage. Emissions from fuels consumed for energy purposes during the production of adipic acid are accounted for in the Energy chapter. The first stage of manufacturing usually involves the oxidation of cyclohexane to form a cyclohexanone/cyclohexanol mixture. The second stage involves oxidizing this mixture with nitric acid to produce adipic acid. Nitrous oxide is generated as a byproduct of the nitric acid oxidation stage and is emitted in the waste gas stream (Thiemens and Trogler 1991). The second stage is represented by the following chemical reaction:

$$(CH_2)_5CO(cyclohexanone) + (CH_2)_5CHOH(cyclohexanol) + wHNO_3 \\ \rightarrow HOOC(CH_2)_4COOH(adipic\ acid) + xN_2O + yH_2O$$

Process emissions from the production of adipic acid vary with the types of technologies and level of emission controls employed by a facility. In 1990, two major adipic acid-producing plants had N_2O abatement technologies in place and, as of 1998, three major adipic acid production facilities had control systems in place (Reimer et al. 1999). In 2016, catalytic reduction, non-selective catalytic reduction (NSCR) and thermal reduction abatement technologies were applied as N_2O abatement measures at adipic acid facilities (EPA 2017).

Worldwide, only a few adipic acid plants exist. The United States, Europe, and China are the major producers, with the United States accounting for the largest share of global adipic acid production capacity in recent years. In 2016, the United States had two companies with a total of two adipic acid production facilities (one in Texas and one in Florida) following the ceased operations of a third major production facility at the end of 2015 (EPA 2017).

Adipic acid is a white crystalline solid used in the manufacture of synthetic fibers, plastics, coatings, urethane foams, elastomers, and synthetic lubricants. Commercially, it is the most important of the aliphatic dicarboxylic acids, which are used to manufacture polyesters. Eighty-four percent of all adipic acid produced in the United States is used in the production of nylon 6,6; 9 percent is used in the production of polyester polyols; 4 percent is used in the production of plasticizers; and the remaining 4 percent is accounted for by other uses, including unsaturated polyester resins and food applications (ICIS 2007). Food grade adipic acid is used to provide some foods with a “tangy” flavor (Thiemens and Trogler 1991).

National adipic acid production has increased by approximately 14 percent over the period of 1990 through 2016, to approximately 860,000 metric tons (ACC 2017). Nitrous oxide emissions from adipic acid production were estimated to be 7.0 MMT CO_2 Eq. (23 kt N_2O) in 2016 (see Table 4-30). Over the period 1990 through 2016, emissions have been reduced by 54 percent due to both the widespread installation of pollution control measures in the late 1990s and plant idling in the late 2000s. Very little information on annual trends in the activity data exist for adipic acid.

Table 4-30: N_2O Emissions from Adipic Acid Production (MMT CO_2 Eq. and kt N_2O)

Year	MMT CO_2 Eq.	kt N_2O
1990	15.2	51
2005	7.1	24
2012	5.5	19
2013	3.9	13
2014	5.4	18
2015	4.3	14
2016	7.0	23

Methodology

Emissions are estimated using both Tier 2 and Tier 3 methods consistent with the *2006 IPCC Guidelines.* Due to confidential business information (CBI), plant names are not provided in this section. Therefore, the four adipic acid-producing facilities that have operated over the time series will be referred to as Plants 1 through 4. Overall, as noted above, the two currently operating facilities use catalytic reduction, NSCR and thermal reduction abatement technologies.

2010 through 2016

All emission estimates for 2010 through 2016 were obtained through analysis of GHGRP data (EPA 2014 through 2017), which is consistent with the *2006 IPCC Guidelines* Tier 3 method. Facility-level greenhouse gas emissions data were obtained from EPA's GHGRP for the years 2010 through 2016 (EPA 2014 through 2017) and aggregated to national N_2O emissions. Consistent with IPCC Tier 3 methods, all adipic acid production facilities are required to calculate emissions using a facility-specific emission factor developed through annual performance testing under typical operating conditions or by directly measuring N_2O emissions using monitoring equipment.[30] More information on the calculation, monitoring and QA/QC methods for process N_2O emissions applicable to adipic acid production facilities under Subpart E can be found in the electronic code of federal regulations.[31] EPA verifies annual facility-level GHGRP reports through a multi-step process (e.g., combination of electronic checks and manual reviews) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent.[32]

1990 through 2009

For years 1990 through 2009, which were prior to EPA's GHGRP reporting, for both Plants 1 and 2, emission estimates were obtained directly from the plant engineers and account for reductions due to control systems in place at these plants during the time series. These prior estimates are considered CBI and hence are not published (Desai 2010, 2011). These estimates were based on continuous process monitoring equipment installed at the two facilities.

For Plant 4, 1990 through 2009 N_2O emissions were estimated using the following Tier 2 equation from the *2006 IPCC Guidelines*:

$$E_{aa} = Q_{aa} \times EF_{aa} \times (1 - [DF \times UF])$$

where,

E_{aa} = N_2O emissions from adipic acid production, metric tons
Q_{aa} = Quantity of adipic acid produced, metric tons
EF_{aa} = Emission factor, metric ton N_2O/metric ton adipic acid produced
DF = N_2O destruction factor
UF = Abatement system utility factor

The adipic acid production is multiplied by an emission factor (i.e., N_2O emitted per unit of adipic acid produced), which has been estimated, based on experiments that the reaction stoichiometry for N_2O production in the preparation of adipic acid, to be approximately 0.3 metric tons of N_2O per metric ton of product (IPCC 2006). The "N_2O destruction factor" in the equation represents the percentage of N_2O emissions that are destroyed by the installed abatement technology. The "abatement system utility factor" represents the percentage of time that the abatement equipment operates during the annual production period. Plant-specific production data for Plant 4 were obtained across the time series through personal communications (Desai 2010, 2011). The plant-specific production data were then used for calculating emissions as described above.

For Plant 3, 2005 through 2009 emissions were obtained directly from the plant (Desai 2010, 2011). For 1990 through 2004, emissions were estimated using plant-specific production data and the IPCC factors as described above for Plant 4. Plant-level adipic acid production for 1990 through 2003 was estimated by allocating national adipic acid production data to the plant level using the ratio of known plant capacity to total national capacity for all U.S. plants (ACC 2017; CMR 2001, 1998; CW 1999; C&EN 1992 through 1995). For 2004, actual plant production data were obtained and used for emission calculations (CW 2005).

Plant capacities for 1990 through 1994 were obtained from *Chemical & Engineering News*, "Facts and Figures" and "Production of Top 50 Chemicals" (C&EN 1992 through 1995). Plant capacities for 1995 and 1996 were kept the same as 1994 data. The 1997 plant capacities were taken from *Chemical Market Reporter*, "Chemical Profile:

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[30] Facilities must use standard methods, either EPA Method 320 or ASTM D6348-03, and must follow associated QA/QC procedures during these performance tests consistent with category-specific QC of direct emission measurements.

[31] See <http://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title40/40cfr98_main_02.tpl>.

[32] See <https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf>.

Adipic Acid" (CMR 1998). The 1998 plant capacities for all four plants and 1999 plant capacities for three of the plants were obtained from *Chemical Week*, Product Focus: Adipic Acid/Adiponitrile (CW 1999). Plant capacities for the year 2000 for three of the plants were updated using *Chemical Market Reporter*, "Chemical Profile: Adipic Acid" (CMR 2001). For 2001 through 2003, the plant capacities for three plants were held constant at year 2000 capacities. Plant capacity for 1999 to 2003 for the one remaining plant was kept the same as 1998.

National adipic acid production data (see Table 4-31) from 1990 through 2016 were obtained from the American Chemistry Council (ACC 2017).

Table 4-31: Adipic Acid Production (kt)

Year	kt
1990	755
2005	865
2012	950
2013	980
2014	1,025
2015	1,055
2016	860

Uncertainty and Time-Series Consistency

Uncertainty associated with N_2O emission estimates includes the methods used by companies to monitor and estimate emissions. While some information has been obtained through outreach with facilities, limited information is available over the time series on these methods, abatement technology destruction and removal efficiency rates and plant-specific production levels.

The results of this Approach 2 quantitative uncertainty analysis are summarized in Table 4-32. Nitrous oxide emissions from adipic acid production for 2016 were estimated to be between 6.7 and 7.3 MMT CO_2 Eq. at the 95 percent confidence level. These values indicate a range of approximately 5 percent below to 5 percent above the 2016 emission estimate of 7.0 MMT CO_2 Eq.

Table 4-32: Approach 2 Quantitative Uncertainty Estimates for N_2O Emissions from Adipic Acid Production (MMT CO_2 Eq. and Percent)

Source	Gas	2016 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Adipic Acid Production	N_2O	7.0	6.7	7.3	-5%	+5%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2016.

For more information on the general QA/QC process applied to this source category, consistent with Volume 1, Chapter 6 of the *2006 IPCC Guidelines*, see the QA/QC and Verification Procedures section in the introduction of the IPPU chapter.

4.9 Caprolactam, Glyoxal and Glyoxylic Acid Production (CRF Source Category 2B4)

Caprolactam

Caprolactam ($C_6H_{11}NO$) is a colorless monomer produced for nylon-6 fibers and plastics, with a substantial proportion of the fiber used in carpet manufacturing. Commercial processes for the manufacture of caprolactam are based on either toluene or benzene. The production of caprolactam can give rise to emissions of nitrous oxide (N_2O).

During the production of caprolactam, emissions of N_2O can occur from the ammonia oxidation step, emissions of carbon dioxide (CO_2) from the ammonium carbonate step, emissions of sulfur dioxide (SO_2) from the ammonium bisulfite step, and emissions of non-methane volatile organic compounds (NMVOCs). Emissions of CO_2, SO_2 and NMVOCs from the conventional process are unlikely to be significant in well-managed plants. Modified caprolactam production processes are primarily concerned with elimination of the high volumes of ammonium sulfate that are produced as a byproduct of the conventional process (Reimschuessel 1977).

Where caprolactam is produced from benzene, the main process, the benzene is hydrogenated to cyclohexane which is then oxidized to produce cyclohexanone ($C_6H_{10}O$). The classical route (Raschig process) and basic reaction equations for production from cyclohexanone are (Reimschuessel 1977; Lowenheim and Moran 1975; IPCC 2006):

$$\text{Oxidation of } NH_3 \text{ to } NO/NO_2$$

$$\downarrow$$

$$NH_3 \text{ reacted with } CO_2/H_2O \text{ to yield ammonium carbonate } (NH_4)_2CO_3$$

$$\downarrow$$

$$(NH_4)_2CO_3 \text{ reacted with } NO/NO_2 \text{ (from } NH_3 \text{ oxidation) to yield ammonium nitrite } (NH_4NO_2)$$

$$\downarrow$$

$$NH_3 \text{ reacted with } SO_2/H_2O \text{ to yield ammonium bisulphite } (NH_4HSO_3)$$

$$\downarrow$$

$$NH_4NO_2 \text{ and } (NH_4HSO_3) \text{ reacted to yield hydroxylamine disulphonate } (NOH(SO_3NH_4)_2)$$

$$\downarrow$$

$$(NOH(SO_3NH_4)_2) \text{ hydrolised to yield hydroxylamine sulphate } ((NH_2OH)_2.H_2SO_4) \text{ and}$$
$$\text{ammonium sulphate } ((NH_4)_2SO_4)$$

$$\downarrow$$

$$\text{Cylohexanone reaction:}$$
$$C_6H_{10}O \ + \frac{1}{2}(NH_2OH)_2.H_2SO_4(+NH_3 \text{ and } H_2SO_4) \rightarrow C_6H_{10}NOH \ + (NH_4)_2SO_4 \ + H_2O$$

$$\downarrow$$

$$\text{Beckmann rearrangement:}$$
$$C_6H_{10}NOH \ \ (+H_2SO_4 \text{ and } SO_2) \rightarrow C_6H_{11}NO.H_2SO_4 \ (+4NH_3 \text{ and } H_2O) \rightarrow C_6H_{11}NO \ + 2(NH4)_2SO_4$$

In 1999, there were four caprolactam production facilities in the United States. As of 2016, the United States had 3 companies with a total of 3 caprolactam production facilities: AdvanSix in Virginia (AdvanSix 2017), BASF in Texas (BASF 2017), and Fibrant LLC in Georgia (Fibrant 2017; TechSci n.d. 2017).

Nitrous oxide emissions from caprolactam production in the United States were estimated to be 2.0 MMT CO_2 Eq. (7 kt N_2O) in 2016 (see Table 4-33). National caprolactam production has increased by approximately 21 percent over the period of 1990 through 2016, to approximately 755 thousand metric tons (ACC 2017). Very little information on annual trends in the activity data exist for caprolactam.

Table 4-33: N_2O Emissions from Caprolactam Production (MMT CO_2 Eq. and kt N_2O)

Year	MMT CO_2 Eq.	kt N_2O
1990	1.7	6
2005	2.1	7
2012	2.0	7
2013	2.0	7
2014	2.0	7
2015	2.0	7
2016	2.0	7

Glyoxal

Glyoxal is mainly used as a crosslinking agent for acrylic resins, disinfectant, gelatin hardening agent, and textile finishing agent etc. It is produced from oxidation of acetaldehyde with concentrated nitric acid, or from the catalytic oxidation of ethylene glycol, and N_2O is emitted in the process of oxidation of acetaldehyde.

Glyoxal (ethanedial) ($C_2H_2O_2$) is produced from oxidation of acetaldehyde (ethanal) (C_2H_4O) with concentrated nitric acid (HNO_3). Glyoxal can also be produced from catalytic oxidation of ethylene glycol (ethanediol) (CH_2OHCH_2OH). Glyoxal is used as a crosslinking agent for vinyl acetate/acrylic resins, disinfectant, gelatin hardening agent, textile finishing agent (permanent-press cotton, rayon fabrics), wet-resistance additive (paper coatings) (Ashford 1994; IPCC 2006).

Glyoxylic Acid

Glyoxylic acid is produced by nitric acid oxidation of glyoxal. Glyoxylic acid is used for the production of synthetic aromas, agrochemicals and pharmaceutical intermediates (Babusiaux 2005).

EPA does not currently estimate the emissions associated with the production of Glyoxal and Glyoxylic Acid due to data availability and a lack of publicly available information on the industry in the United States.

Methodology

Emissions of N_2O were calculated using the estimation methods provided by the *2006 IPCC Guidelines*. The *2006 IPCC Guidelines* Tier 1 method was used to estimate emissions from caprolactam production for 1990 through 2016, as shown in this formula:

$$E_{N_2O} = EF\ x\ CP$$

where,

E_{N2O} = Annual N_2O Emissions (kg)
EF = N_2O emission factor (default) (kg N_2O/metric ton caprolactam produced)
CP = Caprolactam production (metric tons)

During the caprolactam production process, N_2O is generated as a byproduct of the high temperature catalytic oxidation of ammonia (NH_3), which is the first reaction in the series of reactions to produce caprolactam. The amount of N_2O emissions can be estimated based on the chemical reaction shown above. Based on this formula, which is consistent with an IPCC Tier 1 approach, approximately 111.1 metric tons of caprolactam are required to generate one metric ton of N_2O, or an emission factor of 9.0 kg N_2O per metric ton of caprolactam (IPCC 2006). When applying the Tier 1 method, the *2006 IPCC Guidelines* state that it is good practice to assume that there is no abatement of N_2O emissions and to use the highest default emission factor available in the guidelines. In addition, EPA did not find support for the use of secondary catalysts to reduce N_2O emissions, like those employed at nitric acid plants. Thus, the 755 thousand metric tons (kt) of caprolactam produced in 2016 (ACC 2017) resulted in N_2O emissions of approximately 2.0 MMT CO_2 Eq. (7 kt).

The activity data for caprolactam production (see Table 4-34) from 1990 to 2016 were obtained from the ACC *Guide to the Business of Chemistry* report (ACC 2017). EPA will continue to analyze and assess alternative sources of production data as a quality control measure.

Table 4-34: Caprolactam Production (kt)

Year	kt
1990	626
2005	795
2012	750
2013	750
2014	755
2015	760
2016	755

Carbon dioxide and methane (CH_4) emissions may also occur from the production of caprolactam but currently the IPCC does not have methodologies for calculating these emissions associated with caprolactam production.

Uncertainty and Time-Series Consistency

Estimation of emissions of N_2O from caprolactam production can be treated as analogous to estimation of emissions of N_2O from nitric acid production. Both production processes involve an initial step of NH_3 oxidation which is the source of N_2O formation and emissions (IPCC 2006). Therefore, uncertainties for the default values in the *2006 IPCC Guidelines* is an estimate based on default values for nitric acid plants. In general, default emission factors for gaseous substances have higher uncertainties because mass values for gaseous substances are influenced by temperature and pressure variations and gases are more easily lost through process leaks. The default values for caprolactam production have a relatively high level of uncertainty due to the limited information available (IPCC 2006).

The results of this Approach 2 quantitative uncertainty analysis are summarized in Table 4-35. Nitrous oxide emissions from Caprolactam, Glyoxal and Glyoxylic Acid Production for 2016 were estimated to be between 1.4 and 2.6 MMT CO_2 Eq. at the 95 percent confidence level. These values indicate a range of approximately 31 percent below to 31 percent above the 2016 emission estimate of 2.0 MMT CO_2 Eq.

Table 4-35: Approach 2 Quantitative Uncertainty Estimates for N_2O Emissions from Caprolactam, Glyoxal and Glyoxylic Acid Production (MMT CO_2 Eq. and Percent)

Source	Gas	2016 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Caprolactam Production	N_2O	2.0	1.4	2.6	-31%	+31%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Details on the emission trends through time are described in more detail in the Methodology section, above. Caprolactam was not reported as a source category in previous Inventory reports (previously reported as not estimated or "NE") and EPA has taken measures to ensure emission estimates are consistent with *2006 IPCC Guidelines* and good practice, ensuring time-series consistency.

For more information on the general QA/QC process applied to this source category, consistent with Volume 1, Chapter 6 of the *2006 IPCC Guidelines*, see the QA/QC and Verification Procedures section in the introduction of the IPPU chapter.

Recalculations Discussion

With the addition of caprolactam production emissions reported within the current Inventory report, recalculations have occurred to the IPPU chapter aggregated total emissions estimate. Across the 1990 to 2016 time series, the addition of caprolactam production has added emissions ranging between 1.6 and 2.2 MMT CO_2 Eq.

Planned Improvements

Pending resources, EPA will research other available datasets for caprolactam production and industry trends, including facility-level data. EPA will also research the production process and emissions associated with the production of glyoxal and glyoxylic acid. During the Expert Review comment period for the current Inventory report, EPA sought expert solicitation on data available for these emissions source categories. EPA did not receive information regarding these industries during Expert Review but will continue to research alternative datasets.

4.10 Silicon Carbide Production and Consumption (CRF Source Category 2B5)

Carbon dioxide (CO_2) and methane (CH_4) are emitted from the production of silicon carbide (SiC), a material used as an industrial abrasive. Silicon carbide is produced for abrasive, metallurgical, and other non-abrasive applications in the United States. Production for metallurgical and other non-abrasive applications is not available and therefore both CO_2 and CH_4 estimates are based solely upon production estimates of silicon carbide for abrasive applications. Emissions from fuels consumed for energy purposes during the production of silicon carbide are accounted for in the Energy chapter.

Carbon dioxide and CH_4 are also emitted during the production of calcium carbide, a chemical used to produce acetylene. Carbon dioxide is implicitly accounted for in the storage factor calculation for the non-energy use of petroleum coke in the Energy chapter. However, CH_4 emissions from calcium carbide production are not included as data are not available to apply the Tier 3 methodology prescribed by the *2006 IPCC Guidelines*. EPA is continuing to investigate the inclusion of these emissions in future Inventory reports.

To produce SiC, silica sand or quartz (SiO_2) is reacted with C in the form of petroleum coke. A portion (about 35 percent) of the carbon contained in the petroleum coke is retained in the SiC. The remaining C is emitted as CO_2, CH_4, or carbon monoxide (CO). The overall reaction is shown below (but in practice it does not proceed according to stoichiometry):

$$SiO_2 + 3C \rightarrow SiC + 2CO\ (+\ O_2 \rightarrow 2CO_2)$$

Carbon dioxide is also emitted from the consumption of SiC for metallurgical and other non-abrasive applications.

Markets for manufactured abrasives, including SiC, are heavily influenced by activity in the U.S. manufacturing sector, especially in the aerospace, automotive, furniture, housing, and steel manufacturing sectors. The U.S. Geological Survey (USGS) reports that a portion (approximately 50 percent) of SiC is used in metallurgical and other non-abrasive applications, primarily in iron and steel production (USGS 2006a). As a result of the economic downturn in 2008 and 2009, demand for SiC decreased in those years. Low cost imports, particularly from China, combined with high relative operating costs for domestic producers, continue to put downward pressure on the production of SiC in the United States. However, demand for SiC consumption in the United States has recovered somewhat from its low in 2009 (USGS 2012a). Abrasive-grade silicon carbide was manufactured at one facility in 2015 in the United States (USGS 2017a).

Carbon dioxide emissions from SiC production and consumption in 2016 were 0.2 MMT CO_2 Eq. (174 kt CO_2) (see Table 4-36 and Table 4-37). Approximately 51 percent of these emissions resulted from SiC production while the remainder resulted from SiC consumption. Methane emissions from SiC production in 2016 were 0.01 MMT CO_2 Eq. (0.4 kt CH_4) (see Table 4-36 and Table 4-37). Emissions have not fluctuated greatly in recent years, but 2016 emissions are about 52 percent lower than emissions in 1990.

Table 4-36: CO_2 and CH_4 Emissions from Silicon Carbide Production and Consumption (MMT CO_2 Eq.)

Year	1990	2005	2012	2013	2014	2015	2016
CO_2	0.4	0.2	0.2	0.2	0.2	0.2	0.2
CH_4	+	+	+	+	+	+	+
Total	**0.4**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**

+ Does not exceed 0.05 MMT CO_2 Eq.

Table 4-37: CO_2 and CH_4 Emissions from Silicon Carbide Production and Consumption (kt)

Year	1990	2005	2012	2013	2014	2015	2016
CO_2	375	219	158	169	173	180	174
CH_4	1	+	+	+	+	+	+

+ Does not exceed 0.5 kt.

Methodology

Emissions of CO_2 and CH_4 from the production of SiC were calculated[33] using the Tier 1 method provided by the *2006 IPCC Guidelines*. Annual estimates of SiC production were multiplied by the appropriate emission factor, as shown below:

$$E_{sc,CO2} = EF_{sc,CO2} \times Q_{sc}$$

$$E_{sc,CH4} = EF_{sc,CH4} \times Q_{sc} \times \left(\frac{1\ metric\ ton}{1000\ kg}\right)$$

where,

$E_{sc,CO2}$ = CO_2 emissions from production of SiC, metric tons
$EF_{sc,CO2}$ = Emission factor for production of SiC, metric ton CO_2/metric ton SiC
Q_{sc} = Quantity of SiC produced, metric tons
$E_{sc,CH4}$ = CH_4 emissions from production of SiC, metric tons
$EF_{sc,CH4}$ = Emission factor for production of SiC, kilogram CH_4/metric ton SiC

Emission factors were taken from the *2006 IPCC Guidelines*:

- 2.62 metric tons CO_2/metric ton SiC
- 11.6 kg CH_4/metric ton SiC

Emissions of CO_2 from silicon carbide consumption for metallurgical uses were calculated by multiplying the annual utilization of SiC for metallurgical uses (reported annually in the USGS *Minerals Yearbook: Silicon*) by the carbon content of SiC (31.5 percent), which was determined according to the molecular weight ratio of SiC.

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[33] EPA has not integrated aggregated facility-level GHGRP information to inform these estimates. The aggregated information (e.g., activity data and emissions) associated with silicon carbide did not meet criteria to shield underlying confidential business information (CBI) from public disclosure.

Emissions of CO_2 from silicon carbide consumption for other non-abrasive uses were calculated by multiplying the annual SiC consumption for non-abrasive uses by the carbon content of SiC (31.5 percent). The annual SiC consumption for non-abrasive uses was calculated by multiplying the annual SiC consumption (production plus net imports) by the percent used in metallurgical and other non-abrasive uses (50 percent) (USGS 2006a) and then subtracting the SiC consumption for metallurgical use.

The petroleum coke portion of the total CO_2 process emissions from silicon carbide production is adjusted for within the Energy chapter, as these fuels were consumed during non-energy related activities. Additional information on the adjustments made within the Energy sector for Non-Energy Use of Fuels is described in both the Methodology section of CO_2 from Fossil Fuel Combustion (3.1 Fossil Fuel Combustion (CRF Source Category 1A)) and Annex 2.1, Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion.

Production data for 1990 through 2013 were obtained from the *Minerals Yearbook: Manufactured Abrasives* (USGS 1991a through 2015). Production data for 2014 and 2015 were obtained from the *Minerals Industry Surveys: Abrasives (Manufactured)* (USGS 2016). Production data for 2016 were obtained from the *Mineral Industry Surveys: Abrasives (Manufactured)* (USGS 2017b). Silicon carbide production data obtained through the USGS National Minerals Information Center has been previously been rounded to the nearest 5,000 metric tons to avoid disclosing company proprietary data. Silicon carbide consumption by major end use for 1990 through 2015 were obtained from the *Minerals Yearbook: Silicon* (USGS 1991b through 2017c) (see Table 4-38). 2016 silicon carbide consumption was not yet published by the USGS; therefore, 2015 data are used as a proxy for 2016. Net imports and exports for the entire time series were obtained from the U.S. International Trade Commission (USITC) database updated from data provided by the U.S. Census Bureau (2005 through 2017).

Table 4-38: Production and Consumption of Silicon Carbide (Metric Tons)

Year	Production	Consumption
1990	105,000	172,465
2005	35,000	220,149
2012	35,000	114,265
2013	35,000	134,055
2014	35,000	140,733
2015	35,000	153,475
2016	35,000	142,104

Uncertainty and Time-Series Consistency

There is uncertainty associated with the emission factors used because they are based on stoichiometry as opposed to monitoring of actual SiC production plants. An alternative would be to calculate emissions based on the quantity of petroleum coke used during the production process rather than on the amount of silicon carbide produced. However, these data were not available. For CH_4, there is also uncertainty associated with the hydrogen-containing volatile compounds in the petroleum coke (IPCC 2006). There is also uncertainty associated with the use or destruction of CH_4 generated from the process in addition to uncertainty associated with levels of production, net imports, consumption levels, and the percent of total consumption that is attributed to metallurgical and other non-abrasive uses.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-39. Silicon carbide production and consumption CO_2 emissions from 2016 were estimated to be between 9 percent below and 9 percent above the emission estimate of 0.17 MMT CO_2 Eq. at the 95 percent confidence level. Silicon carbide production CH_4 emissions were estimated to be between 9 percent below and 10 percent above the emission estimate of 0.01 MMT CO_2 Eq. at the 95 percent confidence level.

Table 4-39: Approach 2 Quantitative Uncertainty Estimates for CH_4 and CO_2 Emissions from Silicon Carbide Production and Consumption (MMT CO_2 Eq. and Percent)

Source	Gas	2016 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Silicon Carbide Production and Consumption	CO_2	0.17	0.15	0.19	-9%	+9%
Silicon Carbide Production	CH_4	+	+	+	-9%	+10%

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2016. Details on the emission trends through time are described in more detail in the Methodology section, above.

For more information on the general QA/QC process applied to this source category, consistent with Volume 1, Chapter 6 of the *2006 IPCC Guidelines*, see the QA/QC and Verification Procedures section in the introduction of the IPPU chapter.

Recalculations Discussion

In the previous Inventory (i.e., 1990 through 2015 report), 2015 silicon carbide consumption data by end-use were not available which resulted in the use of 2014 data as proxy. In the current Inventory, advance release data were available for 2015 and the value was updated (USGS 2017c). This recalculation resulted in an insignificant change to the total silicon carbide emissions estimate for the year 2015 compared to the previous Inventory.

4.11 Titanium Dioxide Production (CRF Source Category 2B6)

Titanium dioxide (TiO_2) is manufactured using one of two processes: the chloride process and the sulfate process. The chloride process uses petroleum coke and chlorine as raw materials and emits process-related carbon dioxide (CO_2). Emissions from fuels consumed for energy purposes during the production of titanium dioxide are accounted for in the Energy chapter. The chloride process is based on the following chemical reactions:

$$2FeTiO_3 + 7Cl_2 + 3C \rightarrow 2TiCl_4 + 2FeCl_3 + 3CO_2$$

$$2TiCl_4 + 2O_2 \rightarrow 2TiO_2 + 4Cl_2$$

The sulfate process does not use petroleum coke or other forms of carbon as a raw material and does not emit CO_2.

The C in the first chemical reaction is provided by petroleum coke, which is oxidized in the presence of the chlorine and $FeTiO_3$ (rutile ore) to form CO_2. Since 2004, all TiO_2 produced in the United States has been produced using the chloride process, and a special grade of “calcined” petroleum coke is manufactured specifically for this purpose.

The principal use of TiO_2 is as a pigment in white paint, lacquers, and varnishes; it is also used as a pigment in the manufacture of plastics, paper, and other products. In 2016, U.S. TiO_2 production totaled 1,200,000 metric tons (USGS 2017). There were a total five plants producing TiO_2 in the United States in 2016.

Emissions of CO_2 from titanium dioxide production in 2016 were estimated to be 1.6 MMT CO_2 Eq. (1,608 kt CO_2), which represents an increase of 35 percent since 1990 (see Table 4-40). Compared to 2015, emissions from titanium dioxide production decreased by 2 percent in 2016 due to a 2 percent decrease in production.

Table 4-40: CO_2 Emissions from Titanium Dioxide (MMT CO_2 Eq. and kt)

Year	MMT CO_2 Eq.	kt
1990	1.2	1,195
2005	1.8	1,755
2012	1.5	1,528
2013	1.7	1,715
2014	1.7	1,688
2015	1.6	1,635
2016	1.6	1,608

Methodology

Emissions of CO_2 from TiO_2 production were calculated by multiplying annual national TiO_2 production by chloride process-specific emission factors using a Tier 1 approach provided in *2006 IPCC Guidelines*. The Tier 1 equation is as follows:

$$E_{td} = EF_{td} \times Q_{td}$$

where,

E_{td} = CO_2 emissions from TiO_2 production, metric tons
EF_{td} = Emission factor (chloride process), metric ton CO_2/metric ton TiO_2
Q_{td} = Quantity of TiO_2 produced

The petroleum coke portion of the total CO_2 process emissions from TiO_2 production is adjusted for within the Energy chapter as these fuels were consumed during non-energy related activities. Additional information on the adjustments made within the Energy sector for Non-Energy Use of Fuels is described in both the Methodology section of CO_2 from Fossil Fuel Combustion (3.1 Fossil Fuel Combustion (CRF Source Category 1A)) and Annex 2.1, Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion.

Data were obtained for the total amount of TiO_2 produced each year. For years prior to 2004, it was assumed that TiO_2 was produced using the chloride process and the sulfate process in the same ratio as the ratio of the total U.S. production capacity for each process. As of 2004, the last remaining sulfate process plant in the United States closed; therefore, 100 percent of post-2004 production uses the chloride process (USGS 2005b). The percentage of production from the chloride process is estimated at 100 percent since 2004. An emission factor of 1.34 metric tons CO_2/metric ton TiO_2 was applied to the estimated chloride-process production (IPCC 2006). It was assumed that all TiO_2 produced using the chloride process was produced using petroleum coke, although some TiO_2 may have been produced with graphite or other carbon inputs.

The emission factor for the TiO_2 chloride process was taken from the *2006 IPCC Guidelines*. Titanium dioxide production data and the percentage of total TiO_2 production capacity that is chloride process for 1990 through 2013 (see Table 4-41) were obtained through the *Minerals Yearbook: Titanium Annual Report* (USGS 1991 through 2015). Production data for 2014 through 2016 were obtained from the *Minerals Commodity Summary: Titanium and Titanium Dioxide* (USGS 2016; USGS 2017).[34] Data on the percentage of total TiO_2 production capacity that is chloride process were not available for 1990 through 1993, so data from the 1994 USGS *Minerals Yearbook* were used for these years. Because a sulfate process plant closed in September 2001, the chloride process percentage for 2001 was estimated based on a discussion with Joseph Gambogi (2002). By 2002, only one sulfate process plant remained online in the United States and this plant closed in 2004 (USGS 2005b).

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[34] EPA has not integrated aggregated facility-level GHGRP information for Titanium Dioxide production facilities (40 CFR Part 98 Subpart EE). The relevant aggregated information (activity data, emission factor) from these facilities did not meet criteria to shield underlying CBI from public disclosure.

Table 4-41: Titanium Dioxide Production (kt)

Year	kt
1990	979
2005	1,310
2012	1,140
2013	1,280
2014	1,260
2015	1,220
2016	1,200

Uncertainty and Time-Series Consistency

Each year, the U.S. Geological Survey (USGS) collects titanium industry data for titanium mineral and pigment production operations. If TiO_2 pigment plants do not respond, production from the operations is estimated based on prior year production levels and industry trends. Variability in response rates varies from 67 to 100 percent of TiO_2 pigment plants over the time series.

Although some TiO_2 may be produced using graphite or other carbon inputs, information and data regarding these practices were not available. Titanium dioxide produced using graphite inputs, for example, may generate differing amounts of CO_2 per unit of TiO_2 produced as compared to that generated using petroleum coke in production. While the most accurate method to estimate emissions would be to base calculations on the amount of reducing agent used in each process rather than on the amount of TiO_2 produced, sufficient data were not available to do so.

As of 2004, the last remaining sulfate-process plant in the United States closed. Since annual TiO_2 production was not reported by USGS by the type of production process used (chloride or sulfate) prior to 2004 and only the percentage of total production capacity by process was reported, the percent of total TiO_2 production capacity that was attributed to the chloride process was multiplied by total TiO_2 production to estimate the amount of TiO_2 produced using the chloride process. Finally, the emission factor was applied uniformly to all chloride-process production, and no data were available to account for differences in production efficiency among chloride-process plants. In calculating the amount of petroleum coke consumed in chloride-process TiO_2 production, literature data were used for petroleum coke composition. Certain grades of petroleum coke are manufactured specifically for use in the TiO_2 chloride process; however, this composition information was not available.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-42. Titanium dioxide consumption CO_2 emissions from 2016 were estimated to be between 1.4 and 1.8 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 12 percent below and 13 percent above the emission estimate of 1.6 MMT CO_2 Eq.

Table 4-42: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Titanium Dioxide Production (MMT CO_2 Eq. and Percent)

Source	Gas	2016 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Titanium Dioxide Production	CO_2	1.6	1.4	1.8	-12%	+13%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2016. Details on the emission trends through time are described in more detail in the Methodology section, above.

For more information on the general QA/QC process applied to this source category, consistent with Volume 1, Chapter 6 of the *2006 IPCC Guidelines*, see the QA/QC and Verification Procedures section in the introduction of the IPPU chapter.

Planned Improvements

Planned improvements include researching the significance of titanium-slag production in electric furnaces and synthetic-rutile production using the Becher process in the United States. Significant use of these production processes will be included in future Inventory reports. Due to resource constraints, this planned improvement is still in development by EPA and is not included in this report. EPA continues to assess the potential of integrating aggregated facility-level GHGRP information for titanium dioxide production facilities based on criteria to shield underlying CBI from public disclosure. Pending available resources, EPA will also evaluate use of GHGRP data to improve category-specific QC consistent with both Volume 1, Chapter 6 of *2006 IPCC Guidelines* and the latest IPCC guidance on the use of facility-level data in national inventories.[35]

4.12 Soda Ash Production (CRF Source Category 2B7)

Carbon dioxide (CO_2) is generated as a byproduct of calcining trona ore to produce soda ash, and is eventually emitted into the atmosphere. In addition, CO_2 may also be released when soda ash is consumed. Emissions from soda ash consumption in chemical production processes are reported under Section 4.4 Other Process Uses of Carbonates (CRF Category 2A4) and emissions from fuels consumed for energy purposes during the production and consumption of soda ash are accounted for in the Energy sector.

Calcining involves placing crushed trona ore into a kiln to convert sodium bicarbonate into crude sodium carbonate that will later be filtered into pure soda ash. The emission of CO_2 during trona-based production is based on the following reaction:

$$2Na_2CO_3 \bullet NaHCO_3 \bullet 2H_2O(Trona) \rightarrow 3Na_2CO_3(Soda\ Ash) + 5H_2O + CO_2$$

Soda ash (sodium carbonate, Na_2CO_3) is a white crystalline solid that is readily soluble in water and strongly alkaline. Commercial soda ash is used as a raw material in a variety of industrial processes and in many familiar consumer products such as glass, soap and detergents, paper, textiles, and food. Emissions from soda ash used in glass production are reported under Section 4.3, Glass Production (CRF Source Category 2A3). Glass production is its own source category and historical soda ash consumption figures have been adjusted to reflect this change. After glass manufacturing, soda ash is used primarily to manufacture many sodium-based inorganic chemicals, including sodium bicarbonate, sodium chromates, sodium phosphates, and sodium silicates (USGS 2015b). Internationally, two types of soda ash are produced, natural and synthetic. The United States produces only natural soda ash and is second only to China in total soda ash production. Trona is the principal ore from which natural soda ash is made.

The United States represents about one-fourth of total world soda ash output. Only two states produce natural soda ash: Wyoming and California. Of these two states, only net emissions of CO_2 from Wyoming were calculated due to specifics regarding the production processes employed in the state.[36] Based on 2016 reported data, the estimated

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[35] See <http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf>.

[36] In California, soda ash is manufactured using sodium carbonate-bearing brines instead of trona ore. To extract the sodium carbonate, the complex brines are first treated with CO_2 in carbonation towers to convert the sodium carbonate into sodium bicarbonate, which then precipitates from the brine solution. The precipitated sodium bicarbonate is then calcined back into sodium carbonate. Although CO_2 is generated as a byproduct, the CO_2 is recovered and recycled for use in the carbonation stage and is not emitted. A third state, Colorado, produced soda ash until the plant was idled in 2004. The lone producer of sodium bicarbonate no longer mines trona in the state. For a brief time, sodium bicarbonate was produced using soda ash feedstocks mined in Wyoming and shipped to Colorado. Prior to 2004, because the trona was mined in Wyoming, the production numbers

distribution of soda ash by end-use in 2016 (excluding glass production) was chemical production, 57 percent; soap and detergent manufacturing, 12 percent; distributors, 11 percent; flue gas desulfurization, 8 percent; other uses, 7 percent; pulp and paper production, 3 percent, and water treatment, 2 percent (USGS 2017).[37]

U.S. natural soda ash is competitive in world markets because the majority of the world output of soda ash is made synthetically. Although the United States continues to be a major supplier of world soda ash, China, which surpassed the United States in soda ash production in 2003, is the world's leading producer.

In 2016, CO_2 emissions from the production of soda ash from trona were approximately 1.7 MMT CO_2 Eq. (1,723 kt CO_2) (see Table 4-43). Total emissions from soda ash production in 2016 increased by approximately 1 percent from emissions in 2015, and have increased by approximately 20 percent from 1990 levels.

Emissions have remained relatively constant over the time series with some fluctuations since 1990. In general, these fluctuations were related to the behavior of the export market and the U.S. economy. The U.S. soda ash industry continued a trend of increased production and value in 2016 since experiencing a decline in domestic and export sales caused by adverse global economic conditions in 2009.

Table 4-43: CO_2 Emissions from Soda Ash Production (MMT CO_2 Eq. and kt CO_2)

Year	MMT CO_2 Eq.	kt CO_2
1990	1.4	1,431
2005	1.7	1,655
2012	1.7	1,665
2013	1.7	1,694
2014	1.7	1,685
2015	1.7	1,714
2016	1.7	1,723

Note: Totals may not sum due to independent rounding.

Methodology

During the production process, trona ore is calcined in a rotary kiln and chemically transformed into a crude soda ash that requires further processing. Carbon dioxide and water are generated as byproducts of the calcination process. Carbon dioxide emissions from the calcination of trona can be estimated based on the chemical reaction shown above. Based on this formula, which is consistent with an IPCC Tier 1 approach, approximately 10.27 metric tons of trona are required to generate one metric ton of CO_2, or an emission factor of 0.0974 metric tons CO_2 per metric ton trona (IPCC 2006). Thus, the 17.7 million metric tons of trona mined in 2016 for soda ash production (USGS 2017) resulted in CO_2 emissions of approximately 1.7 MMT CO_2 Eq. (1,723 kt).

Once produced, most soda ash is consumed in chemical production, with minor amounts in soap production, pulp and paper, flue gas desulfurization, and water treatment (excluding soda ash consumption for glass manufacturing). As soda ash is consumed for these purposes, additional CO_2 is usually emitted. Consistent with the *2006 IPCC Guidelines for National Greenhouse Gas Inventories*, emissions from soda ash consumption in chemical production processes are reported under Section 4.4 Other Process Uses of Carbonates (CRF Category 2A4).

The activity data for trona production (see Table 4-44) for 1990 to 2016 were obtained from the U.S. Geological Survey (USGS) *Minerals Yearbook for Soda Ash* (1994 through 2015b) and USGS *Mineral Industry Surveys for*

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given by the USGS included the feedstocks mined in Wyoming and shipped to Colorado. In this way, the sodium bicarbonate production that took place in Colorado was accounted for in the Wyoming numbers.

[37] Percentages may not add up to 100 percent due to independent rounding.

Soda Ash (USGS 2017). Soda ash production[38] data were collected by the USGS from voluntary surveys of the U.S. soda ash industry. EPA will continue to analyze and assess opportunities to use facility-level data from EPA's GHGRP to improve the emission estimates for Soda Ash Production source category consistent with IPCC[39] and UNFCCC guidelines.

Table 4-44: Soda Ash Production (kt)

Year	Production[a]
1990	14,700
2005	17,000
2012	17,100
2013	17,400
2014	17,300
2015	17,600
2016	17,700

[a] Soda ash produced from trona ore only.

Uncertainty and Time-Series Consistency

Emission estimates from soda ash production have relatively low associated uncertainty levels in that reliable and accurate data sources are available for the emission factor and activity data for trona-based soda ash production. EPA plans to work with other entities to reassess the uncertainty of these emission factors and activity data based on the most recent information and data. Through EPA's GHGRP, EPA is aware of one facility producing soda ash from a liquid alkaline feedstock process. Soda ash production data was collected by the USGS from voluntary surveys. A survey request was sent to each of the five soda ash producers, all of which responded, representing 100 percent of the total production data (USGS 2016). One source of uncertainty is the purity of the trona ore used for manufacturing soda ash. The emission factor used for this estimate assumes the ore is 100 percent pure, and likely overestimates the emissions from soda ash manufacture. The average water-soluble sodium carbonate-bicarbonate content for ore mined in Wyoming ranges from 85.5 to 93.8 percent (USGS 1995).

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-45. Soda Ash Production CO_2 emissions for 2016 were estimated to be between 1.5 and 1.8 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 9 percent below and 8 percent above the emission estimate of 1.7 MMT CO_2 Eq.

Table 4-45: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Soda Ash Production (MMT CO_2 Eq. and Percent)

Source	Gas	2016 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Soda Ash Production	CO_2	1.7	1.5	1.8	-9%	+8%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

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[38] EPA has assessed feasibility of using emissions information (including activity data) from EPA's GHGRP program; however, at this time, the aggregated information associated with production of soda ash did not meet criteria to shield underlying confidential business information (CBI) from public disclosure.

[39] See <http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf>.

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2016.

For more information on the general QA/QC process applied to this source category, consistent with Volume 1, Chapter 6 of the *2006 IPCC Guidelines*, see the QA/QC and Verification Procedures section in the introduction of the IPPU chapter.

Recalculations Discussion

Emissions from soda ash consumption in chemical production processes were removed from this section and reported under Section 4.4 Other Process Uses of Carbonates (CRF Source Category 2A4) to be consistent with *2006 IPCC Guidelines*. This revision resulted in a decrease in emissions associated with the soda ash production source category ranging from approximately 39 percent to 49 percent across the time series of 1990 through 2015 compared to the previous Inventory.

Planned Improvements

EPA plans to use GHGRP data for conducting category-specific QC of emission estimates consistent with both Volume 1, Chapter 6 of *2006 IPCC Guidelines* and the latest IPCC guidance on the use of facility-level data in national inventories.[40] This planned improvement is ongoing and has not been incorporated into this Inventory report.

4.13 Petrochemical Production (CRF Source Category 2B8)

The production of some petrochemicals results in the release of small amounts of carbon dioxide (CO_2) and methane (CH_4) emissions. Petrochemicals are chemicals isolated or derived from petroleum or natural gas. Carbon dioxide emissions from the production of acrylonitrile, carbon black, ethylene, ethylene dichloride, ethylene oxide, and methanol, and CH_4 emissions from the production of methanol and acrylonitrile are presented here and reported under CRF Source Category 2B8. The petrochemical industry uses primary fossil fuels (i.e., natural gas, coal, petroleum, etc.) for non-fuel purposes in the production of carbon black and other petrochemicals. Emissions from fuels and feedstocks transferred out of the system for use in energy purposes (e.g., indirect or direct process heat or steam production) are currently accounted for in the Energy sector. The allocation and reporting of emissions from feedstocks transferred out of the system for use in energy purposes to the Energy chapter is consistent with *2006 IPCC Guidelines*.

Worldwide more than 90 percent of acrylonitrile (vinyl cyanide, C_3H_3N) is made by way of direct ammoxidation of propylene with ammonia (NH_3) and oxygen over a catalyst. This process is referred to as the SOHIO process after the Standard Oil Company of Ohio (SOHIO) (IPCC 2006). The primary use of acrylonitrile is as the raw material for the manufacture of acrylic and modacrylic fibers. Other major uses include the production of plastics (acrylonitrile-butadiene-styrene [ABS] and styrene-acrylonitrile [SAN]), nitrile rubbers, nitrile barrier resins, adiponitrile, and acrylamide. All U.S. acrylonitrile facilities use the SOHIO process (AN 2014). The SOHIO process involves a fluidized bed reaction of chemical-grade propylene, ammonia, and oxygen over a catalyst. The process produces acrylonitrile as its primary product and the process yield depends on the type of catalyst used and the process configuration. The ammoxidation process also produces byproduct CO_2, carbon monoxide (CO), and water from the direct oxidation of the propylene feedstock, and produces other hydrocarbons from side reactions in the ammoxidation process.

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[40] See <http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf>.

Carbon black is a black powder generated by the incomplete combustion of an aromatic petroleum- or coal-based feedstock at a high temperature. Most carbon black produced in the United States is added to rubber to impart strength and abrasion resistance, and the tire industry is by far the largest consumer. The other major use of carbon black is as a pigment. The predominant process used in the United States is the furnace black (or oil furnace) process. In the furnace black process, carbon black oil (a heavy aromatic liquid) is continuously injected into the combustion zone of a natural gas-fired furnace. Furnace heat is provided by the natural gas and a portion of the carbon black feedstock; the remaining portion of the carbon black feedstock is pyrolyzed to carbon black. The resultant CO_2 and uncombusted CH_4 emissions are released from thermal incinerators used as control devices, process dryers, and equipment leaks. Carbon black is also produced in the United States by the thermal cracking of acetylene-containing feedstocks (i.e., acetylene black process), by the thermal cracking of other hydrocarbons (i.e., thermal black process), and by the open burning of carbon black feedstock (i.e., lamp black process); each of these processes is used at only one U.S. plant (EPA 2000).

Ethylene (C_2H_4) is consumed in the production processes of the plastics industry including polymers such as high, low, and linear low density polyethylene (HDPE, LDPE, LLDPE); polyvinyl chloride (PVC); ethylene dichloride; ethylene oxide; and ethylbenzene. Virtually all ethylene is produced from steam cracking of ethane, propane, butane, naphtha, gas oil, and other feedstocks. The representative chemical equation for steam cracking of ethane to ethylene is shown below:

$$C_2H_6 \rightarrow C_2H_4 + H_2$$

Small amounts of CH_4 are also generated from the steam cracking process. In addition, CO_2 and CH_4 emissions are also generated from combustion units.

Ethylene dichloride ($C_2H_4Cl_2$) is used to produce vinyl chloride monomer, which is the precursor to polyvinyl chloride (PVC). Ethylene dichloride was used as a fuel additive until 1996 when leaded gasoline was phased out. Ethylene dichloride is produced from ethylene by either direct chlorination, oxychlorination, or a combination of the two processes (i.e., the “balanced process”); most U.S. facilities use the balanced process. The direct chlorination and oxychlorination reactions are shown below:

$$C_2H_4 + Cl_2 \rightarrow C_2H_4Cl_2 \text{ (direct chlorination)}$$

$$C_2H_4 + \tfrac{1}{2}O_2 + 2HCl \rightarrow C_2H_4Cl_2 + 2H_2O \text{ (oxychlorination)}$$

$$C_2H_4 + 3O_2 \rightarrow 2CO_2 + 2H_2O \text{ (direct oxidation of ethylene during oxychlorination)}$$

In addition to the byproduct CO_2 produced from the direction oxidation of the ethylene feedstock, CO_2 and CH_4 emissions are also generated from combustion units.

Ethylene oxide (C_2H_4O) is used in the manufacture of glycols, glycol ethers, alcohols, and amines. Approximately 70 percent of ethylene oxide produced worldwide is used in the manufacture of glycols, including monoethylene glycol. Ethylene oxide is produced by reacting ethylene with oxygen over a catalyst. The oxygen may be supplied to the process through either an air (air process) or a pure oxygen stream (oxygen process). The byproduct CO_2 from the direct oxidation of the ethylene feedstock is removed from the process vent stream using a recycled carbonate solution, and the recovered CO_2 may be vented to the atmosphere or recovered for further utilization in other sectors, such as food production (IPCC 2006). The combined ethylene oxide reaction and byproduct CO_2 reaction is exothermic and generates heat, which is recovered to produce steam for the process. The ethylene oxide process also produces other liquid and off-gas byproducts (e.g., ethane, etc.) that may be burned for energy recovery within the process. Almost all facilities, except one in Texas, use the oxygen process to manufacture ethylene oxide (EPA 2008).

Methanol (CH_3OH) is a chemical feedstock most often converted into formaldehyde, acetic acid and olefins. It is also an alternative transportation fuel, as well as an additive used by municipal wastewater treatment facilities in the denitrification of wastewater. Methanol is most commonly synthesized from a synthesis gas (i.e., “syngas” – a mixture containing H_2, CO, and CO_2) using a heterogeneous catalyst. There are a number of process techniques that can be used to produce syngas. Worldwide, steam reforming of natural gas is the most common method; most methanol producers in the United States also use steam reforming of natural gas to produce syngas. Other syngas production processes in the United States include partial oxidation of natural gas and coal gasification.

Emissions of CO_2 and CH_4 from petrochemical production in 2016 were 28.1 MMT CO_2 Eq. (28,110 kt CO_2) and 0.2 MMT CO_2 Eq. (10 kt CH_4), respectively (see Table 4-46 and Table 4-47). Since 1990, total CO_2 emissions from petrochemical production increased by 33 percent. Methane emissions from petrochemical (methanol and acrylonitrile) production reached a low of 1.8 kt CH_4 in 2011, given declining production; however, CH_4 emissions have been increasing every year since 2011 and are now 13 percent greater than in 1990 (though still less than the peak in 1997) due to a rebound in methanol production.

Table 4-46: CO_2 and CH_4 Emissions from Petrochemical Production (MMT CO_2 Eq.)

Year	1990	2005	2012	2013	2014	2015	2016
CO_2	21.2	26.8	26.5	26.4	26.5	28.1	28.1
CH_4	0.2	0.1	0.1	0.1	0.1	0.2	0.2
Total	**21.4**	**26.9**	**26.6**	**26.5**	**26.6**	**28.2**	**28.4**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table 4-47: CO_2 and CH_4 Emissions from Petrochemical Production (kt)

Year	1990	2005	2012	2013	2014	2015	2016
CO_2	21,203	26,794	26,501	26,395	26,496	28,062	28,110
CH_4	9	3	3	3	5	7	10

Methodology

Emissions of CO_2 and CH_4 were calculated using the estimation methods provided by the *2006 IPCC Guidelines* and country-specific methods from EPA's GHGRP. The *2006 IPCC Guidelines* Tier 1 method was used to estimate CO_2 and CH_4 emissions from production of acrylonitrile and methanol,[41] and a country-specific approach similar to the IPCC Tier 2 method was used to estimate CO_2 emissions from carbon black, ethylene, ethylene oxide, and ethylene dichloride. The Tier 2 method for petrochemicals is a total feedstock C mass balance method used to estimate total CO_2 emissions, but is not applicable for estimating CH_4 emissions. As noted in the *2006 IPCC Guidelines*, the total feedstock C mass balance method (Tier 2) is based on the assumption that all of the C input to the process is converted either into primary and secondary products or into CO_2. Further, the guideline states that while the total C mass balance method estimates total C emissions from the process but does not directly provide an estimate of the amount of the total C emissions emitted as CO_2, CH_4, or non-CH_4 volatile organic compounds (NMVOCs). This method accounts for all the C as CO_2, including CH_4. Note, a subset of facilities reporting under EPA's GHGRP use alternate methods to the C balance approach (e.g., Continuous Emission Monitoring Systems (CEMS) or other engineering approaches) to monitor CO_2 emissions and these facilities are required to also report CH_4 and N_2O emissions from combustion of process off-gas. Preliminary analysis of aggregated annual reports shows that these emissions are less than 500 kt/year. EPA's GHGRP is still reviewing this data across reported years to facilitate update of category-specific QC documentation and EPA plans to address this more completely in future reports.

Carbon Black, Ethylene, Ethylene Dichloride and Ethylene Oxide

2010 through 2016

Carbon dioxide emissions and national production were aggregated directly from EPA's GHGRP dataset for 2010 through 2016 (EPA 2017). In 2016, GHGRP data reported CO_2 emissions of 3,160,000 metric tons from carbon black production; 19,600,000 metric tons of CO_2 from ethylene production; 447,000 metric tons of CO_2 from ethylene dichloride production; and 1,100,000 metric tons of CO_2 from ethylene oxide production. These emissions reflect application of a country-specific approach similar to the IPCC Tier 2 method and were used to estimate CO_2

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[41] EPA has not integrated aggregated facility-level GHGRP information for acrylonitrile and methanol production. The aggregated information associated with production of these petrochemicals did not meet criteria to shield underlying CBI from public disclosure.

emissions from the production of carbon black, ethylene, ethylene dichloride, and ethylene oxide. Since 2010, EPA's GHGRP, under Subpart X, requires all domestic producers of petrochemicals to report annual emissions and supplemental emissions information (e.g., production data, etc.) to facilitate verification of reported emissions. Under EPA's GHGRP, most petrochemical production facilities are required to use either a mass balance approach or CEMS to measure and report emissions for each petrochemical process unit to estimate facility-level process CO_2 emissions; ethylene production facilities also have a third option. The mass balance method is used by most facilities[42] and assumes that all the carbon input is converted into primary and secondary products, byproducts, or is emitted to the atmosphere as CO_2. To apply the mass balance, facilities must measure the volume or mass of each gaseous and liquid feedstock and product, mass rate of each solid feedstock and product, and carbon content of each feedstock and product for each process unit and sum for their facility. More details on the greenhouse gas calculation, monitoring and QA/QC methods applicable to petrochemical facilities can be found under Subpart X (Petrochemical Production) of the regulation (40 CFR Part 98).[43] EPA verifies annual facility-level GHGRP reports through a multi-step process (e.g., combination of electronic checks and manual reviews) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent.[44]

All non-energy uses of residual fuel and some non-energy uses of "other oil" are assumed to be used in the production of carbon black; therefore, consumption of these fuels is adjusted for within the Energy chapter to avoid double-counting of emissions from fuel used in the carbon black production presented here within the IPPU sector. Additional information on the adjustments made within the Energy sector for Non-Energy Use of Fuels is described in both the Methodology section of CO_2 from Fossil Fuel Combustion (3.1 Fossil Fuel Combustion (CRF Source Category 1A)) and Annex 2.1, Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion.

1990 through 2009

Prior to 2010, for each of these 4 types of petrochemical processes, an average national CO_2 emission factor was calculated based on the 2010 through 2016 GHGRP data and applied to production for earlier years in the time series (i.e., 1990 through 2009) to estimate CO_2 emissions from carbon black, ethylene, ethylene dichloride, and ethylene oxide production. Carbon dioxide emission factors were derived from EPA's GHGRP data by dividing annual CO_2 emissions for petrochemical type "i" with annual production for petrochemical type "i" and then averaging the derived emission factors obtained for each calendar year 2010 through 2016. The average emission factors for each petrochemical type were applied across all prior years because petrochemical production processes in the United States have not changed significantly since 1990, though some operational efficiencies have been implemented at facilities over the time series.

The average country-specific CO_2 emission factors that were calculated from the 2010 through 2016 GHGRP data are as follows:

- 2.62 metric tons CO_2/metric ton carbon black produced
- 0.77 metric tons CO_2/metric ton ethylene produced
- 0.040 metric tons CO_2/metric ton ethylene dichloride produced
- 0.43 metric tons CO_2/metric ton ethylene oxide produced

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[42] A few facilities producing ethylene dichloride used CO_2 CEMS, those CO_2 emissions have been included in the aggregated GHGRP emissions presented here. For ethylene production processes, nearly all process emissions are from the combustion of process off-gas. Under EPA's GHGRP, Subpart X, ethylene facilities can report CO_2 emissions from burning of process gases using the optional combustion methodology for ethylene production processes, which is requires estimating emissions based on fuel quantity and carbon contents of the fuel. This is consistent with the *2006 IPCC Guidelines* (p. 3.57) which recommends including combustion emissions from fuels obtained from feedstocks (e.g., off-gases) in petrochemical production under in the IPPU sector. In 2014, for example, this methodology was used by more than 20 of the 65 reporting facilities. In addition to CO_2, these facilities are required to report emissions of CH_4 and N_2O from combustion of ethylene process off-gas in flares. Facilities using CEMS (consistent with a Tier 3 approach) are also required to report emissions of CH_4 and N_2O from combustion of petrochemical process-off gases in flares, as applicable. Preliminary analysis of the aggregated reported CH_4 and N_2O emissions from facilities using CEMS and the optional combustion methodology suggests that these annual emissions are less than 500 kt/yr so not significant enough to prioritize for inclusion in the report at this time. Pending resources and significance, EPA may include these emissions in future reports to enhance completeness.

[43] See <http://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title40/40cfr98_main_02.tpl>.

[44] See <https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf>.

Annual production data for carbon black for 1990 through 2009 were obtained from the International Carbon Black Association (Johnson 2003 and 2005 through 2010). Annual production data for ethylene and ethylene dichloride for 1990 through 2009 were obtained from the American Chemistry Council's (ACC's) *Guide to the Business of Chemistry* (ACC 2002, 2003, 2005 through 2011). Annual production data for ethylene oxide were obtained from ACC's *U.S. Chemical Industry Statistical Handbook* for 2003 through 2009 (ACC 2014a) and from ACC's *Business of Chemistry* for 1990 through 2002 (ACC 2014b). As noted above, annual 2010 through 2016 production data for carbon black, ethylene, ethylene dichloride, and ethylene oxide, were obtained from EPA's GHGRP.

Acrylonitrile

Carbon dioxide and CH_4 emissions from acrylonitrile production were estimated using the Tier 1 method in the *2006 IPCC Guidelines*. Annual acrylonitrile production data were used with IPCC default Tier 1 CO_2 and CH_4 emission factors to estimate emissions for 1990 through 2016. Emission factors used to estimate acrylonitrile production emissions are as follows:

- 0.18 kg CH_4/metric ton acrylonitrile produced
- 1.00 metric tons CO_2/metric ton acrylonitrile produced

Annual acrylonitrile production data for 1990 through 2016 were obtained from ACC's *Business of Chemistry* (ACC 2017).

Methanol

Carbon dioxide and CH_4 emissions from methanol production were estimated using Tier 1 method in the *2006 IPCC Guidelines*. Annual methanol production data were used with IPCC default Tier 1 CO_2 and CH_4 emission factors to estimate emissions for 1990 through 2016. Emission factors used to estimate methanol production emissions are as follows:

- 2.3 kg CH_4/metric ton methanol produced
- 0.67 metric tons CO_2/metric ton methanol produced

Annual methanol production data for 1990 through 2016 were obtained from the ACC's *Business of Chemistry* (ACC 2017).

Table 4-48: Production of Selected Petrochemicals (kt)

Chemical	1990	2005	2012	2013	2014	2015	2016
Carbon Black	1,307	1,651	1,280	1,230	1,210	1,220	1,190
Ethylene	16,542	23,975	24,800	25,300	25,500	26,900	26,600
Ethylene Dichloride	6,283	11,260	11,300	11,500	11,300	11,300	11,700
Ethylene Oxide	2,429	3,220	3,110	3,150	3,140	3,240	3,210
Acrylonitrile	1,214	1,325	1,220	1,075	1,095	1,050	955
Methanol	3,750	1,225	995	1,235	2,105	3,065	4,250

As noted earlier in the introduction of the Petrochemical Production section, the allocation and reporting of emissions from both fuels and feedstocks transferred out of the system for use in energy purposes to the Energy chapter differs slightly from the *2006 IPCC Guidelines*. According to the *2006 IPCC Guidelines*, emissions from fuel combustion from petrochemical production should be allocated to this source category within the IPPU chapter. Due to national circumstances, EIA data on primary fuel for feedstock use within the energy balance are presented by commodity only, with no resolution on data by industry sector (i.e., petrochemical production). In addition, under EPA's GHGRP, reporting facilities began reporting in reporting year 2014 on annual feedstock quantities for mass balance and CEMS methodologies (79 FR 63794), as well as the annual average carbon content of each feedstock (and molecular weight for gaseous feedstocks) for the mass balance methodology beginning in reporting year 2017

(81 FR 89260).[45] The United States is currently unable to report non-energy fuel use from petrochemical production under the IPPU chapter due to CBI issues. Therefore, consistent with *2006 IPCC Guidelines*, fuel consumption data reported by EIA are modified to account for these overlaps to avoid double-counting. More information on the non-energy use of fossil fuel feedstocks for petrochemical production can be found in Annex 2.3.

Uncertainty and Time-Series Consistency

The CH_4 and CO_2 emission factors used for acrylonitrile and methanol production are based on a limited number of studies. Using plant-specific factors instead of default or average factors could increase the accuracy of the emission estimates; however, such data were not available for the current Inventory report.

The results of the quantitative uncertainty analysis for the CO_2 emissions from carbon black production, ethylene, ethylene dichloride, and ethylene oxide are based on reported GHGRP data. Refer to the Methodology section for more details on how these emissions were calculated and reported to EPA's GHGRP. There is some uncertainty in the applicability of the average emission factors for each petrochemical type across all prior years. While petrochemical production processes in the United States have not changed significantly since 1990, some operational efficiencies have been implemented at facilities over the time series.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-49. Petrochemical production CO_2 emissions from 2016 were estimated to be between 26.7 and 29.6 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 5 percent below to 5 percent above the emission estimate of 28.1 MMT CO_2 Eq. Petrochemical production CH_4 emissions from 2016 were estimated to be between 0.09 and 0.30 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 57 percent below to 46 percent above the emission estimate of 0.2 MMT CO_2 Eq.

Table 4-49: Approach 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Petrochemical Production and CO_2 Emissions from Petrochemical Production (MMT CO_2 Eq. and Percent)

Source	Gas	2016 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Petrochemical Production	CO_2	28.1	26.7	29.6	-5%	+5%
Petrochemical Production	CH_4	0.2	0.09	0.30	-57%	+46%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2016.

For more information on the general QA/QC process applied to this source category, consistent with Volume 1, Chapter 6 of the *2006 IPCC Guidelines*, see the QA/QC and Verification Procedures section in the introduction of the IPPU chapter.

QA/QC and Verification

For Petrochemical Production, QA/QC activities were conducted consistent with the U.S. QA/QC plan, as described in the QA/QC and Verification Procedures section of the IPPU chapter. Source-specific quality control measures for this category included the QA/QC requirements and verification procedures of EPA's GHGRP. Future QC efforts to

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[45] See <https://www.epa.gov/ghgreporting/historical-rulemakings>.

validate the use of Tier 1 default emission factors and report on the comparison of Tier 1 emissions estimates and GHGRP data are described below in the Planned Improvements section.

Planned Improvements

Improvements include completing category-specific QC of activity data and emission factors, along with further assessment of CH_4 and N_2O emissions to enhance completeness in reporting of emissions from U.S. petrochemical production, pending resources, significance, and time-series consistency considerations. As of this current report, timing and resources have not allowed EPA to complete this analysis of activity data and emission factors and remains a priority improvement within the IPPU chapter.

Pending resources, a secondary potential improvement for this source category would focus on continuing to analyze the fuel and feedstock data from EPA's GHGRP to better disaggregate energy-related emissions and allocate them more accurately between the Energy and IPPU sectors of the Inventory. Some degree of double counting may occur between CO_2 estimates of non-energy use of fuels in the energy sector and CO_2 process emissions from petrochemical production in this sector. As noted previously in the methodology section, data integration is not feasible at this time as feedstock data from the EIA used to estimate non-energy uses of fuels are aggregated by fuel type, rather than disaggregated by both fuel type and particular industries. As described in the methodology section of this source category, EPA is currently unable to use GHGRP reported data on quantities of fuel consumed as feedstocks by petrochemical producers, only feedstock type, due to the data failing GHGRP CBI aggregation criteria. Incorporating this data into future inventories will allow for easier data integration between the non-energy uses of fuels category and the petrochemicals category presented in this chapter. This planned improvement is still under development and has not been completed to report on progress in this current Inventory.

4.14 HCFC-22 Production (CRF Source Category 2B9a)

Trifluoromethane (HFC-23 or CHF_3) is generated as a byproduct during the manufacture of chlorodifluoromethane (HCFC-22), which is primarily employed in refrigeration and air conditioning systems and as a chemical feedstock for manufacturing synthetic polymers. Between 1990 and 2000, U.S. production of HCFC-22 increased significantly as HCFC-22 replaced chlorofluorocarbons (CFCs) in many applications. Between 2000 and 2007, U.S. production fluctuated but generally remained above 1990 levels. In 2008 and 2009, U.S. production declined markedly and has remained near 2009 levels since. Because HCFC-22 depletes stratospheric ozone, its production for non-feedstock uses is scheduled to be phased out by 2020 under the U.S. Clean Air Act.[46] Feedstock production, however, is permitted to continue indefinitely.

HCFC-22 is produced by the reaction of chloroform ($CHCl_3$) and hydrogen fluoride (HF) in the presence of a catalyst, $SbCl_5$. The reaction of the catalyst and HF produces $SbCl_xF_y$, (where $x + y = 5$), which reacts with chlorinated hydrocarbons to replace chlorine atoms with fluorine. The HF and chloroform are introduced by submerged piping into a continuous-flow reactor that contains the catalyst in a hydrocarbon mixture of chloroform and partially fluorinated intermediates. The vapors leaving the reactor contain HCFC-21 ($CHCl_2F$), HCFC-22 ($CHClF_2$), HFC-23 (CHF_3), HCl, chloroform, and HF. The under-fluorinated intermediates (HCFC-21) and chloroform are then condensed and returned to the reactor, along with residual catalyst, to undergo further fluorination. The final vapors leaving the condenser are primarily HCFC-22, HFC-23, HCl and residual HF. The HCl is recovered as a useful byproduct, and the HF is removed. Once separated from HCFC-22, the HFC-23 may be released to the atmosphere, recaptured for use in a limited number of applications, or destroyed.

Two facilities produced HCFC-22 in the United States in 2016. Emissions of HFC-23 from this activity in 2016 were estimated to be 2.8 MMT CO_2 Eq. (0.19 kt) (see Table 4-50). This quantity represents a 34 percent decrease

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[46] As construed, interpreted, and applied in the terms and conditions of the Montreal Protocol on Substances that Deplete the Ozone Layer. [42 U.S.C. §7671m(b), CAA §614]

from 2015 emissions and a 94 percent decrease from 1990 emissions. The decrease from 2015 emissions and the decrease from 1990 emissions were caused primarily by changes in the HFC-23 emission rate (kg HFC-23 emitted/kg HCFC-22 produced). The long-term decrease in the emission rate is primarily attributable to six factors: (a) five plants that did not capture and destroy the HFC-23 generated have ceased production of HCFC-22 since 1990; (b) one plant that captures and destroys the HFC-23 generated began to produce HCFC-22; (c) one plant implemented and documented a process change that reduced the amount of HFC-23 generated; (d) the same plant began recovering HFC-23, primarily for destruction and secondarily for sale; (e) another plant began destroying HFC-23; and (f) the same plant, whose emission factor was higher than that of the other two plants, ceased production of HCFC-22 in 2013.

Table 4-50: HFC-23 Emissions from HCFC-22 Production (MMT CO_2 Eq. and kt HFC-23)

Year	MMT CO_2 Eq.	kt HFC-23
1990	46.1	3
2005	20.0	1
2012	5.5	0.4
2013	4.1	0.3
2014	5.0	0.3
2015	4.3	0.3
2016	2.8	0.2

Methodology

To estimate HFC-23 emissions for five of the eight HCFC-22 plants that have operated in the United States since 1990, methods comparable to the Tier 3 methods in the *2006 IPCC Guidelines* (IPCC 2006) were used. Emissions for 2010 through 2016 were obtained through reports submitted by U.S. HCFC-22 production facilities to EPA's Greenhouse Gas Reporting Program (GHGRP). EPA's GHGRP mandates that all HCFC-22 production facilities report their annual emissions of HFC-23 from HCFC-22 production processes and HFC-23 destruction processes. Previously, data were obtained by EPA through collaboration with an industry association that received voluntarily reported HCFC-22 production and HFC-23 emissions annually from all U.S. HCFC-22 producers from 1990 through 2009. These emissions were aggregated and reported to EPA on an annual basis.

For the other three plants, the last of which closed in 1993, methods comparable to the Tier 1 method in the *2006 IPCC Guidelines* were used. Emissions from these three plants have been calculated using the recommended emission factor for unoptimized plants operating before 1995 (0.04 kg HCFC-23/kg HCFC-22 produced).

The five plants that have operated since 1994 measure (or, for the plants that have since closed, measured) concentrations of HFC-23 to estimate their emissions of HFC-23. Plants using thermal oxidation to abate their HFC-23 emissions monitor the performance of their oxidizers to verify that the HFC-23 is almost completely destroyed. Plants that release (or historically have released) some of their byproduct HFC-23 periodically measure HFC-23 concentrations in the output stream using gas chromatography. This information is combined with information on quantities of products (e.g., HCFC-22) to estimate HFC-23 emissions.

To estimate 1990 through 2009 emissions, reports from an industry association were used that aggregated HCFC-22 production and HFC-23 emissions from all U.S. HCFC-22 producers and reported them to EPA (ARAP 1997, 1999, 2000, 2001, 2002, 2003, 2004, 2005, 2006, 2007, 2008, 2009, and 2010). To estimate 2010 through 2016 emissions, facility-level data (including both HCFC-22 production and HFC-23 emissions) reported through EPA's GHGRP were analyzed. In 1997 and 2008, comprehensive reviews of plant-level estimates of HFC-23 emissions and HCFC-22 production were performed (RTI 1997; RTI 2008). The 1997 and 2008 reviews enabled U.S. totals to be reviewed, updated, and where necessary, corrected, and also for plant-level uncertainty analyses (Monte-Carlo simulations) to be performed for 1990, 1995, 2000, 2005, and 2006. Estimates of annual U.S. HCFC-22 production are presented in Table 4-51.

Table 4-51: HCFC-22 Production (kt)

Year	kt
1990	139
2005	156
2012	96
2013	C
2014	C
2015	C
2016	C

C (CBI)
Note: HCFC-22 production in 2012 through 2016 is considered Confidential Business Information (CBI) as there were only two producers of HCFC-22 in those years.

Uncertainty and Time-Series Consistency

The uncertainty analysis presented in this section was based on a plant-level Monte Carlo Stochastic Simulation for 2006. The Monte Carlo analysis used estimates of the uncertainties in the individual variables in each plant's estimating procedure. This analysis was based on the generation of 10,000 random samples of model inputs from the probability density functions for each input. A normal probability density function was assumed for all measurements and biases except the equipment leak estimates for one plant; a log-normal probability density function was used for this plant's equipment leak estimates. The simulation for 2006 yielded a 95-percent confidence interval for U.S. emissions of 6.8 percent below to 9.6 percent above the reported total.

The relative errors yielded by the Monte Carlo Stochastic Simulation for 2006 were applied to the U.S. emission estimate for 2016. The resulting estimates of absolute uncertainty are likely to be reasonably accurate because (1) the methods used by the two remaining plants to estimate their emissions are not believed to have changed significantly since 2006, and (2) although the distribution of emissions among the plants has changed between 2006 and 2016 (because one plant has closed), the plant that currently accounts for most emissions had a relative uncertainty in its 2006 (as well as 2005) emissions estimate that was similar to the relative uncertainty for total U.S. emissions. Thus, the closure of one plant is not likely to have a large impact on the uncertainty of the national emission estimate.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-52. HFC-23 emissions from HCFC-22 production were estimated to be between 2.6 and 3.1 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 7 percent below and 10 percent above the emission estimate of 2.8 MMT CO_2 Eq.

Table 4-52: Approach 2 Quantitative Uncertainty Estimates for HFC-23 Emissions from HCFC-22 Production (MMT CO_2 Eq. and Percent)

Source	Gas	2016 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a]			
			(MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
HCFC-22 Production	HFC-23	2.8	2.6	3.1	-7%	+10%

[a] Range of emissions reflects a 95 percent confidence interval.

QA/QC and Verification

General (Tier 1) and category-specific (Tier 2) QA/QC activities were conducted consistent with the U.S. QA/QC plan. Source-specific quality control measures for the HCFC-22 Production category included the QA/QC requirements and verification procedures of EPA's GHGRP. Under EPA's GHGRP, HCFC-22 producers are required to (1) measure concentrations of HFC-23 and HCFC-22 in the product stream at least weekly using equipment and methods (e.g., gas chromatography) with an accuracy and precision of 5 percent or better at the concentrations of the process samples, (2) measure mass flows of HFC-23 and HCFC-22 at least weekly using measurement devices (e.g., flowmeters) with an accuracy and precision of 1 percent of full scale or better, (3) calibrate mass measurement devices at the frequency recommended by the manufacturer using traceable standards and suitable methods published by a consensus standards organization, (4) calibrate gas chromatographs at least monthly through analysis of certified standards, and (5) document these calibrations.

EPA verifies annual facility-level reports from HCFC-22 producers through a multi-step process (e.g., a combination of electronic checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent. Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred.[47]

4.15 Carbon Dioxide Consumption (CRF Source Category 2B10)

Carbon dioxide (CO_2) is used for a variety of commercial applications, including food processing, chemical production, carbonated beverage production, and refrigeration, and is also used in petroleum production for enhanced oil recovery (EOR). Carbon dioxide used for EOR is injected underground to enable additional petroleum to be produced. For the purposes of this analysis, CO_2 used in commercial applications other than EOR is assumed to be emitted to the atmosphere. Carbon dioxide used in EOR applications is discussed in the Energy chapter under "Carbon Capture and Storage, including Enhanced Oil Recovery" and is not discussed in this section.

Carbon dioxide is produced from naturally-occurring CO_2 reservoirs, as a byproduct from the energy and industrial production processes (e.g., ammonia production, fossil fuel combustion, ethanol production), and as a byproduct from the production of crude oil and natural gas, which contain naturally occurring CO_2 as a component. Only CO_2 produced from naturally occurring CO_2 reservoirs, and as a byproduct from energy and industrial processes, and used in industrial applications other than EOR is included in this analysis. Carbon dioxide captured from biogenic sources (e.g., ethanol production plants) is not included in the Inventory. Carbon dioxide captured from crude oil and gas production is used in EOR applications and is therefore reported in the Energy chapter.

Carbon dioxide is produced as a byproduct of crude oil and natural gas production. This CO_2 is separated from the crude oil and natural gas using gas processing equipment, and may be emitted directly to the atmosphere, or captured and reinjected into underground formations, used for EOR, or sold for other commercial uses. A further discussion of CO_2 used in EOR is described in the Energy chapter in Box 3-7 titled "Carbon Dioxide Transport, Injection, and Geological Storage."

In 2016, the amount of CO_2 produced and captured for commercial applications and subsequently emitted to the atmosphere was 4.5 MMT CO_2 Eq. (4,471 kt) (see Table 4-53). This is consistent with 2014 and 2015 levels and is an increase of approximately 204 percent since 1990.

Table 4-53: CO_2 Emissions from CO_2 Consumption (MMT CO_2 Eq. and kt)

Year	MMT CO_2 Eq.	kt
1990	1.5	1,472
2005	1.4	1,375
2012	4.0	4,019
2013	4.2	4,188

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[47] See <https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf>.

Year	MMT CO_2 Eq.	kt
2014	4.5	4,471
2015	4.5	4,471
2016	4.5	4,471

Methodology

Carbon dioxide emission estimates for 1990 through 2016 were based on the quantity of CO_2 extracted and transferred for industrial applications (i.e., non-EOR end-uses). Some of the CO_2 produced by these facilities is used for EOR and some is used in other commercial applications (e.g., chemical manufacturing, food production). It is assumed that 100 percent of the CO_2 production used in commercial applications other than EOR is eventually released into the atmosphere.

2010 through 2016

For 2010 through 2014, data from EPA's GHGRP (Subpart PP) were aggregated from facility-level reports to develop a national-level estimate for use in the Inventory (EPA 2016). Facilities report CO_2 extracted or produced from natural reservoirs and industrial sites, and CO_2 captured from energy and industrial processes and transferred to various end-use applications to EPA's GHGRP. This analysis includes only reported CO_2 transferred to food and beverage end-uses. EPA is continuing to analyze and assess integration of CO_2 transferred to other end-uses to enhance the completeness of estimates under this source category. Other end-uses include industrial applications, such as metal fabrication. EPA is analyzing the information reported to ensure that other end-use data excludes non-emissive applications and publication will not reveal confidential business information (CBI). Reporters subject to EPA's GHGRP Subpart PP are also required to report the quantity of CO_2 that is imported and/or exported. Currently, these data are not publicly available through the GHGRP due to data confidentiality reasons and hence are excluded from this analysis.

Facilities subject to Subpart PP of EPA's GHGRP are required to measure CO_2 extracted or produced. More details on the calculation and monitoring methods applicable to extraction and production facilities can be found under Subpart PP: Suppliers of Carbon Dioxide of the regulation, Part 98.[48] The number of facilities that reported data to EPA's GHGRP Subpart PP (Suppliers of Carbon Dioxide) for 2010 through 2014 is much higher (ranging from 44 to 48) than the number of facilities included in the Inventory for the 1990 to 2009 time period prior to the availability of GHGRP data (4 facilities). The difference is largely due to the fact the 1990 to 2009 data includes only CO_2 transferred to end-use applications from naturally occurring CO_2 reservoirs and excludes industrial sites.

Starting in 2015, data from EPA's GHGRP (Subpart PP) was unavailable for use in the current Inventory report due to data confidentiality reasons. As a result, the emissions estimates for 2015 and 2016 have been held constant from 2014 levels to avoid disclosure of proprietary information. EPA will continue to evaluate options for utilizing GHGRP data to update these values in future Inventories.

1990 through 2009

For 1990 through 2009, data from EPA's GHGRP are not available. For this time period, CO_2 production data from four naturally-occurring CO_2 reservoirs were used to estimate annual CO_2 emissions. These facilities were Jackson Dome in Mississippi, Brave and West Bravo Domes in New Mexico, and McCallum Dome in Colorado. The facilities in Mississippi and New Mexico produced CO_2 for use in both EOR and in other commercial applications (e.g., chemical manufacturing, food production). The fourth facility in Colorado (McCallum Dome**)** produced CO_2 for commercial applications only (New Mexico Bureau of Geology and Mineral Resources 2006).

Carbon dioxide production data and the percentage of production that was used for non-EOR applications for the Jackson Dome, Mississippi facility were obtained from Advanced Resources International (ARI 2006, 2007) for 1990 to 2000, and from the Annual Reports of Denbury Resources (Denbury Resources 2002 through 2010) for

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[48] See <http://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title40/40cfr98_main_02.tpl>.

2001 to 2009 (see Table 4-54). Denbury Resources reported the average CO_2 production in units of MMCF CO_2 per day for 2001 through 2009 and reported the percentage of the total average annual production that was used for EOR. Production from 1990 to 1999 was set equal to 2000 production, due to lack of publicly available production data for 1990 through 1999. Carbon dioxide production data for the Bravo Dome and West Bravo Dome were obtained from ARI for 1990 through 2009 (ARI 1990 to 2010). Data for the West Bravo Dome facility were only available for 2009. The percentage of total production that was used for non-EOR applications for the Bravo Dome and West Bravo Dome facilities for 1990 through 2009 were obtained from New Mexico Bureau of Geology and Mineral Resources (Broadhead 2003; New Mexico Bureau of Geology and Mineral Resources 2006). Production data for the McCallum Dome (Jackson County), Colorado facility were obtained from the Colorado Oil and Gas Conservation Commission (COGCC) for 1999 through 2009 (COGCC 2014). Production data for 1990 to 1998 and percentage of production used for EOR were assumed to be the same as for 1999, due to lack of publicly-available data.

Table 4-54: CO_2 Production (kt CO_2) and the Percent Used for Non-EOR Applications

Year	Jackson Dome, MS CO_2 Production (kt) (% Non-EOR)	Bravo Dome, NM CO_2 Production (kt) (% Non-EOR)	West Bravo Dome, NM CO_2 Production (kt) (% Non-EOR)	McCallum Dome, CO CO_2 Production (kt) (% Non-EOR)	Total CO_2 Production from Extraction and Capture Facilities (kt)	% Non-EOR[a]
1990	1,344 (100%)	63 (1%)	+	65 (100%)	NA	NA
2005	1,254 (27%)	58 (1%)	+	63 (100%)	NA	NA
2012	NA	NA	NA	NA	66,326	6%
2013	NA	NA	NA	NA	68,435	6%
2014	NA	NA	NA	NA	72,000	6%
2015	NA	NA	NA	NA	72,000	6%
2016	NA	NA	NA	NA	72,000	6%

+ Does not exceed 0.5 percent.

NA (Not available) – For 2010 through 2014, the publicly available GHGRP data were aggregated at the national level. For 2015 and 2016, values were held constant with those from 2014. Facility-level data are not publicly available from EPA's GHGRP.

[a] Includes only food & beverage applications.

Uncertainty and Time-Series Consistency

There is uncertainty associated with the data reported through EPA's GHGRP. Specifically, there is uncertainty associated with the amount of CO_2 consumed for food and beverage applications given a threshold for reporting under GHGRP applicable to those reporting under Subpart PP, in addition to the exclusion of the amount of CO_2 transferred to all other end-use categories. This latter category might include CO_2 quantities that are being used for non-EOR industrial applications such as firefighting. Second, uncertainty is associated with the exclusion of imports/exports data for CO_2 suppliers. Currently these data are not publicly available through EPA's GHGRP and hence are excluded from this analysis. EPA verifies annual facility-level reports through a multi-step process (e.g., combination of electronic checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent. Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred.[49]

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-55. Carbon dioxide consumption CO_2 emissions for 2016 were estimated to be between 4.2 and 4.7 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 5 percent below to 5 percent above the emission estimate of 4.5 MMT CO_2 Eq.

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[49] See <https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf >.

Table 4-55: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from CO_2 Consumption (MMT CO_2 Eq. and Percent)

Source	Gas	2016 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
CO_2 Consumption	CO_2	4.5	4.2	4.7	-5%	+5%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2016.

For more information on the general QA/QC process applied to this source category, consistent with Volume 1, Chapter 6 of the *2006 IPCC Guidelines*, see the QA/QC and Verification Procedures section in the introduction of the IPPU chapter.

Planned Improvements

EPA will continue to evaluate the potential to include additional GHGRP data on other emissive end-uses to improve the accuracy and completeness of estimates for this source category. Particular attention will be made to ensuring time-series consistency of the emissions estimates presented in future Inventory reports, consistent with IPCC and UNFCCC guidelines. This is required as the facility-level reporting data from EPA's GHGRP, with the program's initial requirements for reporting of emissions in calendar year 2010, are not available for all inventory years (i.e., 1990 through 2009) as required for this Inventory. In implementing improvements and integration of data from EPA's GHGRP, the latest guidance from the IPCC on the use of facility-level data in national inventories will be relied upon.[50] These improvements, in addition to updating the time series when new data is available, are still in process and will be incorporated into future Inventory reports.

4.16 Phosphoric Acid Production (CRF Source Category 2B10)

Phosphoric acid (H_3PO_4) is a basic raw material used in the production of phosphate-based fertilizers. Phosphoric acid production from natural phosphate rock is a source of carbon dioxide (CO_2) emissions, due to the chemical reaction of the inorganic carbon (calcium carbonate) component of the phosphate rock.

Phosphate rock is mined in Florida and North Carolina, which account for more than 75 percent of total domestic output, as well as in Idaho and Utah and is used primarily as a raw material for wet-process phosphoric acid production (USGS 2017). The composition of natural phosphate rock varies depending upon the location where it is mined. Natural phosphate rock mined in the United States generally contains inorganic carbon in the form of calcium carbonate (limestone) and also may contain organic carbon. The calcium carbonate component of the phosphate rock is integral to the phosphate rock chemistry. Phosphate rock can also contain organic carbon that is physically incorporated into the mined rock but is not an integral component of the phosphate rock chemistry.

The phosphoric acid production process involves chemical reaction of the calcium phosphate ($Ca_3(PO_4)_2$) component of the phosphate rock with sulfuric acid (H_2SO_4) and recirculated phosphoric acid (H_3PO_4) (EFMA 2000). However, the generation of CO_2 is due to the associated limestone-sulfuric acid reaction, as shown below:

$$CaCO_3 + H_2SO_4 + H_2O \rightarrow CaSO_4 \bullet 2H_2O + CO_2$$

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[50] See <http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf>.

Total U.S. phosphate rock production sold or used in 2016 was 26.5 million metric tons (USGS 2017). Total imports of phosphate rock to the United States in 2016 were approximately 1.6 million metric tons (USGS 2017). Between 2012 and 2015, most of the imported phosphate rock (58 percent) came from Peru, with the remaining 42 percent being from Morocco (USGS 2017). All phosphate rock mining companies are vertically integrated with fertilizer plants that produce phosphoric acid located near the mines. Some additional phosphoric acid production facilities are located in Texas, Louisiana, and Mississippi that used imported phosphate rock.

Over the 1990 to 2016 period, domestic production has decreased by nearly 47 percent. Total CO_2 emissions from phosphoric acid production were 1.0 MMT CO_2 Eq. (992 kt CO_2) in 2016 (see Table 4-56). Domestic consumption of phosphate rock in 2016 was estimated to have gone unchanged over 2015 levels (USGS 2017).

Table 4-56: CO_2 Emissions from Phosphoric Acid Production (MMT CO_2 Eq. and kt)

Year	MMT CO_2 Eq.	kt
1990	1.5	1,529
2005	1.3	1,342
2012	1.1	1,118
2013	1.1	1,149
2014	1.0	1,038
2015	1.0	999
2016	1.0	992

Methodology

Carbon dioxide emissions from production of phosphoric acid from phosphate rock are estimated by multiplying the average amount of inorganic carbon (expressed as CO_2) contained in the natural phosphate rock as calcium carbonate by the amount of phosphate rock that is used annually to produce phosphoric acid, accounting for domestic production and net imports for consumption. The estimation methodology is as follows:

$$E_{pa} = C_{pr} \times Q_{pr}$$

where,

E_{pa} = CO_2 emissions from phosphoric acid production, metric tons

C_{pr} = Average amount of carbon (expressed as CO_2) in natural phosphate rock, metric ton CO_2/ metric ton phosphate rock

Q_{pr} = Quantity of phosphate rock used to produce phosphoric acid

The CO_2 emissions calculation methodology is based on the assumption that all of the inorganic C (calcium carbonate) content of the phosphate rock reacts to produce CO_2 in the phosphoric acid production process and is emitted with the stack gas. The methodology also assumes that none of the organic C content of the phosphate rock is converted to CO_2 and that all of the organic C content remains in the phosphoric acid product. The United States uses a country-specific methodology to calculate emissions from production of phosphoric acid from phosphate rock.

From 1993 to 2004, the U.S. Geological Survey (USGS) *Mineral Yearbook: Phosphate Rock* disaggregated phosphate rock mined annually in Florida and North Carolina from phosphate rock mined annually in Idaho and Utah, and reported the annual amounts of phosphate rock exported and imported for consumption (see Table 4-57). For the years 1990 through 1992, and 2005 through 2016, only nationally aggregated mining data was reported by USGS. For the years 1990, 1991, and 1992, the breakdown of phosphate rock mined in Florida and North Carolina, and the amount mined in Idaho and Utah, are approximated using average share of U.S. production in those states from 1993 to 2004 data. For the years 2005 through 2016, the same approximation method is used, but the share of U.S. production in those states data were obtained from the USGS commodity specialist for phosphate rock (USGS 2012). Data for domestic sales or consumption of phosphate rock, exports of phosphate rock (primarily from Florida and North Carolina), and imports of phosphate rock for consumption for 1990 through 2016 were obtained from USGS *Minerals Yearbook: Phosphate Rock* (USGS 1994 through 2015b), and from USGS *Minerals Commodity*

Summaries: Phosphate Rock (USGS 2016, 2017). From 2004 through 2016, the USGS reported no exports of phosphate rock from U.S. producers (USGS 2005 through 2015b).

The carbonate content of phosphate rock varies depending upon where the material is mined. Composition data for domestically mined and imported phosphate rock were provided by the Florida Institute of Phosphate Research (FIPR 2003a). Phosphate rock mined in Florida contains approximately 1 percent inorganic C, and phosphate rock imported from Morocco contains approximately 1.46 percent inorganic carbon. Calcined phosphate rock mined in North Carolina and Idaho contains approximately 0.41 percent and 0.27 percent inorganic C, respectively (see Table 4-58).

Carbonate content data for phosphate rock mined in Florida are used to calculate the CO_2 emissions from consumption of phosphate rock mined in Florida and North Carolina (80 percent of domestic production) and carbonate content data for phosphate rock mined in Morocco are used to calculate CO_2 emissions from consumption of imported phosphate rock. The CO_2 emissions calculation is based on the assumption that all of the domestic production of phosphate rock is used in uncalcined form. As of 2006, the USGS noted that one phosphate rock producer in Idaho produces calcined phosphate rock; however, no production data were available for this single producer (USGS 2006). The USGS confirmed that no significant quantity of domestic production of phosphate rock is in the calcined form (USGS 2012).

Table 4-57: Phosphate Rock Domestic Consumption, Exports, and Imports (kt)

Location/Year	1990		2005		2012	2013	2014	2015	2016
U.S. Domestic Consumption	49,800		35,200		27,300	28,800	26,700	26,200	26,500
FL and NC	42,494		28,160		21,840	23,040	21,360	20,960	21,200
ID and UT	7,306		7,040		5,460	5,760	5,340	5,240	5,300
Exports—FL and NC	6,240		0		0	0	0	0	0
Imports	451		2,630		3,570	3,170	2,390	1,960	1,600
Total U.S. Consumption	**44,011**		**37,830**		**30,870**	**31,970**	**29,090**	**28,160**	**28,100**

Table 4-58: Chemical Composition of Phosphate Rock (Percent by Weight)

Composition	Central Florida	North Florida	North Carolina (calcined)	Idaho (calcined)	Morocco
Total Carbon (as C)	1.60	1.76	0.76	0.60	1.56
Inorganic Carbon (as C)	1.00	0.93	0.41	0.27	1.46
Organic Carbon (as C)	0.60	0.83	0.35	0.00	0.10
Inorganic Carbon (as CO_2)	3.67	3.43	1.50	1.00	5.00

Source: FIPR (2003a).

Uncertainty and Time-Series Consistency

Phosphate rock production data used in the emission calculations were developed by the USGS through monthly and semiannual voluntary surveys of the active phosphate rock mines during 2016. For previous years in the time series, USGS provided the data disaggregated regionally; however, beginning in 2006, only total U.S. phosphate rock production was reported. Regional production for 2016 was estimated based on regional production data from previous years and multiplied by regionally-specific emission factors. There is uncertainty associated with the degree to which the estimated 2016 regional production data represents actual production in those regions. Total U.S. phosphate rock production data are not considered to be a significant source of uncertainty because all the domestic phosphate rock producers report their annual production to the USGS. Data for exports of phosphate rock used in the emission calculation are reported by phosphate rock producers and are not considered to be a significant source of uncertainty. Data for imports for consumption are based on international trade data collected by the U.S. Census Bureau. These U.S. government economic data are not considered to be a significant source of uncertainty.

An additional source of uncertainty in the calculation of CO_2 emissions from phosphoric acid production is the carbonate composition of phosphate rock; the composition of phosphate rock varies depending upon where the material is mined, and may also vary over time. The Inventory relies on one study (FIPR 2003a) of chemical composition of the phosphate rock; limited data are available beyond this study. Another source of uncertainty is the disposition of the organic carbon content of the phosphate rock. A representative of the Florida Institute of Phosphate Research (FIPR) indicated that in the phosphoric acid production process, the organic C content of the mined phosphate rock generally remains in the phosphoric acid product, which is what produces the color of the phosphoric acid product (FIPR 2003b). Organic carbon is therefore not included in the calculation of CO_2 emissions from phosphoric acid production.

A third source of uncertainty is the assumption that all domestically-produced phosphate rock is used in phosphoric acid production and used without first being calcined. Calcination of the phosphate rock would result in conversion of some of the organic C in the phosphate rock into CO_2. However, according to air permit information available to the public, at least one facility has calcining units permitted for operation (NCDENR 2013).

Finally, USGS indicated that approximately 7 percent of domestically-produced phosphate rock is used to manufacture elemental phosphorus and other phosphorus-based chemicals, rather than phosphoric acid (USGS 2006). According to USGS, there is only one domestic producer of elemental phosphorus, in Idaho, and no data were available concerning the annual production of this single producer. Elemental phosphorus is produced by reducing phosphate rock with coal coke, and it is therefore assumed that 100 percent of the carbonate content of the phosphate rock will be converted to CO_2 in the elemental phosphorus production process. The calculation for CO_2 emissions is based on the assumption that phosphate rock consumption, for purposes other than phosphoric acid production, results in CO_2 emissions from 100 percent of the inorganic carbon content in phosphate rock, but none from the organic carbon content.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-59. 2016 phosphoric acid production CO_2 emissions were estimated to be between 0.8 and 1.3 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 19 percent below and 22 percent above the emission estimate of 1.0 MMT CO_2 Eq.

Table 4-59: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Phosphoric Acid Production (MMT CO_2 Eq. and Percent)

Source	Gas	2016 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Phosphoric Acid Production	CO_2	1.0	0.8	1.3	-19%	+22%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2016. Details on the emission trends through time are described in more detail in the Methodology section, above.

For more information on the general QA/QC process applied to this source category, consistent with Volume 1, Chapter 6 of the *2006 IPCC Guidelines*, see the QA/QC and Verification Procedures section in the introduction of the IPPU chapter.

Planned Improvements

EPA continues to evaluate potential improvements to the Inventory estimates for this source category, which include direct integration of EPA's GHGRP data for 2010 through 2016 and the use of reported GHGRP data to update the inorganic C content of phosphate rock for prior years. Confidentiality of CBI continues to be assessed, in addition to the applicability of GHGRP data for the averaged inorganic C content data (by region) from 2010 through 2016 to inform estimates in prior years in the required time series (i.e., 1990 through 2009). In implementing improvements and integration of data from EPA's GHGRP, the latest guidance from the IPCC on the use of facility-level data in national inventories will be relied upon.[51] This planned improvement is still in development by EPA and have not been implemented into the current Inventory report.

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[51] See <http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf>.

4.17 Iron and Steel Production (CRF Source Category 2C1) and Metallurgical Coke Production

Iron and steel production is a multi-step process that generates process-related emissions of carbon dioxide (CO_2) and methane (CH_4) as raw materials are refined into iron and then transformed into crude steel. Emissions from conventional fuels (e.g., natural gas, fuel oil) consumed for energy purposes during the production of iron and steel are accounted for in the Energy chapter.

Iron and steel production includes six distinct production processes: coke production, sinter production, direct reduced iron (DRI) production, pig iron[52] production, electric arc furnace (EAF) steel production, and basic oxygen furnace (BOF) steel production. The number of production processes at a particular plant is dependent upon the specific plant configuration. Most process CO_2 generated from the iron and steel industry is a result of the production of crude iron.

In addition to the production processes mentioned above, CO_2 is also generated at iron and steel mills through the consumption of process byproducts (e.g., blast furnace gas, coke oven gas) used for various purposes including heating, annealing, and electricity generation. Process byproducts sold for use as synthetic natural gas are deducted and reported in the Energy chapter. In general, CO_2 emissions are generated in these production processes through the reduction and consumption of various carbon-containing inputs (e.g., ore, scrap, flux, coke byproducts). In addition, fugitive CH_4 emissions can also be generated from these processes, as well as from sinter, direct iron and pellet production.

Currently, there are approximately 11 integrated iron and steel steelmaking facilities that utilize BOFs to refine and produce steel from iron. These facilities have 21 active blast furnaces between them as of 2015. More than 100 steelmaking facilities utilize EAFs to produce steel primarily from recycled ferrous scrap (USGS 2017). The trend in the United States for integrated facilities has been a shift towards fewer BOFs and more EAFs. EAFs use scrap steel as their main input and use significantly less energy than BOFs. In addition, there are 16 cokemaking facilities, of which 6 facilities are co-located with integrated iron and steel facilities (ACCCI 2016). In the United States, raw steel is produced in 37 states, but six states – Alabama, Arkansas, Indiana, Kentucky, Mississippi, and Tennessee – count for roughly 50 percent of total production (AISI 2017).

Total annual production of crude steel in the United States was fairly constant between 2000 and 2008 ranged from a low of 99,320,000 tons to a high of 109,880,000 tons (2001 and 2004, respectively). Due to the decrease in demand caused by the global economic downturn (particularly from the automotive industry), crude steel production in the United States sharply decreased to 65,459,000 tons in 2009. In 2010, crude steel production rebounded to 88,731,000 tons as economic conditions improved and then continued to increase to 95,237,000 tons in 2011 and 97,769,000 tons in 2012; crude steel production slightly decreased to 95,766,000 tons in 2013 and then slightly increased to 97,195,000 tons in 2014 (AISI 2017); crude steel production decreased to 86,912,000 tons in 2015 and decreased again slightly in 2016 to 86,504,000 tons, a decrease of roughly 11 percent from 2014 levels. The United States was the fourth largest producer of raw steel in the world, behind China, Japan and India, accounting for approximately 4.8 percent of world production in 2016 (AISI 2017).

The majority of CO_2 emissions from the iron and steel production process come from the use of coke in the production of pig iron and from the consumption of other process byproducts, with lesser amounts emitted from the use of flux and from the removal of carbon from pig iron used to produce steel.

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[52] Pig iron is the common industry term to describe what should technically be called crude iron. Pig iron is a subset of crude iron that has lost popularity over time as industry trends have shifted. Throughout this report pig iron will be used interchangeably with crude iron, but it should be noted that in other data sets or reports pig iron and crude iron may not be used interchangeably and may provide different values.

According to the *2006 IPCC Guidelines*, the production of metallurgical coke from coking coal is considered to be an energy use of fossil fuel and the use of coke in iron and steel production is considered to be an industrial process source. Therefore, the *2006 IPCC Guidelines* suggest that emissions from the production of metallurgical coke should be reported separately in the Energy sector, while emissions from coke consumption in iron and steel production should be reported in the Industrial Processes and Product Use sector. However, the approaches and emission estimates for both metallurgical coke production and iron and steel production are presented here because much of the relevant activity data is used to estimate emissions from both metallurgical coke production and iron and steel production. For example, some byproducts (e.g., coke oven gas) of the metallurgical coke production process are consumed during iron and steel production, and some byproducts of the iron and steel production process (e.g., blast furnace gas) are consumed during metallurgical coke production. Emissions associated with the consumption of these byproducts are attributed at the point of consumption. Emissions associated with the use of conventional fuels (e.g., natural gas, fuel oil) for electricity generation, heating and annealing, or other miscellaneous purposes downstream of the iron and steelmaking furnaces are reported in the Energy chapter.

Metallurgical Coke Production

Emissions of CO_2 from metallurgical coke production in 2016 were 1.3 MMT CO_2 Eq. (1,327 kt CO_2) (see Table 4-60 and Table 4-61). Emissions decreased significantly in 2016 by 53 percent from 2015 levels and have decreased by 47 percent (1.2 MMT CO_2 Eq.) since 1990. Coke production in 2016 was 43 percent lower than in 2000 and 57 percent below 1990.

Table 4-60: CO_2 Emissions from Metallurgical Coke Production (MMT CO_2 Eq.)

Gas	1990	2005	2012	2013	2014	2015	2016
CO_2	2.5	2.1	0.5	1.8	2.0	2.8	1.3
Total	**2.5**	**2.1**	**0.5**	**1.8**	**2.0**	**2.8**	**1.3**

Table 4-61: CO_2 Emissions from Metallurgical Coke Production (kt)

Gas	1990	2005	2012	2013	2014	2015	2016
CO_2	2,504	2,050	550	1,830	2,020	2,843	1,327
Total	**2,504**	**2,050**	**550**	**1,830**	**2,020**	**2,843**	**1,327**

Iron and Steel Production

Emissions of CO_2 and CH_4 from iron and steel production in 2016 were 41.0 MMT CO_2 Eq. (40,979 kt) and 0.0074 MMT CO_2 Eq. (0.3 kt CH_4), respectively (see Table 4-62 through Table 4-65), totaling approximately 41.0 MMT CO_2 Eq. Emissions decreased in 2016 from 2015 and have decreased overall since 1990 due to restructuring of the industry, technological improvements, and increased scrap steel utilization. Carbon dioxide emission estimates include emissions from the consumption of carbonaceous materials in the blast furnace, EAF, and BOF, as well as blast furnace gas and coke oven gas consumption for other activities at the steel mill.

In 2016, domestic production of pig iron decreased by 12 percent from 2015 levels. Overall, domestic pig iron production has declined since the 1990s. Pig iron production in 2016 was 53 percent lower than in 2000 and 55 percent below 1990. Carbon dioxide emissions from iron production have decreased by 78 percent since 1990. Carbon dioxide emissions from steel production have decreased by 14 percent (1.1 MMT CO_2 Eq.) since 1990, while overall CO_2 emissions from iron and steel production have declined by 59 percent (58.1 MMT CO_2 Eq.) from 1990 to 2016.

Table 4-62: CO_2 Emissions from Iron and Steel Production (MMT CO_2 Eq.)

Source/Activity Data	1990	2005	2012	2013	2014	2015	2016
Sinter Production	2.4	1.7	1.2	1.1	1.1	1.0	0.9
Iron Production	45.7	17.7	11.0	12.0	18.7	11.8	9.9
Pellet Production	1.8	1.5	1.2	1.1	1.1	1.0	0.9
Steel Production	8.0	9.4	9.9	8.6	7.5	6.9	6.9

Other Activities[a]	41.2	35.9	31.7	28.7	27.9	24.3	22.4
Total	**99.1**	**66.2**	**55.1**	**51.6**	**56.3**	**45.0**	**41.0**

[a] Includes emissions from blast furnace gas and coke oven gas combustion for activities at the steel mill other than consumption in blast furnace, EAFs, or BOFs.

Note: Totals may not sum due to independent rounding.

Table 4-63: CO_2 Emissions from Iron and Steel Production (kt)

Source/Activity Data	1990	2005	2012	2013	2014	2015	2016
Sinter Production	2,448	1,663	1,159	1,117	1,104	1,016	877
Iron Production	45,704	17,664	11,041	12,031	18,722	11,780	9,928
Pellet Production	1,817	1,503	1,219	1,146	1,126	964	869
Steel Production	7,965	9,396	9,882	8,638	7,469	6,941	6,858
Other Activities[a]	41,193	35,934	31,750	28,709	27,911	24,280	22,448
Total	**99,126**	**66,160**	**55,050**	**51,641**	**56,332**	**44,981**	**40,979**

[a] Includes emissions from blast furnace gas and coke oven gas combustion for activities at the steel mill other than consumption in blast furnace, EAFs, or BOFs.

Note: Totals may not sum due to independent rounding.

Table 4-64: CH_4 Emissions from Iron and Steel Production (MMT CO_2 Eq.)

Source/Activity Data	1990	2005	2012	2013	2014	2015	2016
Sinter Production	+	+	+	+	+	+	+
Total	+	+	+	+	+	+	+

+ Does not exceed 0.05 MMT CO_2 Eq.

Table 4-65: CH_4 Emissions from Iron and Steel Production (kt)

Source/Activity Data	1990	2005	2012	2013	2014	2015	2016
Sinter Production	0.9	0.6	0.4	0.4	0.4	0.3	0.3
Total	**0.9**	**0.6**	**0.4**	**0.4**	**0.4**	**0.3**	**0.3**

Methodology

Emission estimates presented in this chapter utilize a country-specific approach based on Tier 2 methodologies provided by the *2006 IPCC Guidelines*. These Tier 2 methodologies call for a mass balance accounting of the carbonaceous inputs and outputs during the iron and steel production process and the metallurgical coke production process. Tier 1 methods are used for certain iron and steel production processes (i.e., sinter production, pellet production and DRI production) for which available data are insufficient to apply a Tier 2 method.

The Tier 2 methodology equation is as follows:

$$E_{CO_2} = \left[\sum_a (Q_a \times C_a) - \sum_b (Q_b \times C_b)\right] \times \frac{44}{12}$$

where,

E_{CO2} = Emissions from coke, pig iron, EAF steel, or BOF steel production, metric tons
a = Input material *a*
b = Output material *b*
Q_a = Quantity of input material *a*, metric tons
C_a = Carbon content of input material *a*, metric tons C/metric ton material
Q_b = Quantity of output material *b*, metric tons
C_b = Carbon content of output material *b*, metric tons C/metric ton material
44/12 = Stoichiometric ratio of CO_2 to C

The Tier 1 methodology equations are as follows:

$$E_{s,p} = Q_s \times EF_{s,p}$$

$$E_{d,CO2} = Q_d \times EF_{d,CO2}$$

$$E_{p,CO2} = Q_p \times EF_{p,CO2}$$

where,

$E_{s,p}$ = Emissions from sinter production process for pollutant *p* (CO_2 or CH_4), metric ton
Q_s = Quantity of sinter produced, metric tons
$EF_{s,p}$ = Emission factor for pollutant *p* (CO_2 or CH_4), metric ton *p*/metric ton sinter
$E_{d,CO2}$ = Emissions from DRI production process for CO_2, metric ton
Q_d = Quantity of DRI produced, metric tons
$EF_{d,CO2}$ = Emission factor for CO_2, metric ton CO_2/metric ton DRI
Q_p = Quantity of pellets produced, metric tons
$EF_{p,CO2}$ = Emission factor for CO_2, metric ton CO_2/metric ton pellets produced

Metallurgical Coke Production

Coking coal is used to manufacture metallurgical coke that is used primarily as a reducing agent in the production of iron and steel, but is also used in the production of other metals including zinc and lead (see Zinc Production and Lead Production sections of this chapter). Emissions associated with producing metallurgical coke from coking coal are estimated and reported separately from emissions that result from the iron and steel production process. To estimate emissions from metallurgical coke production, a Tier 2 method provided by the *2006 IPCC Guidelines* was utilized. The amount of carbon contained in materials produced during the metallurgical coke production process (i.e., coke, coke breeze and coke oven gas) is deducted from the amount of carbon contained in materials consumed during the metallurgical coke production process (i.e., natural gas, blast furnace gas, and coking coal). Light oil, which is produced during the metallurgical coke production process, is excluded from the deductions due to data limitations. The amount of carbon contained in these materials is calculated by multiplying the material-specific carbon content by the amount of material consumed or produced (see Table 4-66). The amount of coal tar produced was approximated using a production factor of 0.03 tons of coal tar per ton of coking coal consumed. The amount of coke breeze produced was approximated using a production factor of 0.075 tons of coke breeze per ton of coking coal consumed (AISI 2008; DOE 2000). Data on the consumption of carbonaceous materials (other than coking coal) as well as coke oven gas production were available for integrated steel mills only (i.e., steel mills with co-located coke plants). Therefore, carbonaceous material (other than coking coal) consumption and coke oven gas production were excluded from emission estimates for merchant coke plants. Carbon contained in coke oven gas used for coke-oven underfiring was not included in the deductions to avoid double-counting.

Table 4-66: Material Carbon Contents for Metallurgical Coke Production

Material	**kg C/kg**
Coal Tar	0.62
Coke	0.83
Coke Breeze	0.83
Coking Coal	0.73
Material	**kg C/GJ**
Coke Oven Gas	12.1
Blast Furnace Gas	70.8

Source: IPCC (2006), Table 4.3. Coke Oven Gas and Blast Furnace Gas, Table 1.3.

Although the *2006 IPCC Guidelines* provide a Tier 1 CH_4 emission factor for metallurgical coke production (i.e., 0.1 g CH_4 per metric ton of coke production), it is not appropriate to use because CO_2 emissions were estimated using the Tier 2 mass balance methodology. The mass balance methodology makes a basic assumption that all carbon that enters the metallurgical coke production process either exits the process as part of a carbon-containing output or as CO_2 emissions. This is consistent with a preliminary assessment of aggregated facility-level greenhouse gas CH_4 emissions reported by coke production facilities under EPA's GHGRP. The assessment indicates that CH_4 emissions from coke production are insignificant and below 500 kt or 0.05 percent of total national emissions. Pending resources and significance, EPA continues to assess the possibility of including these emissions in future Inventories to enhance completeness but has not incorporated these emissions into this report.

Data relating to the mass of coking coal consumed at metallurgical coke plants and the mass of metallurgical coke produced at coke plants were taken from the Energy Information Administration (EIA) *Quarterly Coal Report: October through December* (EIA 1998 through 2017) (see Table 4-67). Data on the volume of natural gas consumption, blast furnace gas consumption, and coke oven gas production for metallurgical coke production at integrated steel mills were obtained from the American Iron and Steel Institute (AISI) *Annual Statistical Report* (AISI 2004 through 2017) and through personal communications with AISI (AISI 2008) (see Table 4-68). The factor for the quantity of coal tar produced per ton of coking coal consumed was provided by AISI (AISI 2008). The factor for the quantity of coke breeze produced per ton of coking coal consumed was obtained through Table 2-1 of the report *Energy and Environmental Profile of the U.S. Iron and Steel Industry* (DOE 2000). Currently, data on natural gas consumption and coke oven gas production at merchant coke plants were not available and were excluded from the emission estimate. Carbon contents for coking coal, metallurgical coke, coal tar, coke oven gas, and blast furnace gas were provided by the *2006 IPCC Guidelines*. The C content for coke breeze was assumed to equal the C content of coke.

Table 4-67: Production and Consumption Data for the Calculation of CO_2 Emissions from Metallurgical Coke Production (Thousand Metric Tons)

Source/Activity Data	1990	2005	2012	2013	2014	2015	2016
Metallurgical Coke Production							
Coking Coal Consumption at Coke Plants	35,269	21,259	18,825	19,481	19,321	17,879	14,955
Coke Production at Coke Plants	25,054	15,167	13,764	13,898	13,748	12,479	10,755
Coal Breeze Production	2,645	1,594	1,412	1,461	1,449	1,341	1,122
Coal Tar Production	1,058	638	565	584	580	536	449

Table 4-68: Production and Consumption Data for the Calculation of CO_2 Emissions from Metallurgical Coke Production (Million ft^3)

Source/Activity Data	1990	2005	2012	2013	2014	2015	2016
Metallurgical Coke Production							
Coke Oven Gas Production	250,767	114,213	113,772	108,162	102,899	84,336	74,807
Natural Gas Consumption	599	2,996	3,267	3,247	3,039	2,338	2,077
Blast Furnace Gas Consumption	24,602	4,460	4,351	4,255	4,346	4,185	3,741

Iron and Steel Production

To estimate emissions from pig iron production in the blast furnace, the amount of carbon contained in the produced pig iron and blast furnace gas were deducted from the amount of carbon contained in inputs (i.e., metallurgical coke, sinter, natural ore, pellets, natural gas, fuel oil, coke oven gas, carbonate fluxes or slagging materials, and direct coal injection). The carbon contained in the pig iron, blast furnace gas, and blast furnace inputs was estimated by multiplying the material-specific C content by each material type (see Table 4-69). Carbon in blast furnace gas used to pre-heat the blast furnace air is combusted to form CO_2 during this process. Carbon contained in blast furnace gas used as a blast furnace input was not included in the deductions to avoid double-counting.

Emissions from steel production in EAFs were estimated by deducting the carbon contained in the steel produced from the carbon contained in the EAF anode, charge carbon, and scrap steel added to the EAF. Small amounts of carbon from DRI and pig iron to the EAFs were also included in the EAF calculation. For BOFs, estimates of carbon contained in BOF steel were deducted from C contained in inputs such as natural gas, coke oven gas, fluxes (e.g. burnt lime or dolomite), and pig iron. In each case, the carbon was calculated by multiplying material-specific carbon contents by each material type (see Table 4-69). For EAFs, the amount of EAF anode consumed was approximated by multiplying total EAF steel production by the amount of EAF anode consumed per metric ton of steel produced (0.002 metric tons EAF anode per metric ton steel produced [AISI 2008]). The amount of flux (e.g., burnt lime or dolomite) used in pig iron production was deducted from the “Other Process Uses of Carbonates” source category (CRF Source Category 2A4) to avoid double-counting.

Carbon dioxide emissions from the consumption of blast furnace gas and coke oven gas for other activities occurring at the steel mill were estimated by multiplying the amount of these materials consumed for these purposes by the material-specific carbon content (see Table 4-69).

Carbon dioxide emissions associated with the sinter production, direct reduced iron production, pig iron production, steel production, and other steel mill activities were summed to calculate the total CO_2 emissions from iron and steel production (see Table 4-62 and Table 4-63).

Table 4-69: Material Carbon Contents for Iron and Steel Production

Material	kg C/kg
Coke	0.83
Direct Reduced Iron	0.02
Dolomite	0.13
EAF Carbon Electrodes	0.82
EAF Charge Carbon	0.83
Limestone	0.12
Pig Iron	0.04
Steel	0.01
Material	**kg C/GJ**
Coke Oven Gas	12.1
Blast Furnace Gas	70.8

Source: IPCC (2006), Table 4.3. Coke Oven Gas and Blast Furnace Gas, Table 1.3.

The production process for sinter results in fugitive emissions of CH_4, which are emitted via leaks in the production equipment, rather than through the emission stacks or vents of the production plants. The fugitive emissions were calculated by applying Tier 1 emission factors taken from the *2006 IPCC Guidelines* for sinter production (see Table 4-70). Although the *1995 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1995) provide a Tier 1 CH_4 emission factor for pig iron production, it is not appropriate to use because CO_2 emissions were estimated using the Tier 2 mass balance methodology. The mass balance methodology makes a basic assumption that all carbon that enters the pig iron production process either exits the process as part of a carbon-containing output or as CO_2 emissions; the estimation of CH_4 emissions is precluded. A preliminary analysis of facility-level emissions reported during iron production further supports this assumption and indicates that CH_4 emissions are below 500 kt CO_2 Eq. and well below 0.05 percent of total national emissions. The production of direct reduced iron also results in emissions of CH_4 through the consumption of fossil fuels (e.g., natural gas, etc.); however, these emission estimates are excluded due to data limitations. Pending further analysis and resources, EPA may include these emissions in future reports to enhance completeness. EPA is still assessing the possibility of including these emissions in future reports and have not included this data in the current report.

Table 4-70: CH_4 Emission Factors for Sinter and Pig Iron Production

Material Produced	Factor	Unit
Sinter	0.07	kg CH_4/metric ton

Source: IPCC (2006), Table 4.2.

Emissions of CO_2 from sinter production, direct reduced iron production and pellet production were estimated by multiplying total national sinter production and the total national direct reduced iron production by Tier 1 CO_2 emission factors (see Table 4-71). Because estimates of sinter production, direct reduced iron production and pellet production were not available, production was assumed to equal consumption.

Table 4-71: CO_2 Emission Factors for Sinter Production, Direct Reduced Iron Production and Pellet Production

Material Produced	Metric Ton CO_2/Metric Ton
Sinter	0.2
Direct Reduced Iron	0.7
Pellet Production	0.03

Source: IPCC (2006), Table 4.1.

The consumption of coking coal, natural gas, distillate fuel, and coal used in iron and steel production are adjusted for within the Energy chapter to avoid double-counting of emissions reported within the IPPU chapter as these fuels were consumed during non-energy related activities. More information on this methodology and examples of adjustments made between the IPPU and Energy chapters are described in Annex 2.1, Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion.

Sinter consumption and pellet consumption data for 1990 through 2016 were obtained from AISI's *Annual Statistical Report* (AISI 2004 through 2017) and through personal communications with AISI (AISI 2008) (see Table 4-72). In general, direct reduced iron (DRI) consumption data were obtained from the U.S. Geological Survey (USGS) *Minerals Yearbook – Iron and Steel Scrap* (USGS 1991 through 2016) and personal communication with the USGS Iron and Steel Commodity Specialist (Fenton 2015). However, data for DRI consumed in EAFs were not available for the years 1990 and 1991. EAF DRI consumption in 1990 and 1991 was calculated by multiplying the total DRI consumption for all furnaces by the EAF share of total DRI consumption in 1992. Also, data for DRI consumed in BOFs were not available for the years 1990 through 1993. BOF DRI consumption in 1990 through 1993 was calculated by multiplying the total DRI consumption for all furnaces (excluding EAFs and cupola) by the BOF share of total DRI consumption (excluding EAFs and cupola) in 1994.

The Tier 1 CO_2 emission factors for sinter production, direct reduced iron production and pellet production were obtained through the *2006 IPCC Guidelines* (IPCC 2006). Time-series data for pig iron production, coke, natural gas, fuel oil, sinter, and pellets consumed in the blast furnace; pig iron production; and blast furnace gas produced at the iron and steel mill and used in the metallurgical coke ovens and other steel mill activities were obtained from AISI's *Annual Statistical Report* (AISI 2004 through 2017) and through personal communications with AISI (AISI 2008) (see Table 4-72 and Table 4-73).

Data for EAF steel production, flux, EAF charge carbon, and natural gas consumption were obtained from AISI's *Annual Statistical Report* (AISI 2004 through 2017) and through personal communications with AISI (AISI 2006 through 2016 and AISI 2008). The factor for the quantity of EAF anode consumed per ton of EAF steel produced was provided by AISI (AISI 2008). Data for BOF steel production, flux, natural gas, natural ore, pellet, sinter consumption as well as BOF steel production were obtained from AISI's *Annual Statistical Report* (AISI 2004 through 2017) and through personal communications with AISI (AISI 2008). Data for EAF and BOF scrap steel, pig iron, and DRI consumption were obtained from the USGS *Minerals Yearbook – Iron and Steel Scrap* (USGS 1991 through 2016). Data on coke oven gas and blast furnace gas consumed at the iron and steel mill (other than in the EAF, BOF, or blast furnace) were obtained from AISI's *Annual Statistical Report* (AISI 2004 through 2017) and through personal communications with AISI (AISI 2008).

Data on blast furnace gas and coke oven gas sold for use as synthetic natural gas were obtained from EIA's *Natural Gas Annual* (EIA 2016b). Carbon contents for direct reduced iron, EAF carbon electrodes, EAF charge carbon, limestone, dolomite, pig iron, and steel were provided by the *2006 IPCC Guidelines*. The carbon contents for natural gas, fuel oil, and direct injection coal were obtained from EIA (EIA 2016c) and EPA (EPA 2010). Heat contents for fuel oil and direct injection coal were obtained from EIA (EIA 1992, 2011); natural gas heat content was obtained from Table 37 of AISI's *Annual Statistical Report* (AISI 2004 through 2017). Heat contents for coke oven gas and blast furnace gas were provided in Table 37 of AISI's *Annual Statistical Report* (AISI 2004 through 2017) and confirmed by AISI staff (Carroll 2016).

Table 4-72: Production and Consumption Data for the Calculation of CO_2 and CH_4 Emissions from Iron and Steel Production (Thousand Metric Tons)

Source/Activity Data	1990	2005	2012	2013	2014	2015	2016
Sinter Production							
Sinter Production	12,239	8,315	5,795	5,583	5,521	5,079	4,385
Direct Reduced Iron Production							
Direct Reduced Iron Production	516	1,303	3,530	3,350	4,790	4,790	4,777
Pellet Production							
Pellet Production	60,563	50,096	40,622	38,198	37,538	32,146	28,967
Pig Iron Production							
Coke Consumption	24,946	13,832	9,571	9,308	11,136	7,969	7,124
Pig Iron Production	49,669	37,222	32,063	30,309	29,375	25,436	22,293
Direct Injection Coal Consumption	1,485	2,573	2,802	2,675	2,425	2,275	1,935
EAF Steel Production							
EAF Anode and Charge Carbon Consumption	67	1,127	1,318	1,122	1,062	1,072	1,120
Scrap Steel Consumption	42,691	46,600	50,900	47,300	48,873	44,000	43,211
Flux Consumption	319	695	748	771	771	998	998
EAF Steel Production	33,511	52,194	52,415	52,641	55,174	49,451	52,589
BOF Steel Production							
Pig Iron Consumption	47,307	34,400	31,500	29,600	23,755	20,349	18,620
Scrap Steel Consumption	14,713	11,400	8,350	7,890	5,917	4,526	4,573
Flux Consumption	576	582	476	454	454	454	408
BOF Steel Production	43,973	42,705	36,282	34,238	33,000	29,396	25,888

Table 4-73: Production and Consumption Data for the Calculation of CO_2 Emissions from Iron and Steel Production (Million ft^3 unless otherwise specified)

Source/Activity Data	1990	2005	2012	2013	2014	2015	2016
Pig Iron Production							
Natural Gas Consumption	56,273	59,844	62,469	48,812	47,734	43,294	38,396
Fuel Oil Consumption (thousand gallons)	163,397	16,170	19,240	17,468	16,674	9,326	6,124
Coke Oven Gas Consumption	22,033	16,557	18,608	17,710	16,896	13,921	12,404
Blast Furnace Gas Production	1,439,380	1,299,980	1,139,578	1,026,973	1,000,536	874,670	811,005
EAF Steel Production							
Natural Gas Consumption	15,905	19,985	11,145	10,514	9,622	8,751	3,915
BOF Steel Production							
Coke Oven Gas Consumption	3,851	524	568	568	524	386	367
Other Activities							
Coke Oven Gas Consumption	224,883	97,132	94,596	89,884	85,479	70,029	62,036
Blast Furnace Gas Consumption	1,414,778	1,295,520	1,135,227	1,022,718	996,190	870,485	807,264

Uncertainty and Time-Series Consistency

The estimates of CO_2 emissions from metallurgical coke production are based on material production and consumption data and average carbon contents. Uncertainty is associated with the total U.S. coking coal consumption, total U.S. coke production and materials consumed during this process. Data for coking coal consumption and metallurgical coke production are from different data sources (EIA) than data for other carbonaceous materials consumed at coke plants (AISI), which does not include data for merchant coke plants. There is uncertainty associated with the fact that coal tar and coke breeze production were estimated based on coke production because coal tar and coke breeze production data were not available. Since merchant coke plant data is not included in the estimate of other carbonaceous materials consumed at coke plants, the mass balance equation for CO_2 from metallurgical coke production cannot be reasonably completed. Therefore, for the purpose of this analysis, uncertainty parameters are applied to primary data inputs to the calculation (i.e., coking coal consumption and metallurgical coke production) only.

The estimates of CO_2 emissions from iron and steel production are based on material production and consumption data and average C contents. There is uncertainty associated with the assumption that pellet production, direct reduced iron and sinter consumption are equal to production. There is uncertainty with the representativeness of the associated IPCC default emission factors. There is uncertainty associated with the assumption that all coal used for purposes other than coking coal is for direct injection coal. There is also uncertainty associated with the C contents for pellets, sinter, and natural ore, which are assumed to equal the C contents of direct reduced iron, when consumed in the blast furnace. There is uncertainty associated with the consumption of natural ore under current industry practices. For EAF steel production, there is uncertainty associated with the amount of EAF anode and charge carbon consumed due to inconsistent data throughout the time series. Also for EAF steel production, there is uncertainty associated with the assumption that 100 percent of the natural gas attributed to “steelmaking furnaces” by AISI is process-related and nothing is combusted for energy purposes. Uncertainty is also associated with the use of process gases such as blast furnace gas and coke oven gas. Data are not available to differentiate between the use of these gases for processes at the steel mill versus for energy generation (i.e., electricity and steam generation); therefore, all consumption is attributed to iron and steel production. These data and carbon contents produce a relatively accurate estimate of CO_2 emissions. However, there are uncertainties associated with each.

For calculating the emissions estimates from iron and steel and metallurgical coke production, EPA utilizes a number of data points taken from the AISI *Annual Statistical Report* (ASR). This report serves as a benchmark for information on steel companies in United States, regardless if they are a member of AISI, which represents integrated producers (i.e., blast furnace and EAF). During the compilation of this Inventory (i.e., 1990 through 2016 report), EPA initiated conversation with AISI to better understand and update the qualitative and quantitative uncertainty metrics associated with AISI data elements. AISI estimates their data collection response rate to range from 75 to 90 percent, with certain sectors of the iron and steel industry not being covered by the ASR. Therefore, there is some inherent uncertainty in the values provided in the AISI ASR, including material production and consumption data. There is also some uncertainty to which materials produced are exported to Canada. As indicated in the introduction to this section, the trend for integrated facilities has moved to more use of EAFs and fewer BOFs. This trend may not be completely captured in the current data which also increases uncertainty. EPA currently uses an uncertainty range of ±10 percent for the primary data inputs to calculate overall uncertainty from iron and steel production, consistent with *2006 IPCC Guidelines*. During EPA’s discussion with AISI, AISI noted that an uncertainty range of ±5 percent would be a more appropriate approximation to reflect their coverage of integrated steel producers in the United States. EPA will continue to assess the best range of uncertainty for these values.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-74 for metallurgical coke production and iron and steel production. Total CO_2 emissions from metallurgical coke production and iron and steel production for 2016 were estimated to be between 35.1 and 49.5 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 17 percent below and 17 percent above the emission estimate of 42.3 MMT CO_2 Eq. Total CH_4 emissions from metallurgical coke production and iron and steel production for 2016 were estimated to be between 0.006 and 0.009 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 20 percent below and 20 percent above the emission estimate of 0.007 MMT CO_2 Eq.

Table 4-74: Approach 2 Quantitative Uncertainty Estimates for CO_2 and CH_4 Emissions from Iron and Steel Production and Metallurgical Coke Production (MMT CO_2 Eq. and Percent)

Source	Gas	2016 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Metallurgical Coke & Iron and Steel Production	CO_2	42.3	35.1	49.5	-17%	+17%
Metallurgical Coke & Iron and Steel Production	CH_4	+	+	+	-20%	+20%

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2016.

For more information on the general QA/QC process applied to this source category, consistent with Volume 1, Chapter 6 of the *2006 IPCC Guidelines*, see the QA/QC and Verification Procedures section in the introduction of the IPPU chapter.

Recalculations Discussion

Updated USGS consumption data was provided for iron and steel manufacturing facilities for years 2014 to 2016. The 2014 consumption from BOF facilities was updated from 2,680 kt to 0 kt, and the 2015 consumption from BOF facilities was updated from a proxy value of 2,680 kt to 992 kt. These updates had measurable impacts on CO_2 emission calculations. The total CO_2 emissions from iron and steel production dropped 0.2 MMT CO_2 Eq. (less than one percent decrease) in 2014 and 1.0 MMT CO_2 Eq. (2 percent decrease) in 2015 to 56.4 and 45.0 MMT CO_2 Eq. respectively (see Table 4-62 and Table 4-63).

The 2015 EAF dolomite consumption value has been updated from 250 thousand tons, used in the previous Inventory report, to 550 thousand tons. This change had an insignificant impact on the emission estimates compared to the previous Inventory.

The 2014 and 2015 EAF charge carbon consumption values have been updated from a proxy of 2013 values in the previous report, to updated values reported by AISI (Carroll 2017). These changes had insignificant impacts on the emissions from steel production in Table 4-62, and on the EAF anode and charge carbon consumption values in Table 4-72.

Planned Improvements

Future improvements involve improving activity data and emission factor sources for estimating CO_2 and CH_4 emissions from pellet production. EPA will also evaluate and analyze data reported under EPA's GHGRP to improve the emission estimates for this and other Iron and Steel Production process categories. Particular attention will be made to ensure time-series consistency of the emissions estimates presented in future Inventory reports, consistent with IPCC and UNFCCC guidelines. This is required as the facility-level reporting data from EPA's GHGRP, with the program's initial requirements for reporting of emissions in calendar year 2010, are not available for all inventory years (i.e., 1990 through 2009) as required for this Inventory. In implementing improvements and integration of data from EPA's GHGRP, the latest guidance from the IPCC on the use of facility-level data in national inventories will be relied upon.[53]

Additional improvements include accounting for emission estimates for the production of metallurgical coke to the Energy chapter as well as identifying the amount of carbonaceous materials, other than coking coal, consumed at merchant coke plants. Other potential improvements include identifying the amount of coal used for direct injection

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[53] See <http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf>.

and the amount of coke breeze, coal tar, and light oil produced during coke production. Efforts will also be made to identify information to better characterize emissions from the use of process gases and fuels within the Energy and IPPU chapters. Additional efforts will be made to improve the reporting between the IPPU and Energy chapters, particularly the inclusion of a quantitative summary of the carbon balance in the United States. This planned improvement is still in development and is not included in this current Inventory report.

EPA also received comments during this Inventory's Expert Review cycle on recommendations to improve the description of the iron and steel industry and emissive processes in the Inventory. EPA has begun to incorporate some of these recommendations into the current Inventory and will require some additional time to implement other substantive changes.

4.18 Ferroalloy Production (CRF Source Category 2C2)

Carbon dioxide (CO_2) and methane (CH_4) are emitted from the production of several ferroalloys. Ferroalloys are composites of iron (Fe) and other elements such as silicon (Si), manganese (Mn), and chromium (Cr). Emissions from fuels consumed for energy purposes during the production of ferroalloys are accounted for in the Energy chapter. Emissions from the production of two types of ferrosilicon (25 to 55 percent and 56 to 95 percent silicon), silicon metal (96 to 99 percent silicon), and miscellaneous alloys (32 to 65 percent silicon) have been calculated. Emissions from the production of ferrochromium and ferromanganese are not included here because of the small number of manufacturers of these materials in the United States, and therefore, government information disclosure rules prevent the publication of production data for these production facilities.

Similar to emissions from the production of iron and steel, CO_2 is emitted when metallurgical coke is oxidized during a high-temperature reaction with iron and the selected alloying element. Due to the strong reducing environment, CO is initially produced, and eventually oxidized to CO_2. A representative reaction equation for the production of 50 percent ferrosilicon (FeSi) is given below:

$$\mathrm{Fe_2O_3 + 2SiO_2 + 7C \rightarrow 2FeSi + 7CO}$$

While most of the carbon contained in the process materials is released to the atmosphere as CO_2, a percentage is also released as CH_4 and other volatiles. The amount of CH_4 that is released is dependent on furnace efficiency, operation technique, and control technology.

When incorporated in alloy steels, ferroalloys are used to alter the material properties of the steel. Ferroalloys are used primarily by the iron and steel industry, and production trends closely follow that of the iron and steel industry. As of 2014, twelve companies in the United States produce ferroalloys (USGS 2016a).

Emissions of CO_2 from ferroalloy production in 2016 were 1.8 MMT CO_2 Eq. (1,796 kt CO_2) (see Table 4-75 and Table 4-76), which is a 17 percent reduction since 1990. Emissions of CH_4 from ferroalloy production in 2016 were 0.01 MMT CO_2 Eq. (0.5 kt CH_4), which is a 26 percent decrease since 1990.

Table 4-75: CO_2 and CH_4 Emissions from Ferroalloy Production (MMT CO_2 Eq.)

Gas	1990		2005		2012	2013	2014	2015	2016
CO_2	2.2		1.4		1.9	1.8	1.9	2.0	1.8
CH_4	+		+		+	+	+	+	+
Total	**2.2**		**1.4**		**1.9**	**1.8**	**1.9**	**2.0**	**1.8**

+ Does not exceed 0.05 MMT CO_2 Eq.

Table 4-76: CO_2 and CH_4 Emissions from Ferroalloy Production (kt)

Gas	1990		2005		2012	2013	2014	2015	2016
CO_2	2,152		1,392		1,903	1,785	1,914	1,960	1,796
CH_4	1		+		1	+	1	1	1

+ Does not exceed 0.5 kt.

Methodology

Emissions of CO_2 and CH_4 from ferroalloy production were calculated[54] using a Tier 1 method from the *2006 IPCC Guidelines* by multiplying annual ferroalloy production by material-specific default emission factors provided by IPCC (IPCC 2006). The Tier 1 equations for CO_2 and CH_4 emissions are as follows:

$$E_{CO2} = \sum_i (MP_i \times EF_i)$$

where,

E_{CO2} = CO_2 emissions, metric tons
MP_i = Production of ferroalloy type *i*, metric tons
EF_i = Generic emission factor for ferroalloy type *i*, metric tons CO_2/metric ton specific ferroalloy product

$$E_{CH4} = \sum_i (MP_i \times EF_i)$$

where,

E_{CH4} = CH_4 emissions, kg
MP_i = Production of ferroalloy type *i*, metric tons
EF_i = Generic emission factor for ferroalloy type *i*, kg CH_4/metric ton specific ferroalloy product

Default emission factors were used because country-specific emission factors are not currently available. The following emission factors were used to develop annual CO_2 and CH_4 estimates:

- Ferrosilicon, 25 to 55 percent Si and Miscellaneous Alloys, 32 to 65 percent Si – 2.5 metric tons CO_2/metric ton of alloy produced; 1.0 kg CH_4/metric ton of alloy produced.
- Ferrosilicon, 56 to 95 percent Si – 4.0 metric tons CO_2/metric ton alloy produced; 1.0 kg CH_4/metric ton of alloy produced.
- Silicon Metal – 5.0 metric tons CO_2/metric ton metal produced; 1.2 kg CH_4/metric ton metal produced.

It was assumed that 100 percent of the ferroalloy production was produced using petroleum coke in an electric arc furnace process (IPCC 2006), although some ferroalloys may have been produced with coking coal, wood, other biomass, or graphite carbon inputs. The amount of petroleum coke consumed in ferroalloy production was calculated assuming that the petroleum coke used is 90 percent carbon (C) and 10 percent inert material (Onder and Bagdoyan 1993).

The use of petroleum coke for ferroalloy production is adjusted for within the Energy chapter as this fuel was consumed during non-energy related activities. Additional information on the adjustments made within the Energy sector for Non-Energy Use of Fuels is described in both the Methodology section of CO_2 from Fossil Fuel

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[54] EPA has not integrated aggregated facility-level GHGRP information to inform these estimates. The aggregated information (e.g., activity data and emissions) associated with production of ferroalloys did not meet criteria to shield underlying confidential business information (CBI) from public disclosure.

Combustion (3.1 Fossil Fuel Combustion (CRF Source Category 1A)) and Annex 2.1, Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion.

Ferroalloy production data for 1990 through 2016 (see Table 4-77) were obtained from the U.S. Geological Survey (USGS) through the *Minerals Yearbook: Silicon* (USGS 1996 through 2013) and the *Mineral Industry Surveys: Silicon* (USGS 2014, 2015b, 2016b, 2017). The following data were available from the USGS publications for the time series:

- Ferrosilicon, 25 to 55 percent Si: Annual production data were available from 1990 through 2010.
- Ferrosilicon, 56 to 95 percent Si: Annual production data were available from 1990 through 2010.
- Silicon Metal: Annual production data were available from 1990 through 2005. The production data for 2005 were used as proxy for 2006 through 2010.
- Miscellaneous Alloys, 32 to 65 percent Si: Annual production data were available from 1990 through 1998. Starting 1999, USGS reported miscellaneous alloys and ferrosilicon containing 25 to 55 percent silicon as a single category.

Starting with the 2011 publication, USGS ceased publication of production quantity by ferroalloy product and began reporting all the ferroalloy production data as a single category (i.e., Total Silicon Materials Production). This is due to the small number of ferroalloy manufacturers in the United States and government information disclosure rules. Ferroalloy product shares developed from the 2010 production data (i.e., ferroalloy product production/total ferroalloy production) were used with the total silicon materials production quantity to estimate the production quantity by ferroalloy product type for 2011 through 2016 (USGS 2013, 2014, 2015b, 2016b, 2017).

Table 4-77: Production of Ferroalloys (Metric Tons)

Year	Ferrosilicon 25%-55%	Ferrosilicon 56%-95%	Silicon Metal	Misc. Alloys 32-65%
1990	321,385	109,566	145,744	72,442
2005	123,000	86,100	148,000	NA
2012	175,108	154,507	169,385	NA
2013	164,229	144,908	158,862	NA
2014	176,161	155,436	170,404	NA
2015	180,372	159,151	174,477	NA
2016	165,282	145,837	159,881	NA

NA - Not Available for product type, aggregated along with ferrosilicon (25-55% Si)

Uncertainty and Time-Series Consistency

Annual ferroalloy production was reported by the USGS in three broad categories until the 2010 publication: ferroalloys containing 25 to 55 percent silicon (including miscellaneous alloys), ferroalloys containing 56 to 95 percent silicon, and silicon metal (through 2005 only, 2005 value used as proxy for 2005 through 2010). Starting with the *2011 Minerals Yearbook*, USGS started reporting all the ferroalloy production under a single category: total silicon materials production. The total silicon materials quantity was allocated across the three categories based on the 2010 production shares for the three categories. Refer to the Methodology section for further details. Additionally, production data for silvery pig iron (alloys containing less than 25 percent silicon) are not reported by the USGS to avoid disclosing proprietary company data. Emissions from this production category, therefore, were not estimated.

Also, some ferroalloys may be produced using wood or other biomass as a primary or secondary carbon source (carbonaceous reductants), however information and data regarding these practices were not available. Emissions from ferroalloys produced with wood or other biomass would not be counted under this source because wood-based carbon is of biogenic origin.[55] Even though emissions from ferroalloys produced with coking coal or graphite inputs

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[55] Emissions and sinks of biogenic carbon are accounted for in the Land Use, Land-Use Change, and Forestry chapter.

would be counted in national trends, they may be generated with varying amounts of CO_2 per unit of ferroalloy produced. The most accurate method for these estimates would be to base calculations on the amount of reducing agent used in the process, rather than the amount of ferroalloys produced. These data, however, were not available, and are also often considered confidential business information.

Emissions of CH_4 from ferroalloy production will vary depending on furnace specifics, such as type, operation technique, and control technology. Higher heating temperatures and techniques such as sprinkle charging will reduce CH_4 emissions; however, specific furnace information was not available or included in the CH_4 emission estimates.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-78. Ferroalloy production CO_2 emissions from 2016 were estimated to be between 1.6 and 2.0 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 12 percent below and 12 percent above the emission estimate of 1.8 MMT CO_2 Eq. Ferroalloy production CH_4 emissions were estimated to be between a range of approximately 12 percent below and 12 percent above the emission estimate of 0.01 MMT CO_2 Eq.

Table 4-78: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Ferroalloy Production (MMT CO_2 Eq. and Percent)

Source	Gas	2016 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Ferroalloy Production	CO_2	1.8	1.6	2.0	-12%	+12%
Ferroalloy Production	CH_4	+	+	+	-12%	+12%

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2016. Details on the emission trends through time are described in more detail in the Methodology section, above.

For more information on the general QA/QC process applied to this source category, consistent with Volume 1, Chapter 6 of the *2006 IPCC Guidelines*, see the QA/QC and Verification Procedures section in the introduction of the IPPU chapter.

Planned Improvements

Pending available resources and prioritization of improvements for more significant sources, EPA will continue to evaluate and analyze data reported under EPA's GHGRP that would be useful to improve the emission estimates and category-specific QC procedures for the Ferroalloy Production source category. Given the small number of facilities, particular attention will be made to ensure time-series consistency of the emissions estimates presented in future Inventory reports, consistent with IPCC and UNFCCC guidelines. This is required as the facility-level reporting data from EPA's GHGRP, with the program's initial requirements for reporting of emissions in calendar year 2010, are not available for all inventory years (i.e., 1990 through 2009) as required for this Inventory. In implementing improvements and integration of data from EPA's GHGRP, the latest guidance from the IPCC on the use of facility-level data in national inventories will be relied upon.[56] EPA is still assessing the possibility of incorporating this planned improvement into the national Inventory report and has not included these data sets into the current Inventory report.

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[56] See <http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf >.

4.19 Aluminum Production (CRF Source Category 2C3)

Aluminum is a light-weight, malleable, and corrosion-resistant metal that is used in many manufactured products, including aircraft, automobiles, bicycles, and kitchen utensils. As of recent reporting, the United States was the ninth largest producer of primary aluminum, with approximately 1 percent of the world total production (USGS 2017). The United States was also a major importer of primary aluminum. The production of primary aluminum—in addition to consuming large quantities of electricity—results in process-related emissions of carbon dioxide (CO_2) and two perfluorocarbons (PFCs): perfluoromethane (CF_4) and perfluoroethane (C_2F_6).

Carbon dioxide is emitted during the aluminum smelting process when alumina (aluminum oxide, Al_2O_3) is reduced to aluminum using the Hall-Heroult reduction process. The reduction of the alumina occurs through electrolysis in a molten bath of natural or synthetic cryolite (Na_3AlF_6). The reduction cells contain a carbon (C) lining that serves as the cathode. Carbon is also contained in the anode, which can be a C mass of paste, coke briquettes, or prebaked C blocks from petroleum coke. During reduction, most of this C is oxidized and released to the atmosphere as CO_2.

Process emissions of CO_2 from aluminum production were estimated to be 1.3 MMT CO_2 Eq. (1,334 kt) in 2016 (see Table 4-79). The C anodes consumed during aluminum production consist of petroleum coke and, to a minor extent, coal tar pitch. The petroleum coke portion of the total CO_2 process emissions from aluminum production is considered to be a non-energy use of petroleum coke, and is accounted for here and not under the CO_2 from Fossil Fuel Combustion source category of the Energy sector. Similarly, the coal tar pitch portion of these CO_2 process emissions is accounted for here.

Table 4-79: CO_2 Emissions from Aluminum Production (MMT CO_2 Eq. and kt)

Year	MMT CO_2 Eq.	kt
1990	6.8	6,831
2005	4.1	4,142
2012	3.4	3,439
2013	3.3	3,255
2014	2.8	2,833
2015	2.8	2,767
2016	1.3	1,334

In addition to CO_2 emissions, the aluminum production industry is also a source of PFC emissions. During the smelting process, when the alumina ore content of the electrolytic bath falls below critical levels required for electrolysis, rapid voltage increases occur, which are termed “anode effects.” These anode effects cause C from the anode and fluorine from the dissociated molten cryolite bath to combine, thereby producing fugitive emissions of CF_4 and C_2F_6. In general, the magnitude of emissions for a given smelter and level of production depends on the frequency and duration of these anode effects. As the frequency and duration of the anode effects increase, emissions increase.

Since 1990, emissions of CF_4 and C_2F_6 have declined by 94 percent and 87 percent, respectively, to 0.9 MMT CO_2 Eq. of CF_4 (0.1 kt) and 0.4 MMT CO_2 Eq. of C_2F_6 (0.04 kt) in 2016, as shown in Table 4-80 and Table 4-81. This decline is due both to reductions in domestic aluminum production and to actions taken by aluminum smelting companies to reduce the frequency and duration of anode effects. These actions include technology and operational changes such as employee training, use of computer monitoring, and changes in alumina feeding techniques. Since 1990, aluminum production has declined by 80 percent, while the combined CF_4 and C_2F_6 emission rate (per metric ton of aluminum produced) has been reduced by 69 percent. Emissions decreased by approximately 32 percent between 2015 and 2016 due to decreases in aluminum production. CF_4 and C_2F_6 emissions per metric ton of aluminum produced increased between 2015 and 2016, in part because production decreased at low PFC emitting facilities and stayed relatively stable at high PFC emitting facilities.

Table 4-80: PFC Emissions from Aluminum Production (MMT CO_2 Eq.)

Year	CF_4	C_2F_6	Total
1990	17.9	3.5	21.5
2005	2.9	0.6	3.4
2012	2.3	0.7	2.9
2013	2.3	0.7	3.0
2014	1.9	0.6	2.5
2015	1.5	0.5	2.0
2016	0.9	0.4	1.4

Note: Totals may not sum due to independent rounding.

Table 4-81: PFC Emissions from Aluminum Production (kt)

Year	CF_4	C_2F_6
1990	2.4	0.3
2005	0.4	+
2012	0.3	0.1
2013	0.3	0.1
2014	0.3	0.1
2015	0.2	+
2016	0.1	+

+ Does not exceed 0.05 kt.

In 2016, U.S. primary aluminum production totaled approximately 0.8 million metric tons, a 48 percent decrease from 2015 production levels (USAA 2017). In 2016, three companies managed production at eight operational primary aluminum smelters. One smelter remained on standby throughout the year, two smelters were temporarily idled, and one non-operating smelters were permanently shut down during 2016 (USGS 2017). During 2016, monthly U.S. primary aluminum production was lower for every month in 2016, when compared to the corresponding months in 2015 (USAA 2017; USAA 2016b).

For 2017, total production for the January to September period was approximately 0.55 million metric tons compared to 0.63 million metric tons for the same period in 2016, a 12 percent decrease (USAA 2017). Based on the decrease in production, process CO_2 and PFC emissions are likely to be lower in 2017 compared to 2016 if there are no significant changes in process controls at operational facilities.

Methodology

Process CO_2 and PFC (i.e., CF_4 and C_2F_6) emission estimates from primary aluminum production for 2010 through 2016 are available from EPA's GHGRP—Subpart F (Aluminum Production) (EPA 2017). Under EPA's GHGRP, facilities began reporting primary aluminum production process emissions (for 2010) in 2011; as a result, GHGRP data (for 2010 through 2016) are available to be incorporated into the Inventory. EPA included reported emissions for one facility that reported late to EPA's GHGRP in the previous Inventory estimate, so the total emissions reported in the Inventory are not exactly equal to the emissions reported in the publically available GHGRP data. EPA's GHGRP mandates that all facilities that contain an aluminum production process must report: CF_4 and C_2F_6 emissions from anode effects in all prebake and Søderberg electrolysis cells, CO_2 emissions from anode consumption during electrolysis in all prebake and Søderberg cells, and all CO_2 emissions from onsite anode baking. To estimate the process emissions, EPA's GHGRP uses the process-specific equations detailed in subpart F (aluminum production).[57] These equations are based on the Tier 2/Tier 3 IPCC (2006) methods for primary aluminum production, and Tier 1 methods when estimating missing data elements. It should be noted that the same methods (i.e., *2006 IPCC Guidelines*) were used for estimating the emissions prior to the availability of the reported GHGRP data in the Inventory. Prior to 2010, aluminum production data were provided through EPA's Voluntary Aluminum Industrial Partnership (VAIP).

As previously noted, the use of petroleum coke for aluminum production is adjusted for within the Energy chapter as this fuel was consumed during non-energy related activities. Additional information on the adjustments made within the Energy sector for Non-Energy Use of Fuels is described in both the Methodology section of CO_2 from Fossil Fuel Combustion (3.1 Fossil Fuel Combustion (CRF Source Category 1A)) and Annex 2.1, Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion.

Process CO_2 Emissions from Anode Consumption and Anode Baking

Carbon dioxide emission estimates for the years prior to the introduction of EPA's GHGRP in 2010 were estimated *2006 IPCC Guidelines* methods, but individual facility reported data were combined with process-specific emissions modeling. These estimates were based on information previously gathered from EPA's Voluntary Aluminum Industrial Partnership (VAIP) program, U.S. Geological Survey (USGS) Mineral Commodity reviews, and The Aluminum Association (USAA) statistics, among other sources. Since pre- and post-GHGRP estimates use the same methodology, emission estimates are comparable across the time series.

Most of the CO_2 emissions released during aluminum production occur during the electrolysis reaction of the C anode, as described by the following reaction:

$$2Al_2O_3 + 3C \rightarrow 4Al + 3CO_2$$

For prebake smelter technologies, CO_2 is also emitted during the anode baking process. These emissions can account for approximately 10 percent of total process CO_2 emissions from prebake smelters.

Depending on the availability of smelter-specific data, the CO_2 emitted from electrolysis at each smelter was estimated from: (1) the smelter's annual anode consumption, (2) the smelter's annual aluminum production and rate of anode consumption (per ton of aluminum produced) for previous and/or following years, or (3) the smelter's annual aluminum production and IPCC default CO_2 emission factors. The first approach tracks the consumption and carbon content of the anode, assuming that all C in the anode is converted to CO_2. Sulfur, ash, and other impurities in the anode are subtracted from the anode consumption to arrive at a C consumption figure. This approach corresponds to either the IPCC Tier 2 or Tier 3 method, depending on whether smelter-specific data on anode impurities are used. The second approach interpolates smelter-specific anode consumption rates to estimate emissions during years for which anode consumption data are not available. This approach avoids substantial errors and discontinuities that could be introduced by reverting to Tier 1 methods for those years. The last approach corresponds to the IPCC Tier 1 method (IPCC 2006), and is used in the absence of present or historic anode consumption data.

The equations used to estimate CO_2 emissions in the Tier 2 and 3 methods vary depending on smelter type (IPCC 2006). For Prebake cells, the process formula accounts for various parameters, including net anode consumption, and the sulfur, ash, and impurity content of the baked anode. For anode baking emissions, the formula accounts for packing coke consumption, the sulfur and ash content of the packing coke, as well as the pitch content and weight of baked anodes produced. For Søderberg cells, the process formula accounts for the weight of paste consumed per metric ton of aluminum produced, and pitch properties, including sulfur, hydrogen, and ash content.

Through the VAIP, anode consumption (and some anode impurity) data have been reported for 1990, 2000, 2003, 2004, 2005, 2006, 2007, 2008, and 2009. Where available, smelter-specific process data reported under the VAIP were used; however, if the data were incomplete or unavailable, information was supplemented using industry average values recommended by IPCC (2006). Smelter-specific CO_2 process data were provided by 18 of the 23 operating smelters in 1990 and 2000, by 14 out of 16 operating smelters in 2003 and 2004, 14 out of 15 operating smelters in 2005, 13 out of 14 operating smelters in 2006, 5 out of 14 operating smelters in 2007 and 2008, and 3 out

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[57] Code of Federal Regulations, Title 40: Protection of Environment, Part 98: Mandatory Greenhouse Gas Reporting, Subpart F—Aluminum Production. See <www.epa.gov/ghgreporting/documents/pdf/infosheets/aluminumproduction.pdf>.

of 13 operating smelters in 2009. For years where CO_2 emissions data or CO_2 process data were not reported by these companies, estimates were developed through linear interpolation, and/or assuming representative (e.g., previously reported or industry default) values.

In the absence of any previous historical smelter-specific process data (i.e., 1 out of 13 smelters in 2009; 1 out of 14 smelters in 2006, 2007, and 2008; 1 out of 15 smelters in 2005; and 5 out of 23 smelters between 1990 and 2003), CO_2 emission estimates were estimated using Tier 1 Søderberg and/or Prebake emission factors (metric ton of CO_2 per metric ton of aluminum produced) from IPCC (2006).

Process PFC Emissions from Anode Effects

Smelter-specific PFC emissions from aluminum production for 2010 through 2016 were reported to EPA under its GHGRP. To estimate their PFC emissions and report them under EPA's GHGRP, smelters use an approach identical to the Tier 3 approach in the *2006 IPCC Guidelines* (IPCC 2006). Specifically, they use a smelter-specific slope coefficient as well as smelter-specific operating data to estimate an emission factor using the following equation:

$$PFC = S \times AE$$

$$AE = F \times D$$

where,

PFC = CF_4 or C_2F_6, kg/MT aluminum
S = Slope coefficient, PFC/AE
AE = Anode effect, minutes/cell-day
F = Anode effect frequency per cell-day
D = Anode effect duration, minutes

They then multiply this emission factor by aluminum production to estimate PFC emissions. All U.S. aluminum smelters are required to report their emissions under EPA's GHGRP.

Perfluorocarbon emissions for the years prior to 2010 were estimated using the same equation, but the slope-factor used for some smelters was technology-specific rather than smelter-specific, making the method a Tier 2 rather than a Tier 3 approach for those smelters. Emissions and background data were reported to EPA under the VAIP. For 1990 through 2009, smelter-specific slope coefficients were available and were used for smelters representing between 30 and 94 percent of U.S. primary aluminum production. The percentage changed from year to year as some smelters closed or changed hands and as the production at remaining smelters fluctuated. For smelters that did not report smelter-specific slope coefficients, IPCC technology-specific slope coefficients were applied (IPCC 2006). The slope coefficients were combined with smelter-specific anode effect data collected by aluminum companies and reported under the VAIP to estimate emission factors over time. For 1990 through 2009, smelter-specific anode effect data were available for smelters representing between 80 and 100 percent of U.S. primary aluminum production. Where smelter-specific anode effect data were not available, representative values (e.g., previously reported or industry averages) were used.

For all smelters, emission factors were multiplied by annual production to estimate annual emissions at the smelter level. For 1990 through 2009, smelter-specific production data were available for smelters representing between 30 and 100 percent of U.S. primary aluminum production. (For the years after 2000, this percentage was near the high end of the range.) Production at non-reporting smelters was estimated by calculating the difference between the production reported under VAIP and the total U.S. production supplied by USGS or USAA, and then allocating this difference to non-reporting smelters in proportion to their production capacity. Emissions were then aggregated across smelters to estimate national emissions.

Between 1990 and 2009, production data were provided under the VAIP by 21 of the 23 U.S. smelters that operated during at least part of that period. For the non-reporting smelters, production was estimated based on the difference between reporting smelters and national aluminum production levels (USGS and USAA 1990 through 2009), with allocation to specific smelters based on reported production capacities (USGS 1990 through 2009).

National primary aluminum production data for 2016 were obtained via USAA (USAA 2017). For 1990 through 2001, and 2006 (see Table 4-82) data were obtained from USGS *Mineral Industry Surveys: Aluminum Annual*

Report (USGS 1995, 1998, 2000, 2001, 2002, 2007). For 2002 through 2005, and 2007 through 2015, national aluminum production data were obtained from the USAA's *Primary Aluminum Statistics* (USAA 2004 through 2006, 2008 through 2016b).

Table 4-82: Production of Primary Aluminum (kt)

Year	kt
1990	4,048
2005	2,478
2012	2,070
2013	1,948
2014	1,710
2015	1,587
2016	818

Uncertainty and Time-Series Consistency

Uncertainty was assigned to the CO_2, CF_4, and C_2F_6 emission values reported by each individual facility to EPA's GHGRP. As previously mentioned, the methods for estimating emissions for EPA's GHGRP and this report are the same, and follow the *2006 IPCC Guidelines* methodology. As a result, it was possible to assign uncertainty bounds (and distributions) based on an analysis of the uncertainty associated with the facility-specific emissions estimated for previous Inventory years. Uncertainty surrounding the reported CO_2, CF_4, and C_2F_6 emission values were determined to have a normal distribution with uncertainty ranges of ±6, ±16, and ±20 percent, respectively. A Monte Carlo analysis was applied to estimate the overall uncertainty of the CO_2, CF_4, and C_2F_6 emission estimates for the U.S. aluminum industry as a whole, and the results are provided below.

The results of this Approach 2 quantitative uncertainty analysis are summarized in Table 4-83. Aluminum production-related CO_2 emissions were estimated to be between 1.3 and 1.4 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 3 percent below to 2 percent above the emission estimate of 1.3 MMT CO_2 Eq. Also, production-related CF_4 emissions were estimated to be between 0.8 and 1.0 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 10 percent below to 10 percent above the emission estimate of 0.9 MMT CO_2 Eq. Finally, aluminum production-related C_2F_6 emissions were estimated to be between 0.4 and 0.5 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 17 percent below to 17 percent above the emission estimate of 0.4 MMT CO_2 Eq.

Table 4-83: Approach 2 Quantitative Uncertainty Estimates for CO_2 and PFC Emissions from Aluminum Production (MMT CO_2 Eq. and Percent)

Source	Gas	2016 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a]			
			(MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Aluminum Production	CO_2	1.3	1.3	1.4	−3%	+2%
Aluminum Production	CF_4	0.9	0.8	1.0	−10%	+10%
Aluminum Production	C_2F_6	0.4	0.4	0.5	−17%	+17%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological approaches were applied to the entire time-series to ensure time-series consistency from 1990 through 2016. Details on the emission trends through time are described in more detail in the Methodology section, above.

For more information on the general QA/QC process applied to this source category, consistent with Volume 1, Chapter 6 of the *2006 IPCC Guidelines*, see the QA/QC and Verification Procedures section in the introduction of the IPPU chapter.

4.20 Magnesium Production and Processing (CRF Source Category 2C4)

The magnesium metal production and casting industry uses sulfur hexafluoride (SF_6) as a cover gas to prevent the rapid oxidation of molten magnesium in the presence of air. Sulfur hexafluoride has been used in this application around the world for more than thirty years. A dilute gaseous mixture of SF_6 with dry air and/or carbon dioxide (CO_2) is blown over molten magnesium metal to induce and stabilize the formation of a protective crust. A small portion of the SF_6 reacts with the magnesium to form a thin molecular film of mostly magnesium oxide and magnesium fluoride. The amount of SF_6 reacting in magnesium production and processing is considered to be negligible and thus all SF_6 used is assumed to be emitted into the atmosphere. Alternative cover gases, such as AM-cover™ (containing HFC-134a), Novec™ 612 (FK-5-1-12) and dilute sulfur dioxide (SO_2) systems can, and are being used by some facilities in the United States. However, many facilities in the United States are still using traditional SF_6 cover gas systems.

The magnesium industry emitted 1.0 MMT CO_2 Eq. (0.04 kt) of SF_6, 0.1 MMT CO_2 Eq. (0.07 kt) of HFC-134a, and 0.003 MMT CO_2 Eq. (2.7 kt) of CO_2 in 2016. This represents an increase of approximately 12 percent from total 2015 emissions (see Table 4-84). The increase can be attributed to an increase in secondary and die casting SF_6 emissions between 2015 and 2016 as reported through EPA's GHGRP. In 2016, SF_6 emissions increased by 12 percent. The increase in SF_6 emissions is likely due in part to increased secondary production from reporting facilities in 2016. In 2016, total HFC-134a emissions increased from 0.09 MMT CO_2 Eq. to 0.10 MMT CO_2 Eq., or a 5 percent increase as compared to 2015 emissions. This is mainly attributable to the increased use of this alternative for primary production. FK 5-1-12 emissions did not change substantially from 2015 levels. The emissions of the carrier gas, CO_2, increased from 2.6 kt in 2015 to 2.7 kt in 2016.

Table 4-84: SF_6, HFC-134a, FK 5-1-12 and CO_2 Emissions from Magnesium Production and Processing (MMT CO_2 Eq.)

Year	1990	2005	2012	2013	2014	2015	2016
SF_6	5.2	2.7	1.6	1.5	1.0	0.9	1.0
HFC-134a	0.0	0.0	+	0.1	0.1	0.1	0.1
CO_2	+	+	+	+	+	+	+
FK 5-1-12[a]	*0.0*	*0.0*	+	+	+	+	+
Total	**5.2**	**2.7**	**1.7**	**1.5**	**1.1**	**1.0**	**1.1**

+ Does not exceed 0.05 MMTCO₂ Eq.

[a] Emissions of FK 5-1-12 are not included in totals.

Table 4-85: SF_6, HFC-134a, FK 5-1-12 and CO_2 Emissions from Magnesium Production and Processing (kt)

Year	1990	2005	2012	2013	2014	2015	2016
SF_6	0.2	0.1	0.1	0.1	+	+	+
HFC-134a	0.0	0.0	+	0.1	0.1	0.1	0.1
CO_2	1.4	2.9	2.3	2.1	2.3	2.6	2.7
FK 5-1-12 [a]	*0.0*	*0.0*	+	+	+	+	+

+ Does not exceed 0.05 kt.

[a] Emissions of FK 5-1-12 are not included in totals.

Methodology

Emission estimates for the magnesium industry incorporate information provided by industry participants in EPA's SF_6 Emission Reduction Partnership for the Magnesium Industry as well as emissions data reported through subpart T (Magnesium Production and Processing) of EPA's GHGRP. The Partnership started in 1999 and, in 2010, participating companies represented 100 percent of U.S. primary and secondary production and 16 percent of the casting sector production (i.e., die, sand, permanent mold, wrought, and anode casting). SF_6 emissions for 1999 through 2010 from primary production, secondary production (i.e., recycling), and die casting were generally reported by Partnership participants. Partners reported their SF_6 consumption, which is assumed to be equivalent to emissions. Along with SF_6, some Partners also reported their HFC-134a and FK 5-1-12 usage, which is also assumed to be equal to emissions. The last reporting year was 2010 under the Partnership. Emissions data for 2011 through 2016 are obtained through EPA's GHGRP. Under the program, owners or operators of facilities that have a magnesium production or casting process must report emissions from use of cover or carrier gases, which include SF_6, HFC-134a, FK 5-1-12 and CO_2. Consequently, cover and carrier gas emissions from magnesium production and processing were estimated for three time periods, depending on the source of the emissions data: 1990 through 1998 (pre-EPA Partnership), 1999 through 2010 (EPA Partnership), and 2011 through 2016 (EPA GHGRP). The methodologies described below also make use of magnesium production data published by the U.S. Geological Survey (USGS).

1990 through 1998

To estimate emissions for 1990 through 1998, industry SF_6 emission factors were multiplied by the corresponding metal production and consumption (casting) statistics from USGS. For this period, it was assumed that there was no use of HFC-134a or FK 5-1-12 cover gases and hence emissions were not estimated for these alternatives.

Sulfur hexafluoride emission factors from 1990 through 1998 were based on a number of sources and assumptions. Emission factors for primary production were available from U.S. primary producers for 1994 and 1995. The primary production emission factors were 1.2 kg SF_6 per metric ton for 1990 through 1993, and 1.1 kg SF_6 per metric ton for 1994 through 1997. The emission factor for secondary production from 1990 through 1998 was assumed to be constant at the 1999 average Partner value. An emission factor for die casting of 4.1 kg SF_6 per metric ton, which was available for the mid-1990s from an international survey (Gjestland and Magers 1996), was used for years 1990 through 1996. For 1996 through 1998, the emission factor for die casting was assumed to decline linearly to the level estimated based on Partner reports in 1999. This assumption is consistent with the trend in SF_6 sales to the magnesium sector that is reported in the RAND survey of major SF_6 manufacturers, which shows a decline of 70 percent from 1996 to 1999 (RAND 2002). Sand casting emission factors for 1990 through 2001 were assumed to be the same as the 2002 emission factor. The emission factors for the other processes (i.e., permanent mold, wrought, and anode casting), about which less is known, were assumed to remain constant at levels defined in Table 4-84. These emission factors for the other processes (i.e., permanent mold, wrought, and anode casting) were based on discussions with industry representatives.

The quantities of CO_2 carrier gas used for each production type have been estimated using the 1999 estimated CO_2 emissions data and the annual calculated rate of change of SF_6 use in the 1990 through 1999 time period. For each year and production type, the rate of change of SF_6 use between the current year and the subsequent year was first estimated. This rate of change is then applied to the CO_2 emissions of the subsequent year to determine the CO_2 emission of the current year. The emissions of carrier gases for permanent mold, wrought and anode processes are not estimated in this Inventory.

1999 through 2010

The 1999 through 2010 emissions from primary and secondary production are based on information provided by EPA's industry Partners. In some instances, there were years of missing Partner data, including SF_6 consumption and metal processed. For these situations, emissions were estimated through interpolation where possible, or by holding company-reported emissions (as well as production) constant from the previous year. For alternative cover gases, including HFC-134a and FK 5-1-12, mainly reported data was relied upon. That is, unless a Partner reported using an alternative cover gas, it was not assumed it was used. Emissions of alternate gases were also estimated through linear interpolation where possible.

The die casting emission estimates for 1999 through 2010 are also based on information supplied by industry Partners. When a Partner was determined to be no longer in production, its metal production and usage rates were set to zero. Missing data on emissions or metal input was either interpolated or held constant at the last available reported value. In 1999 and from 2008 through 2010, Partners did not account for all die casting tracked by USGS, and, therefore, it was necessary to estimate the emissions of die casters who were not Partners. For 1999, die casters who were not Partners were assumed to be similar to Partners who cast small parts. Due to process requirements, these casters consume larger quantities of SF_6 per metric ton of processed magnesium than casters that process large parts. Consequently, emission estimates from this group of die casters were developed using an average emission factor of 5.2 kg SF_6 per metric ton of magnesium. This emission factor was developed using magnesium production and SF_6 usage data for the year 1999. For 2008 through 2010, the characteristics of the die casters who were not Partners were not well known, and therefore the emission factor for these die casters was set equal to 3.0 kg SF_6 per metric ton of magnesium, the average of the emission factors reported over the same period by the die casters who were Partners.

The emissions from other casting operations were estimated by multiplying emission factors (kg SF_6 per metric ton of metal produced or processed) by the amount of metal produced or consumed from USGS, with the exception of some years for which Partner sand casting emissions data are available. The emission factors for sand casting activities were acquired through the data reported by the Partnership for 2002 to 2006. For 1999-2001, the sand casting emission factor was held constant at the 2002 Partner-reported level. For 2007 through 2010, the sand casting Partner did not report and the reported emission factor from 2005 was applied to the Partner and to all other sand casters. Activity data for 2005 was obtained from USGS (USGS 2005b).

The emission factors for primary production, secondary production and sand casting for the 1999 to 2010 are not published to protect company-specific production information. However, the emission factor for primary production has not risen above the average 1995 Partner value of 1.1 kg SF_6 per metric ton. The emission factors for the other industry sectors (i.e., permanent mold, wrought, and anode casting) were based on discussions with industry representatives. The emission factors for casting activities are provided below in Table 4-86.

The emissions of HFC-134a and FK-5-1-12 were included in the estimates for only instances where Partners reported that information to the Partnership. Emissions of these alternative cover gases were not estimated for instances where emissions were not reported.

Carbon dioxide carrier gas emissions were estimated using the emission factors developed based on GHGRP-reported carrier gas and cover gas data, by production type. It was assumed that the use of carrier gas, by production type, is proportional to the use of cover gases. Therefore, an emission factor, in kg CO_2 per kg cover gas and weighted by the cover gases used, was developed for each of the production types. GHGRP data on which these emissions factors are based was available for primary, secondary, die casting and sand casting. The emission factors were applied to the total quantity of all cover gases used (SF_6, HFC-134a, and FK-5-1-12) by production type in this time period. Carrier gas emissions for the 1999 through 2010 time period were only estimated for those Partner companies that reported using CO_2 as a carrier gas through the GHGRP. Using this approach helped ensure time-series consistency. The emissions of carrier gases for permanent mold, wrought and anode processes are not estimated in this Inventory.

Table 4-86: SF_6 Emission Factors (kg SF_6 per metric ton of magnesium)

Year	Die Casting[a]	Permanent Mold	Wrought	Anodes
1999	1.75[b]	2	1	1
2000	0.72	2	1	1
2001	0.72	2	1	1
2002	0.71	2	1	1
2003	0.81	2	1	1
2004	0.79	2	1	1
2005	0.77	2	1	1
2006	0.88	2	1	1
2007	0.64	2	1	1
2008	0.97	2	1	1
2009	2.30	2	1	1
2010	2.94	2	1	1

[a] Weighted average includes all die casters, Partners and non-Partners. For the majority of the time series (2000-2007), Partners made up 100 percent of die casters in the United States.

[b] Weighted average that includes an estimated emission factor of 5.2 kg SF_6 per metric ton of magnesium for die casters that do not participate in the Partnership.

2011 through 2016

For 2011 through 2016, for the primary and secondary producers, GHGRP-reported cover and carrier gases emissions data were used. For die and sand casting, some emissions data was obtained through EPA's GHGRP. The balance of the emissions for these industry segments were estimated based on previous Partner reporting (i.e., for Partners that did not report emissions through EPA's GHGRP) or were estimated by multiplying emission factors by the amount of metal produced or consumed. Partners who did not report through EPA's GHGRP were assumed to have continued to emit SF_6 at the last reported level, which was from 2010 in most cases, unless publically available sources indicated that these facilities have closed or otherwise eliminated SF_6 emissions from magnesium production (ARB 2015). All Partners were assumed to have continued to consume magnesium at the last reported level. Where the total metal consumption estimated for the Partners fell below the U.S. total reported by USGS, the difference was multiplied by the emission factors discussed in the section above, i.e. non-partner emission factors. For the other types of production and processing (i.e., permanent mold, wrought, and anode casting), emissions were estimated by multiplying the industry emission factors with the metal production or consumption statistics obtained from USGS (USGS 2016). USGS data for 2016 was not yet available at the time of the analysis, so the 2015 values were held constant through 2016 as a proxy.

Uncertainty and Time-Series Consistency

Uncertainty surrounding the total estimated emissions in 2016 is attributed to the uncertainties around SF_6, HFC-134a, and CO_2 emission estimates. To estimate the uncertainty surrounding the estimated 2016 SF_6 emissions from magnesium production and processing, the uncertainties associated with three variables were estimated: (1) emissions reported by magnesium producers and processors for 2016 through EPA's GHGRP, (2) emissions estimated for magnesium producers and processors that reported via the Partnership in prior years but did not report 2016 emissions through EPA's GHGRP, and (3) emissions estimated for magnesium producers and processors that did not participate in the Partnership or report through EPA's GHGRP. An uncertainty of 5 percent was assigned to the emissions (usage) data reported by each GHGRP reporter for all the cover and carrier gases (per the *2006 IPCC Guidelines*). If facilities did not report emissions data during the current reporting year through EPA's GHGRP reporting program, SF_6 emissions data were held constant at the most recent available value reported through the Partnership. The uncertainty associated with these values was estimated to be 30 percent for each year of extrapolation. Alternate cover gas and carrier gases data was set equal to zero if the facilities did not report via the GHGRP program. For those industry processes that are not represented in the Partnership, such as permanent mold and wrought casting, SF_6 emissions were estimated using production and consumption statistics reported by USGS and estimated process-specific emission factors (see Table 4-87). The uncertainties associated with the emission factors and USGS-reported statistics were assumed to be 75 percent and 25 percent, respectively. Emissions associated with die casting and sand casting activities utilized emission factors based on Partner reported data with an uncertainty of 75 percent. In general, where precise quantitative information was not available on the uncertainty of a parameter, a conservative (upper-bound) value was used.

Additional uncertainties exist in these estimates that are not addressed in this methodology, such as the basic assumption that SF_6 neither reacts nor decomposes during use. The melt surface reactions and high temperatures associated with molten magnesium could potentially cause some gas degradation. Previous measurement studies have identified SF_6 cover gas degradation in die casting applications on the order of 20 percent (Bartos et al. 2007). Sulfur hexafluoride may also be used as a cover gas for the casting of molten aluminum with high magnesium content; however, the extent to which this technique is used in the United States is unknown.

The results of this Approach 2 quantitative uncertainty analysis are summarized in Table 4-87. Total emissions associated with magnesium production and processing were estimated to be between 1.1 and 1.2 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 5 percent below to 5 percent above the 2016 emission estimate of 1.1 MMT CO_2 Eq. The uncertainty estimates for 2016 are smaller relative to the uncertainty reported for 2015 in the previous Inventory. In the previous Inventory, the emissions factor of sand casting had a significant impact on the uncertainty because of relatively high uncertainty from the facility that was not reporting under EPA's GHGRP. This year, the sand casting facility was confirmed to have ceased emissions of SF_6, lowering the uncertainty bounds on the total emission estimate.

Table 4-87: Approach 2 Quantitative Uncertainty Estimates for SF_6, HFC-134a and CO_2 Emissions from Magnesium Production and Processing (MMT CO_2 Eq. and Percent)

Source	Gas	2016 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		Uncertainty Range Relative to Emission Estimate[a] (%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Magnesium Production	SF_6, HFC-134a, CO_2	1.1	1.1	1.2	-5%	+5%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological approaches were applied to the entire time series to ensure time-series consistency from 1990 through 2016. Details on the emission trends through time are described in more detail in the Methodology section, above.

For more information on the general QA/QC process applied to this source category, consistent with Volume 1, Chapter 6 of the *2006 IPCC Guidelines*, see the QA/QC and Verification Procedures section in the introduction of the IPPU chapter.

Recalculations Discussion

Estimates for SF_6 emissions from secondary production for 2014 and 2015 were slightly adjusted to correct for a mathematical error. This resulted in a slight increase in SF_6 emissions for both 2014 and 2015.

Research on former Partner facilities showed that one facility whose SF_6 emissions were previously held constant at 2010 levels stopped emitting SF_6 at the beginning of 2015. This facility's 2015 SF_6 emissions estimates were adjusted to correct for this change, slightly decreasing overall SF_6 emissions for 2015.

Planned Improvements

Cover gas research conducted over the last decade has found that SF_6 used for magnesium melt protection can have degradation rates on the order of 20 percent in die casting applications (Bartos et al. 2007). Current emission estimates assume (per the *2006 IPCC Guidelines*) that all SF_6 utilized is emitted to the atmosphere. Additional research may lead to a revision of the *2006 IPCC Guidelines* to reflect this phenomenon and until such time, developments in this sector will be monitored for possible application to the Inventory methodology.

Usage and emission details of carrier gases in permanent mold, wrought and anode processes will be researched as part of a future Inventory. Based on this research, it will be determined if CO_2 carrier gas emissions are to be estimated.

Additional emissions are generated as byproducts from the use of alternate cover gases, which are not currently accounted for. Research on this topic is developing, and as reliable emission factors become available, these emissions will be incorporated into the Inventory.

4.21 Lead Production (CRF Source Category 2C5)

In 2016, lead was produced in the United States only using secondary production processes. Until 2014, both lead production in the United States involved both primary and secondary processes—both of which emit carbon dioxide (CO_2) (Sjardin 2003). Emissions from fuels consumed for energy purposes during the production of lead are accounted for in the Energy chapter.

Primary production of lead through the direct smelting of lead concentrate produces CO_2 emissions as the lead concentrates are reduced in a furnace using metallurgical coke (Sjardin 2003). Primary lead production, in the form of direct smelting, previously occurred at a single smelter in Missouri. This primary lead smelter was closed at the end of 2013. In 2014, the smelter processed a small amount of residual lead during demolition of the site (USGS 2015) and in 2016 the smelter processed no lead (USGS 2016, 2017).

Similar to primary lead production, CO_2 emissions from secondary lead production result when a reducing agent, usually metallurgical coke, is added to the smelter to aid in the reduction process. Carbon dioxide emissions from secondary production also occur through the treatment of secondary raw materials (Sjardin 2003). Secondary production primarily involves the recycling of lead acid batteries and post-consumer scrap at secondary smelters. Of all the domestic secondary smelters operational in 2016, 11 smelters had capacities of 30,000 tons or more and were collectively responsible for more than 95 percent of secondary lead production in 2016 (USGS 2017). Secondary lead production has increased in the United States over the past decade while primary lead production has decreased to production levels of zero. In 2016, secondary lead production accounted for 100 percent of total lead production. The lead-acid battery industry accounted for about 85 percent of the reported U.S. lead consumption in 2016 (USGS 2017).

In 2016, total secondary lead production in the United States was slightly higher than that in 2015. A new secondary lead refinery, located in Nevada, was completed in 2016 and production was expected to begin by the end of the year. The plant was expected to produce about 80 tons per day of high-purity refined lead for use in advanced lead-acid batteries using an electromechanical battery recycling technology system. The United States has become more reliant on imported refined lead in recent years owing to the closure of the last primary lead smelter in 2013, and to an increase in exports of spent starting-lighting-ignition lead-acid batteries that reduced the availability of scrap for secondary smelters (USGS 2017).

As in 2015, U.S. primary lead production remained at production levels of zero for 2016, and has also decreased by 100 percent since 1990. This is due to the closure of the only domestic primary lead smelter in 2013 (year-end), as stated previously. In 2016, U.S. secondary lead production increased from 2015 levels (increase of 2 percent), and has increased by 16 percent since 1990 (USGS 1995 through 2017).

In 2016, U.S. primary and secondary lead production totaled 1,070,000 metric tons (USGS 2017). The resulting emissions of CO_2 from 2016 lead production were estimated to be 0.5 MMT CO_2 Eq. (482 kt) (see Table 4-88). All 2016 lead production is from secondary processes, which accounted for 100 percent of total 2016 CO_2 emissions from lead production. At last reporting, the United States was the third largest mine producer of lead in the world, behind China and Australia, accounting for approximately 7 percent of world production in 2016 (USGS 2017).

Table 4-88: CO_2 Emissions from Lead Production (MMT CO_2 Eq. and kt)

Year	MMT CO_2 Eq.	kt
1990	0.5	516
2005	0.6	553
2012	0.5	527
2013	0.5	546
2014	0.5	459
2015	0.5	473
2016	0.5	482

After a steady increase in total emissions from 1995 to 2000, total emissions have gradually decreased since 2000 and are currently 7 percent lower than 1990 levels.

Methodology

The methods used to estimate emissions for lead production[58] are based on Sjardin's work (Sjardin 2003) for lead production emissions and Tier 1 methods from the *2006 IPCC Guidelines*. The Tier 1 equation is as follows:

$$CO_2\ Emissions = (DS \times EF_{DS}) + (S \times EF_S)$$

where,

DS = Lead produced by direct smelting, metric ton
S = Lead produced from secondary materials
EF_{DS} = Emission factor for direct Smelting, metric tons CO_2/metric ton lead product
EF_S = Emission factor for secondary materials, metric tons CO_2/metric ton lead product

For primary lead production using direct smelting, Sjardin (2003) and the IPCC (2006) provide an emission factor of 0.25 metric tons CO_2/metric ton lead. For secondary lead production, Sjardin (2003) and IPCC (2006) provide an emission factor of 0.25 metric tons CO_2/metric ton lead for direct smelting, as well as an emission factor of 0.2 metric tons CO_2/metric ton lead produced for the treatment of secondary raw materials (i.e., pretreatment of lead acid batteries). Since the secondary production of lead involves both the use of the direct smelting process and the treatment of secondary raw materials, Sjardin recommends an additive emission factor to be used in conjunction with the secondary lead production quantity. The direct smelting factor (0.25) and the sum of the direct smelting and pretreatment emission factors (0.45) are multiplied by total U.S. primary and secondary lead production, respectively, to estimate CO_2 emissions.

The production and use of coking coal for lead production is adjusted for within the Energy chapter as this fuel was consumed during non-energy related activities. Additional information on the adjustments made within the Energy sector for Non-Energy Use of Fuels is described in both the Methodology section of CO_2 from Fossil Fuel Combustion (3.1 Fossil Fuel Combustion (CRF Source Category 1A)) and Annex 2.1, Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion.

The 1990 through 2016 activity data for primary and secondary lead production (see Table 4-89) were obtained from the U.S. Geological Survey (USGS 1995 through 2017).

Table 4-89: Lead Production (Metric Tons)

Year	Primary	Secondary
1990	404,000	922,000
2005	143,000	1,150,000
2012	111,000	1,110,000
2013	114,000	1,150,000
2014	1,000	1,020,000
2015	0	1,050,000
2016	0	1,070,000

Uncertainty and Time-Series Consistency

Uncertainty associated with lead production relates to the emission factors and activity data used. The direct smelting emission factor used in primary production is taken from Sjardin (2003) who averaged the values provided by three other studies (Dutrizac et al. 2000; Morris et al. 1983; Ullman 1997). For secondary production, Sjardin (2003) added a CO_2 emission factor associated with battery treatment. The applicability of these emission factors to

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[58] EPA has not integrated aggregated facility-level Greenhouse Gas Reporting Program (GHGRP) information to inform these estimates. The aggregated information (e.g., activity data and emissions) associated with Lead Production did not meet criteria to shield underlying confidential business information (CBI) from public disclosure.

plants in the United States is uncertain. There is also a smaller level of uncertainty associated with the accuracy of primary and secondary production data provided by the USGS which is collected via voluntary surveys; the uncertainty of the activity data is a function of the reliability of reported plant-level production data and the completeness of the survey response.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-90. Lead production CO_2 emissions in 2016 were estimated to be between 0.4 and 0.6 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 14 percent below and 15 percent above the emission estimate of 0.5 MMT CO_2 Eq.

Table 4-90: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Lead Production (MMT CO_2 Eq. and Percent)

Source	Gas	2016 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Lead Production	CO_2	0.5	0.4	0.6	-14%	+15%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological approaches discussed below were applied to applicable years to ensure time-series consistency in emissions from 1990 through 2016. Details on the emission trends through time are described in more detail in the Methodology section, above.

For more information on the general QA/QC process applied to this source category, consistent with Volume 1, Chapter 6 of the *2006 IPCC Guidelines*, see the QA/QC and Verification Procedures section in the introduction of the IPPU chapter.

Planned Improvements

Pending resources and prioritization of improvements for more significant sources, EPA will continue to evaluate and analyze data reported under EPA's GHGRP that would be useful to improve the emission estimates and category-specific QC for the Lead Production source category, in particular considering completeness of reported lead production given the reporting threshold. Particular attention will be made to ensuring time-series consistency of the emissions estimates presented in future Inventory reports, consistent with IPCC and UNFCCC guidelines. This is required as the facility-level reporting data from EPA's GHGRP, with the program's initial requirements for reporting of emissions in calendar year 2010, are not available for all inventory years (i.e., 1990 through 2009) as required for this Inventory. In implementing improvements and integration of data from EPA's GHGRP, the latest guidance from the IPCC on the use of facility-level data in national inventories will be relied upon.[59] EPA is still reviewing available GHGRP data and assessing the possibility of including this planned improvement in future Inventory reports.

4.22 Zinc Production (CRF Source Category 2C6)

Zinc production in the United States consists of both primary and secondary processes. Of the primary and secondary processes used in the United States, only the electrothermic and Waelz kiln secondary processes result in

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[59] See <http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf >.

non-energy carbon dioxide (CO_2) emissions (Viklund-White 2000). Emissions from fuels consumed for energy purposes during the production of zinc are accounted for in the Energy chapter.

The majority of zinc produced in the United States is used for galvanizing. Galvanizing is a process where zinc coating is applied to steel in order to prevent corrosion. Zinc is used extensively for galvanizing operations in the automotive and construction industry. Zinc is also used in the production of zinc alloys and brass and bronze alloys (e.g., brass mills, copper foundries, and copper ingot manufacturing). Zinc compounds and dust are also used, to a lesser extent, by the agriculture, chemicals, paint, and rubber industries.

Primary production in the United States is conducted through the electrolytic process, while secondary techniques include the electrothermic and Waelz kiln processes, as well as a range of other metallurgical, hydrometallurgical, and pyrometallurgical processes. Worldwide primary zinc production also employs a pyrometallurgical process using the Imperial Smelting Furnace process; however, this process is not used in the United States (Sjardin 2003).

In the electrothermic process, roasted zinc concentrate and secondary zinc products enter a sinter feed where they are burned to remove impurities before entering an electric retort furnace. Metallurgical coke is added to the electric retort furnace as a carbon-containing reductant. This concentration step, using metallurgical coke and high temperatures, reduces the zinc oxides and produces vaporized zinc, which is then captured in a vacuum condenser. This reduction process also generates non-energy CO_2 emissions.

$$ZnO + C \rightarrow Zn(gas) + CO_2 \qquad \text{(Reaction 1)}$$

$$ZnO + CO \rightarrow Zn(gas) + CO_2 \qquad \text{(Reaction 2)}$$

In the Waelz kiln process, electric arc furnace (EAF) dust, which is captured during the recycling of galvanized steel, enters a kiln along with a reducing agent (typically carbon-containing metallurgical coke). When kiln temperatures reach approximately 1,100 to 1,200 degrees Celsius, zinc fumes are produced, which are combusted with air entering the kiln. This combustion forms zinc oxide, which is collected in a baghouse or electrostatic precipitator, and is then leached to remove chloride and fluoride. The use of carbon-containing metallurgical coke in a high-temperature fuming process results in non-energy CO_2 emissions. Through this process, approximately 0.33 metric tons of zinc is produced for every metric ton of EAF dust treated (Viklund-White 2000).

The only companies in the United States that use emissive technology to produce secondary zinc products are American Zinc Recycling (AZR) (formerly “Horsehead Corporation”), PIZO, and Steel Dust Recycling (SDR). For AZR, EAF dust is recycled in Waelz kilns at their Calumet, IL; Palmerton, PA; Rockwood, TN; and Barnwell, SC facilities. These Waelz kiln facilities produce intermediate zinc products (crude zinc oxide or calcine), most of which was transported to their Monaca, PA facility where the products were smelted into refined zinc using electrothermic technology. In April 2014, AZR permanently shut down their Monaca smelter. This was replaced by their new facility in Mooresboro, NC. The new Mooresboro facility uses a hydrometallurgical process (i.e., solvent extraction with electrowinning technology) to produce zinc products. The current capacity of the new facility is 155,000 short tons, with plans to expand to 170,000 short tons per year. Direct consumption of coal, coke, and natural gas have been replaced with electricity consumption at the new Mooresboro facility. The new facility is reported to have a significantly lower greenhouse gas and other air emissions than the Monaca smelter (Horsehead 2012b).

The Mooresboro facility uses leaching and solvent extraction (SX) technology combined with electrowinning, melting, and casting technology. In this process, Waelz Oxide (WOX) is first washed in water to remove soluble elements such as chlorine, potassium, and sodium, and then is leached in a sulfuric acid solution to dissolve the contained zinc creating a pregnant liquor solution (PLS). The PLS is then processed in a solvent extraction step in which zinc is selectively extracted from the PLS using an organic solvent creating a purified zinc-loaded electrolyte solution. The loaded electrolyte solution is then fed into the electrowinning process in which electrical energy is applied across a series of anodes and cathodes submerged in the electrolyte solution causing the zinc to deposit on the surfaces of the cathodes. As the zinc metal builds up on these surfaces, the cathodes are periodically harvested in order to strip the zinc from their surfaces (Horsehead 2015). Hydrometallurgical production processes are assumed to be non-emissive since no carbon is used in these processes (Sjardin 2003).

PIZO and SDR recycle EAF dust into intermediate zinc products using Waelz kilns, and then sell the intermediate products to companies who smelt it into refined products.

In 2016, United States primary and secondary refined zinc production were estimated to total 140,000 metric tons (USGS 2017) (see Table 4-91). Domestic zinc mine production decreased by 5 percent in 2016, owing mostly to a decrease in production in Tennessee; in December 2015, the Middle Tennessee Mines (50,000-ton-per-year capacity) were closed in response to low zinc prices at the time. Refined zinc production decreased by 19 percent as a result of a decline in secondary zinc production; in January, the zinc recycling facility in Mooresboro, NC (140,000-ton-per-year capacity) closed as a result of low zinc prices and ongoing equipment and technical issues (USGS 2017). Primary zinc production (primary slab zinc) decreased by 11 percent in 2016, while secondary zinc production in 2016 decreased by 42 percent relative to 2015.

Emissions of CO_2 from zinc production in 2016 were estimated to be 0.9 MMT CO_2 Eq. (925 kt CO_2) (see Table 4-92). All 2016 CO_2 emissions resulted from secondary zinc production processes. Emissions from zinc production in the United States have increased overall since 1990 due to a gradual shift from non-emissive primary production to emissive secondary production. In 2016, emissions were estimated to be 46 percent higher than they were in 1990.

Table 4-91: Zinc Production (Metric Tons)

Year	Primary	Secondary	Total
1990	262,704	95,708	358,412
2005	191,120	156,000	347,120
2012	114,000	147,000	261,000
2013	106,000	127,000	233,000
2014	110,000	70,000	180,000
2015	125,000	50,000	175,000
2016	111,000	29,000	140,000

Table 4-92: CO_2 Emissions from Zinc Production (MMT CO_2 Eq. and kt)

Year	MMT CO_2 Eq.	kt
1990	0.6	632
2005	1.0	1,030
2012	1.5	1,486
2013	1.4	1,429
2014	1.0	956
2015	0.9	933
2016	0.9	925

Methodology

The methods used to estimate non-energy CO_2 emissions from zinc production[60] using the electrothermic primary production and Waelz kiln secondary production processes are based on Tier 1 methods from the *2006 IPCC Guidelines* (IPCC 2006). The Tier 1 equation used to estimate emissions from zinc production is as follows:

$$E_{CO2} = Zn \times EF_{default}$$

where,

E_{CO2} = CO_2 emissions from zinc production, metric tons
Zn = Quantity of zinc produced, metric tons
$EF_{default}$ = Default emission factor, metric tons CO_2/metric ton zinc produced

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[60] EPA has not integrated aggregated facility-level Greenhouse Gas Reporting Program (GHGRP) information to inform these estimates. The aggregated information (e.g., activity data and emissions) associated with Zinc Production did not meet criteria to shield underlying confidential business information (CBI) from public disclosure.

The Tier 1 emission factors provided by IPCC for Waelz kiln-based secondary production were derived from coke consumption factors and other data presented in Vikland-White (2000). These coke consumption factors as well as other inputs used to develop the Waelz kiln emission factors are shown below. IPCC does not provide an emission factor for electrothermic processes due to limited information; therefore, the Waelz kiln-specific emission factors were also applied to zinc produced from electrothermic processes. Starting in 2014, refined zinc produced in the United States used hydrometallurgical processes and is assumed to be non-emissive.

For Waelz kiln-based production, IPCC recommends the use of emission factors based on EAF dust consumption, if possible, rather than the amount of zinc produced since the amount of reduction materials used is more directly dependent on the amount of EAF dust consumed. Since only a portion of emissive zinc production facilities consume EAF dust, the emission factor based on zinc production is applied to the non-EAF dust consuming facilities while the emission factor based on EAF dust consumption is applied to EAF dust consuming facilities.

The Waelz kiln emission factor based on the amount of zinc produced was developed based on the amount of metallurgical coke consumed for non-energy purposes per ton of zinc produced (i.e., 1.19 metric tons coke/metric ton zinc produced) (Viklund-White 2000), and the following equation:

$$EF_{Waelz\ Kiln} = \frac{1.19\ metric\ tons\ coke}{metric\ tons\ zinc} \times \frac{0.85\ metric\ tons\ C}{metric\ tons\ coke} \times \frac{3.67\ metric\ tons\ CO_2}{metric\ tons\ C} = \frac{3.70\ metric\ tons\ CO_2}{metric\ tons\ zinc}$$

The Waelz kiln emission factor based on the amount of EAF dust consumed was developed based on the amount of metallurgical coke consumed per ton of EAF dust consumed (i.e., 0.4 metric tons coke/metric ton EAF dust consumed) (Viklund-White 2000), and the following equation:

$$EF_{EAF\ Dust} = \frac{0.4\ metric\ tons\ coke}{metric\ tons\ EAF\ Dust} \times \frac{0.85\ metric\ tons\ C}{metric\ tons\ coke} \times \frac{3.67\ metric\ tons\ CO_2}{metric\ tons\ C} = \frac{1.24\ metric\ tons\ CO_2}{metric\ tons\ EAF\ Dust}$$

The total amount of EAF dust consumed by AZR at their Waelz kilns was available from AZR (formerly "Horsehead Corporation") financial reports for years 2006 through 2015 (Horsehead 2007, 2008, 2010a, 2011, 2012a, 2013, 2014, 2015, and 2016). Total EAF dust consumed by AZR at their Waelz kilns was not available for 2016 so 2015 data was used as proxy. Consumption levels for 1990 through 2005 were extrapolated using the percentage change in annual refined zinc production at secondary smelters in the United States as provided by the U.S. Geological Survey (USGS) *Minerals Yearbook: Zinc* (USGS 1995 through 2006). The EAF dust consumption values for each year were then multiplied by the 1.24 metric tons CO_2/metric ton EAF dust consumed emission factor to develop CO_2 emission estimates for AZR's Waelz kiln facilities.

The amount of EAF dust consumed by SDR and their total production capacity were obtained from SDR's facility in Alabama for the years 2011 through 2016 (SDR 2012, 2014, 2015, and 2017). SDR's facility in Alabama underwent expansion in 2011 to include a second unit (operational since early- to mid-2012). SDR's facility has been operational since 2008. Annual consumption data for SDR was not publicly available for the years 2008, 2009, and 2010. These data were estimated using data for AZR's Waelz kilns for 2008 through 2010 (Horsehead 2007, 2008, 2010a, 2010b, and 2011). Annual capacity utilization ratios were calculated using AZR's annual consumption and total capacity for the years 2008 through 2010. AZR's annual capacity utilization ratios were multiplied with SDR's total capacity to estimate SDR's consumption for each of the years, 2008 through 2010 (SDR 2013).

PIZO Technologies Worldwide LLC's facility in Arkansas has been operational since 2009. The amount of EAF dust consumed by PIZO's facility for 2009 through 2016 was not publicly available. EAF dust consumption for PIZO's facility for 2009 and 2010 were estimated by calculating annual capacity utilization of AZR's Waelz kilns and multiplying this utilization ratio by PIZO's total capacity (PIZO 2012). EAF dust consumption for PIZO's facility for 2011 through 2016 were estimated by applying the average annual capacity utilization rates for AZR and SDR (Grupo PROMAX) to PIZO's annual capacity (Horsehead 2012, 2013, 2014, 2015, and 2016; SDR 2012, 2014 and 2017; PIZO 2012, 2014 and 2017). The 1.24 metric tons CO_2/metric ton EAF dust consumed emission factor was then applied to PIZO's and SDR's estimated EAF dust consumption to develop CO_2 emission estimates for those Waelz kiln facilities.

Refined zinc production levels for AZR's Monaca, PA facility (utilizing electrothermic technology) were available from the company for years 2005 through 2013 (Horsehead 2008, 2011, 2012, 2013, and 2014). The Monaca facility was permanently shut down in April 2014 and was replaced by AZR's new facility in Mooresboro, NC. The new facility uses hydrometallurgical process to produce refined zinc products. This process is assumed to be non-emissive. Production levels for 1990 through 2004 were extrapolated using the percentage changes in annual refined zinc production at secondary smelters in the United States as provided by USGS *Minerals Yearbook: Zinc* (USGS 1995 through 2005). The 3.70 metric tons CO_2/metric ton zinc emission factor was then applied to the Monaca facility's production levels to estimate CO_2 emissions for the facility. The Waelz kiln production emission factor was applied in this case rather than the EAF dust consumption emission factor since AZR's Monaca facility did not consume EAF dust.

The production and use of coking coal for zinc production is adjusted for within the Energy chapter as this fuel was consumed during non-energy related activities. Additional information on the adjustments made within the Energy sector for Non-Energy Use of Fuels is described in both the Methodology section of CO_2 from Fossil Fuel Combustion (3.1 Fossil Fuel Combustion (CRF Source Category 1A)) and Annex 2.1, Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion.

Beginning with the 2017 USGS *Minerals Commodity Summary: Zinc*, United States primary and secondary refined zinc production were reported as one value, total refined zinc production. Prior to this publication, primary and secondary refined zinc production statistics were reported separately. For the current Inventory report, EPA sought expert judgement from the USGS mineral commodity expert to assess approaches for splitting total production into primary and secondary values. During 2016, only one facility produced primary zinc. Primary zinc produced from this facility was subtracted from the USGS 2016 total zinc production statistic to estimate secondary zinc production for 2016.

Uncertainty and Time-Series Consistency

The uncertainty associated with these estimates is two-fold, relating to activity data and emission factors used.

First, there is uncertainty associated with the amount of EAF dust consumed in the United States to produce secondary zinc using emission-intensive Waelz kilns. The estimate for the total amount of EAF dust consumed in Waelz kilns is based on (1) an EAF dust consumption value reported annually by AZR/Horsehead Corporation as part of its financial reporting to the Securities and Exchange Commission (SEC), and (2) an EAF dust consumption value obtained from the Waelz kiln facility operated in Alabama by Steel Dust Recycling LLC. Since actual EAF dust consumption information is not available for PIZO's facility (2009 through 2010) and SDR's facility (2008 through 2010), the amount is estimated by multiplying the EAF dust recycling capacity of the facility (available from the company's website) by the capacity utilization factor for AZR (which is available from Horsehead Corporation financial reports). Also, the EAF dust consumption for PIZO's facility for 2011 through 2016 was estimated by multiplying the average capacity utilization factor developed from AZR and SDR's annual capacity utilization rates by PIZO's EAF dust recycling capacity. Therefore, there is uncertainty associated with the assumption used to estimate PIZO and SDR's annual EAF dust consumption values (except SDR's EAF dust consumption for 2011 through 2016, which were obtained from SDR's recycling facility in Alabama).

Second, there is uncertainty associated with the emission factors used to estimate CO_2 emissions from secondary zinc production processes. The Waelz kiln emission factors are based on materials balances for metallurgical coke and EAF dust consumed as provided by Viklund-White (2000). Therefore, the accuracy of these emission factors depend upon the accuracy of these materials balances. Data limitations prevented the development of emission factors for the electrothermic process. Therefore, emission factors for the Waelz kiln process were applied to both electrothermic and Waelz kiln production processes.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-93. Zinc production CO_2 emissions from 2016 were estimated to be between 0.8 and 1.1 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 16 percent below and 16 percent above the emission estimate of 0.9 MMT CO_2 Eq.

Table 4-93: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Zinc Production (MMT CO_2 Eq. and Percent)

Source	Gas	2016 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Zinc Production	CO_2	0.9	0.8	1.1	-16%	+16%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2016. Details on the emission trends through time are described in more detail in the Methodology section, above.

For more information on the general QA/QC process applied to this source category, consistent with Volume 1, Chapter 6 of the *2006 IPCC Guidelines*, see the QA/QC and Verification Procedures section in the introduction of the IPPU chapter.

Planned Improvements

Pending resources and prioritization of improvements for more significant sources, EPA will continue to evaluate and analyze data reported under EPA's GHGRP that would be useful to improve the emission estimates and category-specific QC for the Zinc Production source category, in particular considering completeness of reported zinc production given the reporting threshold. Given the small number of facilities in the United States, particular attention will be made to risks for disclosing CBI and ensuring time series consistency of the emissions estimates presented in future Inventory reports, consistent with IPCC and UNFCCC guidelines. This is required as the facility-level reporting data from EPA's GHGRP, with the program's initial requirements for reporting of emissions in calendar year 2010, are not available for all inventory years (i.e., 1990 through 2009) as required for this Inventory. In implementing improvements and integration of data from EPA's GHGRP, the latest guidance from the IPCC on the use of facility-level data in national inventories will be relied upon.[61] EPA is still assessing the possibility of including this planned improvement in future Inventory reports.

4.23 Semiconductor Manufacture (CRF Source Category 2E1)

The semiconductor industry uses multiple greenhouse gases in its manufacturing processes. These include long-lived fluorinated greenhouse gases used for plasma etching and chamber cleaning, fluorinated heat transfer fluids used for temperature control and other applications, and nitrous oxide (N_2O) used to produce thin films through chemical vapor deposition.

The gases most commonly employed in plasma etching and chamber cleaning are trifluoromethane (HFC-23 or CHF_3), perfluoromethane (CF_4), perfluoroethane (C_2F_6), nitrogen trifluoride (NF_3), and sulfur hexafluoride (SF_6), although other fluorinated compounds such as perfluoropropane (C_3F_8) and perfluorocyclobutane (c-C_4F_8) are also used. The exact combination of compounds is specific to the process employed.

A single 300 mm silicon wafer that yields between 400 to 600 semiconductor products (devices or chips) may require more than 100 distinct fluorinated-gas-using process steps, principally to deposit and pattern dielectric films. Plasma etching (or patterning) of dielectric films, such as silicon dioxide and silicon nitride, is performed to provide

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[61] See <http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf>.

pathways for conducting material to connect individual circuit components in each device. The patterning process uses plasma-generated fluorine atoms, which chemically react with exposed dielectric film to selectively remove the desired portions of the film. The material removed as well as undissociated fluorinated gases flow into waste streams and, unless emission abatement systems are employed, into the atmosphere. Plasma enhanced chemical vapor deposition (PECVD) chambers, used for depositing dielectric films, are cleaned periodically using fluorinated and other gases. During the cleaning cycle the gas is converted to fluorine atoms in plasma, which etches away residual material from chamber walls, electrodes, and chamber hardware. Undissociated fluorinated gases and other products pass from the chamber to waste streams and, unless abatement systems are employed, into the atmosphere.

In addition to emissions of unreacted gases, some fluorinated compounds can also be transformed in the plasma processes into different fluorinated compounds which are then exhausted, unless abated, into the atmosphere. For example, when C_2F_6 is used in cleaning or etching, CF_4 is generated and emitted as a process byproduct. In some cases, emissions of the byproduct gas can rival or even exceed emissions of the input gas, as is the case for NF_3 used in remote plasma chamber cleaning, which generates CF_4 as a byproduct.

Besides dielectric film etching and PECVD chamber cleaning, much smaller quantities of fluorinated gases are used to etch polysilicon films and refractory metal films like tungsten.

Nitrous oxide is used in manufacturing semiconductor devices to produce thin films by CVD and nitridation processes as well as for N-doping of compound semiconductors and reaction chamber conditioning (Doering 2000).

Liquid perfluorinated compounds are also used as heat transfer fluids (F-HTFs) for temperature control, device testing, cleaning substrate surfaces and other parts, and soldering in certain types of semiconductor manufacturing production processes. Leakage and evaporation of these fluids during use is a source of fluorinated gas emissions (U.S. EPA 2006). Unweighted F-HTF emissions consist primarily of perfluorinated amines, hydrofluoroethers, perfluoropolyethers, and perfluoroalkylmorpholines. One percent or less consist of HFCs or PFCs (where PFCs are defined as compounds including only carbon and fluorine). With the exceptions of the hydrofluoroethers and most of the HFCs, all of these compounds are very long-lived in the atmosphere and have global warming potentials (GWPs) near 10,000.[62]

For 2016, total GWP-weighted emissions of all fluorinated greenhouse gases and N_2O from deposition, etching, and chamber cleaning processes in the U.S. semiconductor industry were estimated to be 5.0 MMT CO_2 Eq. These emissions are presented in Table 4-94 and Table 4-95 below for the years 1990, 2005, and the period 2011 to 2016. (Emissions of F-HTFs that are HFCs or PFCs are presented in Table 4-94 and Table 4-95. Emissions of F-HTFs that are not HFCs or PFCs are presented in Table 4-95, Table 4-96, and Table 4-97 but are not included in Inventory totals.) The rapid growth of this industry and the increasing complexity (growing number of layers)[63] of semiconductor products led to an increase in emissions of 153 percent between 1990 and 1999, when emissions peaked at 9.1 MMTCO_2 Eq. Emissions began to decline after 1999, reaching a low point in 2009 before rebounding slightly and plateauing at the current level, which represents a 46 percent decline from 1999 levels. Together, industrial growth, adoption of emissions reduction technologies (including but not limited to abatement technologies), and shifts in gas usages resulted in a net increase in emissions of 38 percent between 1990 and 2016.

Total emissions from semiconductor manufacture in 2016 were similar to 2015 emissions, increasing less than 1 percent.

Only F-HTF emissions that consist of HFCs or PFCs are included in the Inventory totals; emissions of other F-HTFs, which account for the vast majority of F-HTF emissions, are provided for informational purposes and are not

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[62] The GWP of PFPMIE, a perfluoropolyether used as an F-HTF, is included in the *IPCC Fourth Assessment Report* with a value of 10,300. The GWPs of the perfluorinated amines and perfluoroalkylmorpholines that are used as F-HTFs have not been evaluated in the peer-reviewed literature. However, evaluations by the manufacturer indicate that their GWPs are near 10,000 (78 FR 20632), which is expected given that these compounds are both saturated and fully fluorinated. EPA assigns a default GWP of 10,000 to compounds that are both saturated and fully fluorinated and that do not have chemical-specific GWPs in either the Fourth or the Fifth Assessment Reports.

[63] Complexity is a term denoting the circuit required to connect the active circuit elements (transistors) on a chip. Increasing miniaturization, for the same chip size, leads to increasing transistor density, which, in turn, requires more complex interconnections between those transistors. This increasing complexity is manifested by increasing the levels (i.e., layers) of wiring, with each wiring layer requiring fluorinated gas usage for its manufacture.

included in the Inventory totals. Since reporting of F-HTF emissions began under EPA's GHGRP in 2011, F-HTF emissions (reported and estimated non-reported) have fluctuated between 0.7 MMT CO_2 Eq. and 1.0 MMT CO_2 Eq., with an overall declining trend. An analysis of the data reported to EPA's GHGRP indicates that F-HTF emissions account for anywhere between 12 percent and 18 percent of total annual emissions (F-GHG, N_2O and F-HTFs) from semiconductor manufacturing.[64] Table 4-97 shows the emissions of the F-HTF compounds with the highest emissions in tons based on reporting to EPA's GHGRP during years 2011 through 2016.

Table 4-94: PFC, HFC, SF_6, NF_3, and N_2O Emissions from Semiconductor Manufacture[65] (MMT CO_2 Eq.)

Year	1990	2005	2012	2013	2014	2015	2016
CF_4	0.8	1.1	1.2	1.2	1.5	1.5	1.5
C_2F_6	2.0	2.0	1.5	1.4	1.4	1.4	1.2
C_3F_8	+	0.1	0.1	0.1	0.1	0.1	0.1
C_4F_8	0.0	0.1	0.1	0.1	0.1	0.1	0.1
HFC-23	0.2	0.2	0.2	0.2	0.3	0.3	0.3
SF_6	0.5	0.7	0.3	0.4	0.7	0.7	0.8
NF_3	+	0.5	0.6	0.6	0.5	0.6	0.6
Total F-GHGs	**3.6**	**4.6**	**4.2**	**3.9**	**4.6**	**4.7**	**4.7**
N_2O	+	0.1	0.2	0.2	0.2	0.2	0.2
HFC and PFC F-HTFs	0.0	+	+	+	+	+	+
Total	**3.6**	**4.7**	**4.4**	**4.0**	**4.9**	**4.9**	**5.0**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table 4-95: PFC, HFC, SF_6, NF_3, and N_2O Emissions from Semiconductor Manufacture (kt)

Year	1990	2005	2012	2013	2014	2015	2016
CF_4	0.11	0.15	0.17	0.16	0.20	0.21	0.21
C_2F_6	0.16	0.16	0.13	0.12	0.11	0.11	0.10
C_3F_8	+	+	+	+	+	+	+
C_4F_8	0.0	+	+	+	+	+	+
HFC-23	+	+	+	+	+	+	+
SF_6	+	+	+	+	+	+	+
NF_3	+	+	+	+	+	+	+
N_2O	0.12	0.41	0.67	0.62	0.73	0.78	0.79
HFC and PFC F-HTFs	0.00	+	+	+	+	+	+
Total	**0.43**	**0.81**	**1.05**	**0.97**	**1.15**	**1.21**	**1.21**

+ Does not exceed 0.05 kt.

Table 4-96: F-HTF Emissions Based on GHGRP Reporting (MMT CO_2 Eq.)

Year	2011	2012	2013	2014	2015	2016
HFCs	0.001	0.001	0.001	0.001	0.002	0.002
PFCs	0.008	0.010	0.004	0.002	0.002	0.002
Other F-HTFs	0.984	0.945	0.668	0.797	0.763	0.651

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[64] Emissions data for HTFs (in tons of gas) from the semiconductor industry from 2011 through 2015 were obtained from the EPA GHGRP annual facility emissions reports.

[65] An extremely small portion of emissions from Semiconductor Manufacture are from the manufacturing of MEMs and photovoltaic cells.

Total F-HTFs	**0.992**	**0.956**	**0.673**	**0.800**	**0.766**	**0.655**

Table 4-97: F-HTF Compounds with Largest Emissions Based on GHGRP Reporting (tons)

		GHGRP-Reported Emissions (tons)					
Fluorinated Heat Transfer Fluid	**GWP**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**
Perfluorotripropylamine (3M™ Fluorinert™ FC-3283/FC-8270)	10,000	27.14	38.46	24.95	45.31	37.95	35.76
Perfluoroisopropylmorpholine (3M™ Fluorinert™ FC-770)	10,000	12.27	10.07	10.12	11.82	7.94	7.41
3-ethoxy-1,1,1,2,3,4,4,5,5,6,6,6-dodecafluoro-2-trifluoromethyl-hexane (3M™ HFE-7500)	270	8.55	7.20	14.18	9.79	9.64	6.35
HFE-569sf2, (3M™ HFE-7200)	59	8.17	10.53	6.73	9.32	5.46	3.88
PFPMIE fraction, BP 200 °C (Solvay Galden™ HT-200)	10,000	6.15	6.45	10.10	3.03	7.14	7.08
Perfluorotributylamine (PTBA, 3M™ Fluorinert™ FC40/FC-43)	10,000	11.85	4.61	3.45	2.09	7.50	1.99
HFE-449s1 (3M™ HFE-7100)	297	10.63	2.94	5.46	1.79	2.54	1.35
PFPMIE fraction, BP 165 °C (Solvay Galden™ DO2-TS)	10,000	2.61	2.45	4.89	4.00	3.35	2.58
PFPMIE fraction, BP 170 °C (Solvay Galden™ HT-170)	10,000	3.37	6.93	0.57	0.90	3.59	2.22
PFPMIE fraction, BP 110 °C (Solvay Galden™ HT-110)	10,000	1.90	1.53	0.87	3.08	1.11	1.43

Additional Emissions from MEMS and PV

Similar to semiconductor manufacturing, the manufacturing of micro-electro-mechanical devices (MEMs) and photovoltaic cells requires the use of multiple long-lived fluorinated GHGs for various processes. GHGRP-reported emissions from the manufacturing of MEMs and photovoltaic cells are available for the years 2011 to 2016. They are not included in the semiconductor manufacturing totals reported above. The emissions reported by facilities manufacturing MEMs included emissions of C_2F_6, C_3F_8, C_4F_8, CF_4, HFC-23, NF_3, and SF_6, and were equivalent to only 0.10 percent to 0.42 percent of the total reported emissions from semiconductor manufacturing in 2011 to 2016. These emissions ranged from 0.0045 to 0.0185 MMT CO_2 Eq. from 2011 to 2016. Similarly, emissions from manufacturing of photovoltaic cells were equivalent to only 0.23 percent and 0.15 percent of the total reported emissions from semiconductor manufacturing in 2015 and 2016 respectively. Reported emissions from photovoltaic cell manufacturing consisted of CF_4, C_2F_6, C_4F_8, and CHF_3.

Based upon information in the World Fab Forecast (WFF), it appears that some GHGRP reporters that manufacture both semiconductors and MEMS are only reporting semiconductor emissions.

Methodology

Emissions are based on data reported through Subpart I, Electronics Manufacture, of EPA's GHGRP, Partner reported emissions data received through EPA's PFC[66] Reduction/Climate Partnership, EPA's PFC Emissions Vintage Model (PEVM)—a model that estimates industry emissions from etching and chamber cleaning processes in the absence of emission control strategies (Burton and Beizaie 2001),[67] and estimates of industry activity (i.e., total manufactured layer area). The availability and applicability of reported emissions data from the EPA Partnership and EPA's GHGRP and activity data differ across the 1990 through 2016 time series. Consequently,

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[66] In the context of the EPA Partnership and PEVM, PFC refers to perfluorocompounds, not perfluorocarbons.

[67] A Partner refers to a participant in the U.S. EPA PFC Reduction/Climate Partnership for the Semiconductor Industry. Through a Memorandum of Understanding (MoU) with the EPA, Partners voluntarily reported their PFC emissions to the EPA by way of a third party, which aggregated the emissions through 2010.

fluorinated greenhouse gas (F-GHG) emissions from etching and chamber cleaning processes were estimated using seven distinct methods, one each for the periods 1990 through 1994, 1995 through 1999, 2000 through 2006, 2007 through 2010, 2011 and 2012, 2013 and 2014, and 2015 and 2016. Nitrous oxide emissions were estimated using five distinct methods, one each for the period 1990 through 1994, 1995 through 2010, 2011 and 2012, 2013 and 2014, and 2015 and 2016.

Facility emissions of F-HTFs from semiconductor manufacturing are reported to EPA under its GHGRP, and are available for the years 2011 through 2016. EPA estimates the emissions of F-HTFs from non-reporting facilities by calculating the ratio of GHGRP-reported fluorinated HTF emissions to GHGRP reported F-GHG emissions from etching and chamber cleaning processes, and then multiplying this ratio by the F-GHG emissions from etching and chamber cleaning processes estimated for non-reporting facilities. Fluorinated HTF use in semiconductor manufacturing is assumed to have begun in the early 2000s and to have gradually displaced other HTFs (e.g., de-ionized water and glycol) in electronics manufacturing (EPA 2006). For time-series consistency, EPA interpolated the share of F-HTF emissions to F-GHG emissions between 2000 (at 0 percent) and 2011 (at 22 percent) and applied these shares to the unadjusted F-GHG emissions during those years to estimate the fluorinated HTF emissions.

1990 through 1994

From 1990 through 1994, Partnership data were unavailable and emissions were modeled using PEVM (Burton and Beizaie 2001).[68] The 1990 to 1994 emissions are assumed to be uncontrolled, since reduction strategies such as chemical substitution and abatement were yet to be developed.

PEVM is based on the recognition that fluorinated greenhouse gas emissions from semiconductor manufacturing vary with: (1) the number of layers that comprise different kinds of semiconductor devices, including both silicon wafer and metal interconnect layers, and (2) silicon consumption (i.e., the area of semiconductors produced) for each kind of device. The product of these two quantities, Total Manufactured Layer Area (TMLA), constitutes the activity data for semiconductor manufacturing. PEVM also incorporates an emission factor that expresses emissions per unit of manufactured layer-area. Emissions are estimated by multiplying TMLA by this emission factor.

PEVM incorporates information on the two attributes of semiconductor devices that affect the number of layers: (1) linewidth technology (the smallest manufactured feature size),[69] and (2) product type (discrete, memory or logic).[70] For each linewidth technology, a weighted average number of layers is estimated using VLSI product-specific worldwide silicon demand data in conjunction with complexity factors (i.e., the number of layers per Integrated Circuit (IC) specific to product type (Burton and Beizaie 2001; ITRS 2007). PEVM derives historical consumption of silicon (i.e., square inches) by linewidth technology from published data on annual wafer starts and average wafer size (VLSI Research, Inc. 2012).

The emission factor in PEVM is the average of four historical emission factors, each derived by dividing the total annual emissions reported by the Partners for each of the four years between 1996 and 1999 by the total TMLA estimated for the Partners in each of those years. Over this period, the emission factors varied relatively little (i.e., the relative standard deviation for the average was 5 percent). Since Partners are believed not to have applied significant emission reduction measures before 2000, the resulting average emission factor reflects uncontrolled

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[68] Various versions of the PEVM exist to reflect changing industrial practices. From 1990 to 1994 emissions estimates are from PEVM v1.0, completed in September 1998. The emission factor used to estimate 1990 to 1994 emissions is an average of the 1995 and 1996 emissions factors, which were derived from Partner reported data for those years.

[69] By decreasing features of Integrated Circuit components, more components can be manufactured per device, which increases its functionality. However, as those individual components shrink it requires more layers to interconnect them to achieve the functionality. For example, a microprocessor manufactured with 65 nm feature sizes might contain as many as 1 billion transistors and require as many as 11 layers of component interconnects to achieve functionality, while a device manufactured with 130 nm feature size might contain a few hundred million transistors and require 8 layers of component interconnects (ITRS 2007).

[70] Memory devices manufactured with the same feature sizes as microprocessors (a logic device) require approximately one-half the number of interconnect layers, whereas discrete devices require only a silicon base layer and no interconnect layers (ITRS 2007). Since discrete devices did not start using PFCs appreciably until 2004, they are only accounted for in the PEVM emissions estimates from 2004 onwards.

emissions. The emission factor is used to estimate world uncontrolled emissions using publicly-available data on world silicon consumption.

As it was assumed for this time period that there was no consequential adoption of fluorinated-gas-reducing measures, a fixed distribution of fluorinated-gas use was assumed to apply to the entire U.S. industry to estimate gas-specific emissions. This distribution was based upon the average fluorinated-gas purchases made by semiconductor manufacturers during this period and the application of IPCC default emission factors for each gas (Burton and Beizaie 2001).

To estimate N_2O emissions, it is assumed the proportion of N_2O emissions estimated for 1995 (discussed below) remained constant for the period of 1990 through 1994.

1995 through 1999

For 1995 through 1999, total U.S. emissions were extrapolated from the total annual emissions reported by the Partners (1995 through 1999). Partner-reported emissions are considered more representative (e.g., in terms of capacity utilization in a given year) than PEVM-estimated emissions, and are used to generate total U.S. emissions when applicable. The emissions reported by the Partners were divided by the ratio of the total capacity of the plants operated by the Partners and the total capacity of all of the semiconductor plants in the United States; this ratio represents the share of capacity attributable to the Partnership. This method assumes that Partners and non-Partners have identical capacity utilizations and distributions of manufacturing technologies. Plant capacity data is contained in the World Fab Forecast (WFF) database and its predecessors, which is updated quarterly. Gas-specific emissions were estimated using the same method as for 1990 through 1994.

For this time period, the N_2O emissions were estimated using an emission factor that was applied to the annual, total U.S. TMLA manufactured. The emission factor was developed using a regression-through-the-origin (RTO) model: GHGRP reported N_2O emissions were regressed against the corresponding TMLA of facilities that reported no use of abatement systems. Details on EPA's GHGRP reported emissions and development of emission factor using the RTO model are presented in the 2011 through 2012 section. The total U.S. TMLA was estimated using PEVM.

2000 through 2006

Emissions for the years 2000 through 2006—the period during which Partners began the consequential application of fluorinated greenhouse gas-reduction measures—were estimated using a combination of Partner-reported emissions and adjusted PEVM modeled emissions. The emissions reported by Partners for each year were accepted as the quantity emitted from the share of the industry represented by those Partners. Remaining emissions, those from non-Partners, were estimated using PEVM, with one change. To ensure time-series consistency and to reflect the increasing use of remote clean technology (which increases the efficiency of the production process while lowering emissions of fluorinated greenhouse gases), the average non-Partner emission factor (PEVM emission factor) was assumed to begin declining gradually during this period. Specifically, the non-Partner emission factor for each year was determined by linear interpolation, using the end points of 1999 (the original PEVM emission factor) and 2011 (a new emission factor determined for the non-Partner population based on GHGRP-reported data, described below).

The portion of the U.S. total emissions attributed to non-Partners is obtained by multiplying PEVM's total U.S. emissions figure by the non-Partner share of U.S. total silicon capacity for each year as described above.[71] Gas-specific emissions from non-Partners were estimated using linear interpolation of gas-specific emission distribution of 1999 (assumed same as total U.S. Industry in 1994) and 2011 (calculated from a subset of non-Partner facilities from GHGRP reported emissions data). Annual updates to PEVM reflect published figures for actual silicon consumption from VLSI Research, Inc., revisions and additions to the world population of semiconductor

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[71] This approach assumes that the distribution of linewidth technologies is the same between Partners and non-Partners. As discussed in the description of the method used to estimate 2007 emissions, this is not always the case.

manufacturing plants, and changes in IC fabrication practices within the semiconductor industry (see ITRS 2008 and Semiconductor Equipment and Materials Industry 2011).[72,73,74]

Nitrous oxide emissions were estimated using the same methodology as the 1995 through 1999 methodology.

2007 through 2010

For the years 2007 through 2010, emissions were also estimated using a combination of Partner reported emissions and adjusted PEVM modeled emissions to provide estimates for non-Partners; however, two improvements were made to the estimation method employed for the previous years in the time series. First, the 2007 through 2010 emission estimates account for the fact that Partners and non-Partners employ different distributions of manufacturing technologies, with the Partners using manufacturing technologies with greater transistor densities and therefore greater numbers of layers.[75] Second, the scope of the 2007 through 2010 estimates was expanded relative to the estimates for the years 2000 through 2006 to include emissions from research and development (R&D) fabs. This additional enhancement was feasible through the use of more detailed data published in the WFF. PEVM databases were updated annually as described above. The published world average capacity utilization for 2007 through 2010 was used for production fabs, while for R&D fabs a 20 percent figure was assumed (SIA 2009).

In addition, publicly-available actual utilization data was used to account for differences in fab utilization for manufacturers of discrete and IC products for 2010 emissions for non-Partners. The Semiconductor Capacity Utilization (SICAS) Reports from SIA provides the global semiconductor industry capacity and utilization, differentiated by discrete and IC products (SIA, 2009 through 2011). PEVM estimates were adjusted using technology-weighted capacity shares that reflect the relative influence of different utilization. Gas-specific emissions for non-Partners were estimated using the same method as for 2000 through 2006.

Nitrous oxide emissions were estimated using the same methodology as the 1995 through 1999 methodology.

2011 through 2012

The fifth method for estimating emissions from semiconductor manufacturing covers the period 2011 through 2012. This methodology differs from previous years because the EPA's Partnership with the semiconductor industry ended

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[72] Special attention was given to the manufacturing capacity of plants that use wafers with 300 mm diameters because the actual capacity of these plants is ramped up to design capacity, typically over a 2–3 year period. To prevent overstating estimates of partner-capacity shares from plants using 300 mm wafers, *design* capacities contained in WFF were replaced with estimates of *actual installed* capacities for 2004 published by Citigroup Smith Barney (2005). Without this correction, the partner share of capacity would be overstated, by approximately 5 percent. For perspective, approximately 95 percent of all new capacity additions in 2004 used 300 mm wafers, and by year-end those plants, on average, could operate at approximately 70 percent of the design capacity. For 2005, actual installed capacities were estimated using an entry in the World Fab Watch database (April 2006 Edition) called "wafers/month, 8-inch equivalent," which denoted the actual installed capacity instead of the fully-ramped capacity. For 2006, actual installed capacities of new fabs were estimated using an average monthly ramp rate of 1100 wafer starts per month (wspm) derived from various sources such as semiconductor fabtech, industry analysts, and articles in the trade press. The monthly ramp rate was applied from the first-quarter of silicon volume (FQSV) to determine the average design capacity over the 2006 period.

[73] In 2006, the industry trend in co-ownership of manufacturing facilities continued. Several manufacturers, who are Partners, now operate fabs with other manufacturers, who in some cases are also Partners and in other cases are not Partners. Special attention was given to this occurrence when estimating the Partner and non-Partner shares of U.S. manufacturing capacity.

[74] Two versions of PEVM are used to model non-Partner emissions during this period. For the years 2000 to 2003 PEVM v3.2.0506.0507 was used to estimate non-Partner emissions. During this time, discrete devices did not use PFCs during manufacturing and therefore only memory and logic devices were modeled in the PEVM v3.2.0506.0507. From 2004 onwards, discrete device fabrication started to use PFCs, hence PEVM v4.0.0701.0701, the first version of PEVM to account for PFC emissions from discrete devices, was used to estimate non-Partner emissions for this time period.

[75] EPA considered applying this change to years before 2007, but found that it would be difficult due to the large amount of data (i.e., technology-specific global and non-Partner TMLA) that would have to be examined and manipulated for each year. This effort did not appear to be justified given the relatively small impact of the improvement on the total estimate for 2007 and the fact that the impact of the improvement would likely be lower for earlier years because the estimated share of emissions accounted for by non-Partners is growing as Partners continue to implement emission-reduction efforts.

(in 2010) and reporting under EPA's GHGRP began. Manufacturers whose estimated uncontrolled emissions equal or exceed 25,000 MT CO_2 Eq. per year (based on default F-GHG-specific emission factors and total capacity in terms of substrate area) are required to report their emissions to EPA. This population of reporters to EPA's GHGRP included both historical Partners of EPA's PFC Reduction/Climate Partnership as well as non-Partners some of which use GaAs technology in addition to Si technology.[76] Emissions from the population of manufacturers that were below the reporting threshold were also estimated for this time period using EPA-developed emission factors and estimates of facility-specific production obtained from WFF. Inventory totals reflect the emissions from both reporting and non-reporting populations.

Under EPA's GHGRP, semiconductor manufacturing facilities report emissions of F-GHGs used in etch and clean processes as well as emissions of fluorinated heat transfer fluids. (Fluorinated heat transfer fluids are used to control process temperatures, thermally test devices, and clean substrate surfaces, among other applications.) They also report N_2O emissions from CVD and other processes. The F-GHGs and N_2O were aggregated, by gas, across all semiconductor manufacturing GHGRP reporters to calculate gas-specific emissions for the GHGRP-reporting segment of the U.S. industry. At this time, emissions that result from heat transfer fluid use that are PFCs and HFCs are included in the total emission estimates from semiconductor manufacturing, and these GHGRP-reported emissions have been compiled and presented in Table 4-94. F-HTF emissions resulting from other types of gases (e.g., HFEs) are not presented in semiconductor manufacturing totals in Table 4-94 and Table 4-95 but are shown in Table 4-96 and Table 4-97 for informational purposes.

For the segment of the semiconductor industry that is below EPA's GHGRP reporting threshold, and for R&D facilities, which are not covered by EPA's GHGRP, emission estimates are based on EPA-developed emission factors for the F-GHGs and N_2O and estimates of manufacturing activity. The new emission factors (in units of mass of CO_2 Eq./TMLA [MSI]) are based on the emissions reported under EPA's GHGRP by facilities without abatement and on the TMLA estimates for these facilities based on the WFF (SEMI 2012; SEMI 2013).[77] In a refinement of the method used to estimate emissions for the non-Partner population for prior years, different emission factors were developed for different subpopulations of fabs, disaggregated by wafer size (200 mm or less and 300 mm). For each of these groups, a subpopulation-specific emission factor was obtained using a regression-through-the-origin (RTO) model: facility-reported aggregate emissions of seven F-GHGs (CF_4, C_2F_6, C_3F_8, C_4F_8, CHF_3, SF_6 and NF_3)[78] were regressed against the corresponding TMLA to estimate an aggregate F-GHG emissions factor (CO_2 Eq./MSI TMLA), and facility-reported N_2O emissions were regressed against the corresponding TMLA to estimate a N_2O emissions factor (CO_2 Eq./MSI TMLA). For each subpopulation, the slope of the RTO model is the emission factor for that subpopulation. Information on the use of point-of-use abatement by non-reporting fabs was not available; thus, EPA conservatively assumed that non-reporting facilities did not use point-of-use abatement.

For 2011 and 2012, estimates of TMLA relied on the capacity utilization of the fabs published by the U.S. Census Bureau's Historical Data Quarterly Survey of Plant Capacity Utilization (USCB 2011, 2012). Similar to the assumption for 2007 through 2010, facilities with only R&D activities were assumed to utilize only 20 percent of their manufacturing capacity. All other facilities in the United States are assumed to utilize the average percent of the manufacturing capacity without distinguishing whether fabs produce discrete products or logic products.

Non-reporting fabs were then broken out into similar subpopulations by wafer size using information available through the WFF. The appropriate emission factor was applied to the total TMLA of each subpopulation of non-reporting facilities to estimate the GWP-weighted emissions of that subpopulation.

Gas-specific, GWP-weighted emissions for each subpopulation of non-reporting facilities were estimated using the corresponding reported distribution of gas-specific, GWP-weighted emissions from which the aggregate emission factors, based on GHGRP-reported data, were developed. Estimated in this manner, the non-reporting population accounted for 4.9 and 5.0 percent of U.S. emissions in 2011 and 2012, respectively. The GHGRP-reported emissions

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[76] GaAs and Si technologies refer to the wafer on which devices are manufactured, which use the same PFCs but in different ways.

[77] EPA does not have information on fab-wide DREs for this time period, so it is not possible to estimate uncontrolled emissions from fabs that reported POU abatement. These fabs were therefore excluded from the regression analysis. (They are still included in the national totals.)

[78] Only seven gases were aggregated because inclusion of F-GHGs that are not reported in the Inventory results in overestimation of emission factor that is applied to the various non-reporting subpopulations.

and the calculated non-reporting population emissions are summed to estimate the total emissions from semiconductor manufacturing.

2013 and 2014

For 2013 and 2014, as for 2011 and 2012, F-GHG and N_2O emissions data received through EPA's GHGRP were aggregated, by gas, across all semiconductor-manufacturing GHGRP reporters to calculate gas-specific emissions for the GHGRP-reporting segment of the U.S. industry. However, for these years WFF data was not available. Therefore, an updated methodology that does not depend on the WFF derived activity data was used to estimate emissions for the segment of the industry that are not covered by EPA's GHGRP. For the facilities that did not report to the GHGRP (i.e., which are below EPA's GHGRP reporting threshold or are R&D facilities), emissions were estimated based on the proportion of total U.S. emissions attributed to non-reporters for 2011 and 2012. EPA used a simple averaging method by first estimating this proportion for both F-GHGs and N_2O for 2011, 2012, and 2015 and 2016, resulting in one set of proportions for F-GHGs and one set for N_2O, and then applied the average of each set to the 2013 and 2014 GHGRP reported emissions to estimate the non-reporters' emissions. Fluorinated gas-specific, GWP-weighted emissions for non-reporters were estimated using the corresponding reported distribution of gas-specific, GWP-weighted emissions reported through EPA's GHGRP for 2013 and 2014.

2015 through 2016

Similar to the methods described above for 2011 and 2012, and 2013 and 2014, EPA relied upon emissions data reported directly through the GHGRP. For 2015 and 2016, EPA took an approach similar to the one used for 2011 and 2012 to estimate emissions for the segment of the semiconductor industry that is below EPA's GHGRP reporting threshold, and for R&D facilities, which are not covered by EPA's GHGRP. However, in a change from previous years, EPA was able to develop new annual emission factors for 2015 and 2016 using TMLA from WFF and a more comprehensive set of emissions, i.e., fabs with as well as without abatement control, as new information about the use of abatement in GHGRP fabs and fab-wide destruction and removal efficiencies (DREs) were available. Fab-wide (DREs) represent total fab CO_2 Eq.-weighted controlled F-GHG and N_2O emissions (emissions after the use of abatement) divided by total fab CO_2 Eq.-weighted uncontrolled F-GHG and N_2O emissions (emission prior to the use of abatement).

Using information about reported emissions and the use of abatement and fab-wide DREs, EPA was able to calculated uncontrolled emissions (each total F-GHG and N_2O) for every GHGRP reporting fab. Using this, coupled with TMLA estimated using methods described above (see 2011 through 2012), EPA derived emission factors by year, gas type (F-GHG or N_2O), and wafer size (200 mm or 300 mm) by dividing the total annual emissions reported by GHGRP reporters by the total TMLA estimated for those reporters. These emission factors were multiplied by estimates of non-reporter TMLA to arrive at estimates of total F-GHG and N_2O emissions for non-reporters for each year. For each wafer size, the total F-GHG emissions were disaggregated into individual gases using the shares of total emissions represented by those gases in the emissions reported to the GHGRP by unabated fabs producing that wafer size.

Data Sources

GHGRP reporters, which consist of former EPA Partners and non-Partners, estimated their emissions using a default emission factor method established by EPA. Like the Tier 2b Method in the *2006 IPCC Guidelines*, this method uses different emission and byproduct generation factors for different F-GHGs and process types, but it goes beyond the Tier 2b Method by requiring use of updated factors for different wafer sizes (i.e., 300mm vs. 150 and 200mm) and CVD clean subtypes (in situ thermal, in situ thermal, and remote plasma). Starting with 2014 reported emissions, EPA's GHGRP required semiconductor manufacturers to apply updated emission factors to estimate their F-GHG emissions (40 CFR Part 98). For the years 2011 through 2013 reported emissions, semiconductor manufacturers used older emission factors to estimate their F-GHG Emissions (Federal Register / Vol. 75, No. 230 /December 1, 2010, 74829). Subpart I emission factors were updated for 2014 by EPA as a result of a larger set of emission factor data becoming available as part of the Subpart I petition process, which took place from 2011 through 2013.

Historically, partners estimated and reported their emissions using a range of methods and uneven documentation. It is assumed that most Partners used a method at least as accurate as the IPCC's Tier 2a Methodology, recommended in the *2006 IPCC Guidelines*. Partners are estimated to have accounted for between 56 and 79 percent of F-GHG emissions from U.S. semiconductor manufacturing between 1995 and 2010, with the percentage declining in recent years as Partners increasingly implemented abatement measures.

Estimates of operating plant capacities and characteristics for Partners and non-Partners were derived from the Semiconductor Equipment and Materials Industry (SEMI) WFF (formerly World Fab Watch) database (1996 through 2012 and 2015) (e.g., Semiconductor Materials and Equipment Industry, 2017). Actual worldwide capacity utilizations for 2008 through 2010 were obtained from Semiconductor International Capacity Statistics (SICAS) (SIA 2009 through 2011). Estimates of the number of layers for each linewidth was obtained from International Technology Roadmap for Semiconductors: 2013 Edition (Burton and Beizaie 2001; ITRS 2007; ITRS 2008; ITRS 2011; ITRS 2013). PEVM utilized the WFF, SICAS, and ITRS, as well as historical silicon consumption estimates published by VLSI. Actual quarterly U.S. capacity utilizations for 2011, 2012 and 2015 were obtained from the U.S. Census Bureau's Historical Data Quarterly Survey of Plant Capacity Utilization (USCB 2011, 2012, 2015, and 2016).

Uncertainty and Time-Series Consistency

A quantitative uncertainty analysis of this source category was performed using the IPCC-recommended Approach 2 uncertainty estimation methodology, the Monte Carlo Stochastic Simulation technique. The equation used to estimate uncertainty is:

$$\text{Total Emissions } (E_T) = \text{GHGRP Reported F-GHG Emissions } (E_{R,F\text{-}GHG}) + \text{Non-Reporters' Estimated F-GHG Emissions } (E_{NR,F\text{-}GHG}) + \text{GHGRP Reported } N_2O \text{ Emissions } (E_{R,N_2O}) + \text{Non-Reporters' Estimated } N_2O \text{ Emissions } (E_{NR,N_2O})$$

where E_R and E_{NR} denote totals for the indicated subcategories of emissions for F-GHG and N_2O, respectively.

The uncertainty in E_T presented in Table-4-98 below results from the convolution of four distributions of emissions, each reflecting separate estimates of possible values of $E_{R,F\text{-}GHG}$, E_{R,N_2O}, $E_{NR,F\text{-}GHG}$, and E_{NR,N_2O}. The approach and methods for estimating each distribution and combining them to arrive at the reported 95 percent confidence interval (CI) are described in the remainder of this section.

The uncertainty estimate of $E_{R,\ F\text{-}GHG}$, or GHGRP-reported F-GHG emissions, is developed based on gas-specific uncertainty estimates of emissions for two industry segments, one processing 200 mm wafers and one processing 300 mm wafers. Uncertainties in emissions for each gas and industry segment were developed during the assessment of emission estimation methods for the subpart I GHGRP rulemaking in 2012 (see *Technical Support for Modifications to the Fluorinated Greenhouse Gas Emission Estimation Method Option for Semiconductor Facilities under Subpart* I, docket EPA–HQ–OAR–2011–0028).[79] The 2012 analysis did not take into account the use of abatement. For the industry segment that processed 200 mm wafers, estimates of uncertainties at a 95 percent CI ranged from ±29 percent for C_3F_8 to ±10 percent for CF_4. For the corresponding 300 mm industry segment, estimates of the 95 percent CI ranged from ±36 percent for C_4F_8 to ±16 percent for CF_4. These gas and wafer-specific uncertainty estimates are applied to the total emissions of the facilities that did not abate emissions as reported under EPA's GHGRP.

For those facilities reporting abatement of emissions under EPA's GHGRP, estimates of uncertainties for the no abatement industry segments are modified to reflect the use of full abatement (abatement of *all* gases from *all*

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[79] On November 13, 2013, EPA published a final rule revising subpart I (Electronics Manufacturing) of the GHGRP (78 FR 68162). The revised rule includes updated default emission factors and updated default destruction and removal efficiencies that are slightly different from those that semiconductor manufacturers were required to use to report their 2012 emissions. The uncertainty analyses that were performed during the development of the revised rule focused on these updated defaults, but are expected to be reasonably representative of the uncertainties associated with the older defaults, particularly for estimates at the country level. (They may somewhat underestimate the uncertainties associated with the older defaults at the facility level.) For simplicity, the 2012 estimates are assumed to be unbiased although in some cases, the updated (and therefore more representative) defaults are higher or lower than the older defaults. Multiple models and sensitivity scenarios were run for the subpart I analysis. The uncertainty analysis presented here made use of the Input gas and wafer size model (Model 1) under the following conditions: Year = 2010, f = 20, n = SIA3.

cleaning and etching equipment) and partial abatement. These assumptions used to develop uncertainties for the partial and full abatement facilities are identical for 200 mm and 300 mm wafer processing facilities. For all facilities reporting gas abatement, a triangular distribution of destruction or removal efficiency is assumed for each gas. The triangular distributions range from an asymmetric and highly uncertain distribution of zero percent minimum to 90 percent maximum with 70 percent most likely value for CF_4 to a symmetric and less uncertain distribution of 85 percent minimum to 95 percent maximum with 90 percent most likely value for C_4F_8, NF_3, and SF_6. For facilities reporting partial abatement, the distribution of fraction of the gas fed through the abatement device, for each gas, is assumed to be triangularly distributed as well. It is assumed that no more than 50 percent of the gases are abated (i.e., the maximum value) and that 50 percent is the most likely value and the minimum is zero percent. Consideration of abatement then resulted in four additional industry segments, two 200-mm wafer-processing segments (one fully and one partially abating each gas) and two 300-mm wafer-processing segment (one fully and the other partially abating each gas). Gas-specific emission uncertainties were estimated by convolving the distributions of unabated emissions with the appropriate distribution of abatement efficiency for fully and partially abated facilities using a Monte Carlo simulation.

The uncertainty in $E_{R,F\text{-}GHG}$ is obtained by allocating the estimates of uncertainties to the total GHGRP-reported emissions from each of the six industry segments, and then running a Monte Carlo simulation which results in the 95 percent CI for emissions from GHGRP reporting facilities ($E_{R,F\text{-}GHG}$).

The uncertainty in $E_{R,N2O}$ is obtained by assuming that the uncertainty in the emissions reported by each of the GHGRP reporting facilities results from the uncertainty in quantity of N_2O consumed and the N_2O emission factor (or utilization). Similar to analyses completed for subpart I (see *Technical Support for Modifications to the Fluorinated Greenhouse Gas Emission Estimation Method Option for Semiconductor Facilities* under Subpart I, docket EPA–HQ–OAR–2011–0028), the uncertainty of N_2O consumed was assumed to be 20 percent. Consumption of N_2O for GHGRP reporting facilities was estimated by back-calculating from emissions reported and assuming no abatement. The quantity of N_2O utilized (the complement of the emission factor) was assumed to have a triangular distribution with a minimum value of zero percent, mode of 20 percent and maximum value of 84 percent. The minimum was selected based on physical limitations, the mode was set equivalent to the subpart I default N_2O utilization rate for chemical vapor deposition, and the maximum was set equal to the maximum utilization rate found in ISMI Analysis of Nitrous Oxide Survey Data (ISMI 2009). The inputs were used to simulate emissions for each of the GHGRP reporting, N_2O-emitting facilities. The uncertainty for the total reported N_2O emissions was then estimated by combining the uncertainties of each of the facilities reported emissions using Monte Carlo simulation.

The estimate of uncertainty in $E_{NR,F\text{-}GHG}$ and $E_{NR,N2O}$ entailed developing estimates of uncertainties for the emissions factors and the corresponding estimates of TMLA.

The uncertainty in TMLA depends on the uncertainty of two variables—an estimate of the uncertainty in the average annual capacity utilization for each level of production of fabs (e.g., full scale or R&D production) and a corresponding estimate of the uncertainty in the number of layers manufactured. For both variables, the distributions of capacity utilizations and number of manufactured layers are assumed triangular for all categories of non-reporting fabs. The most probable utilization is assumed to be 82 percent, with the highest and lowest utilization assumed to be 89 percent, and 70 percent, respectively. For the triangular distributions that govern the number of possible layers manufactured, it is assumed the most probable value is one layer less than reported in the ITRS; the smallest number varied by technology generation between one and two layers less than given in the ITRS and largest number of layers corresponded to the figure given in the ITRS.

The uncertainty bounds for the average capacity utilization and the number of layers manufactured are used as inputs in a separate Monte Carlo simulation to estimate the uncertainty around the TMLA of both individual facilities as well as the total non-reporting TMLA of each sub-population.

The uncertainty around the emission factors for non-reporting facilities is dependent on the uncertainty of the total emissions (MMT CO_2 Eq. units) and the TMLA of each reporting facility in that category. For each wafer size for reporting facilities, total emissions were regressed on TMLA (with an intercept forced to zero) for 10,000 emission and 10,000 TMLA values in a Monte Carlo simulation, which results in 10,000 total regression coefficients (emission factors). The 2.5th and the 97.5th percentile of these emission factors are determined and the bounds are assigned as the percent difference from the estimated emission factor.

For simplicity, the results of the Monte Carlo simulations on the bounds of the gas- and wafer size-specific emissions as well as the TMLA and emission factors are assumed to be normally distributed and the uncertainty bounds are assigned at 1.96 standard deviations around the estimated mean. The departures from normality were observed to be small.

The final step in estimating the uncertainty in emissions of non-reporting facilities is convolving the distribution of emission factors with the distribution of TMLA using Monte Carlo simulation.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table-4-98, which is also obtained by convolving—using Monte Carlo simulation—the distributions of emissions for each reporting and non-reporting facility. The emissions estimate for total U.S. F-GHG and N_2O emissions from semiconductor manufacturing were estimated to be between 4.7 and 5.2 MMT CO_2 Eq. at a 95 percent confidence level. This range represents 6 percent below to 6 percent above the 2015 emission estimate of 5.0 MMT CO_2 Eq. This range and the associated percentages apply to the estimate of total emissions rather than those of individual gases. Uncertainties associated with individual gases will be somewhat higher than the aggregate, but were not explicitly modeled.

Table-4-98: Approach 2 Quantitative Uncertainty Estimates for HFC, PFC, SF_6, NF_3 and N_2O Emissions from Semiconductor Manufacture (MMT CO_2 Eq. and Percent)[a]

Source	Gas	2016 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[b] (MMT CO_2 Eq.)		(%)	
			Lower Bound[c]	Upper Bound[c]	Lower Bound	Upper Bound
Semiconductor Manufacture	HFC, PFC, SF_6, NF_3, and N_2O	5.0	4.7	5.2	-6%	6%

[a] This uncertainty analysis does not include quantification of the uncertainty of emissions from heat transfer fluids.

[b] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

[c] Absolute lower and upper bounds were calculated using the corresponding lower and upper bounds in percentages.

It should be noted that the uncertainty analysis for this source category does not quantify the uncertainty of HFC and PFC emissions from the use of heat transfer fluids. While these emissions are now, for the first time, included in the semiconductor manufacturing F-GHG total emissions, they make up a considerably small portion of total emissions from the source category (less than 1 percent). Any uncertainty of these emissions would have minimal impact on the overall uncertainty estimates, and therefore the uncertainties associated for HTF HFC and PFC emissions was not included in this analysis for this Inventory year. In an effort to improve the uncertainty analysis for this source category, HTC and PFC emissions from the use of heat transfer fluids may be added in future inventory years (see Planned Improvements section below). The emissions reported under EPA's GHGRP for 2014, 2015, and 2016, which are included in the overall emissions estimates, were based on an updated set of default emission factors. This may have affected the trend seen between 2013 and 2014 (a 24-percent increase), which reversed the trend seen between 2011 and 2013. As discussed in the Planned Improvements section, EPA is planning to conduct analysis to determine how much of the 2013 to 2014 trend may be attributable to the updated factors and to improve time-series consistency.

For more information on the general QA/QC process applied to this source category, consistent with Volume 1, Chapter 6 of the *2006 IPCC Guidelines*, see the QA/QC and Verification Procedures section in the introduction of the IPPU chapter.

Recalculations Discussion

Emissions from 2011 through 2015 were updated to reflect updated emissions reporting in EPA's GHGRP, relative to the previous Inventory. Additionally, for 2011, 2012, and 2015, a new set of emission factors were used to estimate emissions for non-GHGRP reporters, based on wafer size and gas type as opposed to substrate (i.e., silicon or GaAS) or production (e.g., R&D) type.

Planned Improvements

Changes to the default emission factors and default destruction or removal efficiencies used for GHGRP reporting affected the emissions trend between 2013 and 2014. These changes did not reflect actual emission rate changes but data improvements. EPA plans to analyze the impact of the changes and, if possible, adjust the time series before 2014 to ensure time-series consistency. EPA plans to analyze this time-series consistency issue within the GHGRP time series (2011 through 2016) and between the EPA Partnership and GHGRP as different emission factors and destruction or removal efficiencies are represented.

This Inventory contains emissions estimates for N_2O and for seven fluorinated gases emitted from etching and chamber cleaning processes. However, other fluorinated gases (e.g., C_5F_8) are also emitted from etching and chamber cleaning processes in much smaller amounts, accounting for less than 0.02 percent of emissions from these processes. Previously, emissions data for these other fluorinated gases was not reported through the EPA Partnership. However, through EPA's GHGRP, these data are available. Therefore, a point of consideration for future Inventory reports is the inclusion of other fluorinated gases from etching and chamber cleaning processes.

In addition, EPA's GHGRP requires the reporting of emissions from other types of electronics manufacturing, including MEMs, flat panel displays, and photovoltaic cells. There currently are seven MEMs manufacturers (most of which report emissions for semiconductor and MEMs manufacturing separately), one photovoltaic cell manufacturer, and no flat panel displays manufacturing facilities reporting to EPA's GHGRP. [80] Emissions from MEMs and photovoltaic cell manufacturing could be included in totals in future Inventory reports–currently they are not represented in Inventory emissions totals for electronics manufacturing. These emissions could be estimated for the full time series (including prior to the GHGRP) and for MEMS and photovoltaic cell manufacturers that are not reporting to the GHGRP; however, at this time the contribution to total emissions is not significant enough to warrant the development of the methodologies that would be necessary to back-cast these emissions to 1990 and estimate emissions for non-reporters for 2011 through 2016.

The Inventory methodology uses data reported through the EPA Partnership (for earlier years) and EPA's GHGRP (for later years) to extrapolate the emissions of the non-reporting population. While these techniques are well developed, the understanding of the relationship between the reporting and non-reporting populations is limited. Further analysis of the reporting and non-reporting populations could aid in the accuracy of the non-reporting population extrapolation in future years. In addition, the accuracy of the emissions estimates for the non-reporting population could be further increased through EPA's further investigation of and improvement upon the accuracy of estimated activity in the form of TMLA.

The Inventory uses utilization from two different sources for various time periods–SEMI to develop PEVM and to estimate non-Partner emissions for the period 1995 to 2010 and U.S. Census Bureau for 2011 through 2014. SEMI reported global capacity utilization for manufacturers through 2011. U.S. Census Bureau capacity utilization include U.S. semiconductor manufacturers as well as assemblers. Further analysis on the impacts of using a new and different source of utilization data could prove to be useful in better understanding of industry trends and impacts of utilization data sources on historical emission estimates.

The current Inventory now includes HFC and PFC emissions resulting the use of heat transfer fluids in the total estimates of F-GHG emissions from semiconductor manufacturing. A point of consideration for future Inventory reports is the inclusion of the uncertainty surrounding these emissions in the source category uncertainty analysis (see also uncertainty and time-series consistency).

4.24 Substitution of Ozone Depleting Substances (CRF Source Category 2F)

Hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs) are used as alternatives to several classes of ozone-depleting substances (ODSs) that are being phased out under the terms of the *Montreal Protocol* and the Clean Air

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[80] Based upon information in the WFF, it appears that a small portion of GHGRP semiconductor reporters are manufacturing both semiconductors and MEMS; however, these reporters are only reporting semiconductor emissions.

Act Amendments of 1990.[81] Ozone depleting substances—chlorofluorocarbons (CFCs), halons, carbon tetrachloride, methyl chloroform, and hydrochlorofluorocarbons (HCFCs)—are used in a variety of industrial applications including refrigeration and air conditioning equipment, solvent cleaning, foam production, sterilization, fire extinguishing, and aerosols. Although HFCs and PFCs are not harmful to the stratospheric ozone layer, they are potent greenhouse gases. Emission estimates for HFCs and PFCs used as substitutes for ODSs are provided in Table 4-99 and Table 4-100.[82]

Table 4-99: Emissions of HFCs and PFCs from ODS Substitutes (MMT CO_2 Eq.)

Gas	1990	2005	2012	2013	2014	2015	2016
HFC-23	0.0	+	+	+	+	+	+
HFC-32	0.0	0.3	2.9	3.5	4.2	4.9	5.6
HFC-125	+	9.4	35.8	40.0	44.3	48.4	52.3
HFC-134a	+	75.8	70.8	65.7	63.6	61.7	58.3
HFC-143a	+	9.4	24.4	26.0	27.3	28.1	28.8
HFC-236fa	0.0	1.2	1.5	1.5	1.4	1.3	1.2
CF_4	0.0	+	+	+	+	+	+
Others[a]	0.3	6.5	9.5	10.0	10.5	11.7	12.9
Total	**0.3**	**102.7**	**144.9**	**146.8**	**151.3**	**156.1**	**159.1**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Others include HFC-152a, HFC-227ea, HFC-245fa, HFC-43-10mee, HCFO-1233zd(E), HFO-1234yf, HFO-1234ze(E), HFO-1336mzz(Z), C_4F_{10}, and PFC/PFPEs, the latter being a proxy for a diverse collection of PFCs and perfluoropolyethers (PFPEs) employed for solvent applications. For estimating purposes, the GWP value used for PFC/PFPEs was based upon C_6F_{14}.

Note: Totals may not sum due to independent rounding.

Table 4-100: Emissions of HFCs and PFCs from ODS Substitution (Metric Tons)

Gas	1990	2005	2012	2013	2014	2015	2016
HFC-23	0	1	2	2	2	2	2
HFC-32	0	509	4,246	5,162	6,167	7,192	8,252
HFC-125	+	2,700	10,218	11,441	12,670	13,831	14,956
HFC-134a	+	53,005	49,499	45,951	44,464	43,113	40,738
HFC-143a	+	2,110	5,460	5,821	6,096	6,281	6,433
HFC-236fa	0	125	148	151	148	135	127
CF_4	0	2	4	4	4	4	4
Others[a]	M	M	M	M	M	M	M

+ Does not exceed 0.5 MT.

M (Mixture of Gases)

[a] Others include HFC-152a, HFC-227ea, HFC-245fa, HFC-43-10mee, HCFO-1233zd(E), HFO-1234yf, HFO-1234ze(E), HFO-1336mzz(Z), C_4F_{10}, and PFC/PFPEs, the latter being a proxy for a diverse collection of PFCs and perfluoropolyethers (PFPEs) employed for solvent applications.

In 1990 and 1991, the only significant emissions of HFCs and PFCs as substitutes to ODSs were relatively small amounts of HFC-152a—used as an aerosol propellant and also a component of the refrigerant blend R-500 used in chillers—and HFC-134a in refrigeration end-uses. Beginning in 1992, HFC-134a was used in growing amounts as a refrigerant in motor vehicle air-conditioners and in refrigerant blends such as R-404A.[83] In 1993, the use of HFCs in foam production began, and in 1994 ODS substitutes for halons entered widespread use in the United States as halon production was phased out. In 1995, these compounds also found applications as solvents.

The use and subsequent emissions of HFCs and PFCs as ODS substitutes has been increasing from small amounts in 1990 to 159.1 MMT CO_2 Eq. emitted in 2016. This increase was in large part the result of efforts to phase out CFCs

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[81] [42 U.S.C § 7671, CAA Title VI]

[82] Emissions of ODS are not included here consistent with UNFCCC reporting guidelines for national inventories noted in Box 4-1. See Annex 6.2 for more details on emissions of ODS.

[83] R-404A contains HFC-125, HFC-143a, and HFC-134a.

and other ODSs in the United States. In the short term, this trend is expected to continue, and will likely continue over the next decade as HCFCs, which are interim substitutes in many applications, are themselves phased-out under the provisions of the Copenhagen Amendments to the *Montreal Protocol*. Improvements in the technologies associated with the use of these gases and the introduction of alternative gases and technologies, however, may help to offset this anticipated increase in emissions.

Table 4-101 presents emissions of HFCs and PFCs as ODS substitutes by end-use sector for 1990 through 2016. The end-use sectors that contributed the most toward emissions of HFCs and PFCs as ODS substitutes in 2016 include refrigeration and air-conditioning (133.8 MMT CO_2 Eq., or approximately 84 percent), aerosols (10.7 MMT CO_2 Eq., or approximately 7 percent), and foams (10.3 MMT CO_2 Eq., or approximately 6 percent). Within the refrigeration and air-conditioning end-use sector, motor vehicle air-conditioning was the highest emitting end-use (34.8 MMT CO_2 Eq.), followed by refrigerated transport. Each of the end-use sectors is described in more detail below.

Table 4-101: Emissions of HFCs and PFCs from ODS Substitutes (MMT CO_2 Eq.) by Sector

Sector	1990		2005		2012	2013	2014	2015	2016
Refrigeration/Air Conditioning	+		90.2		123.7	124.8	128.3	131.5	133.8
Aerosols	0.3		7.6		10.3	10.5	10.8	11.0	10.7
Foams	+		2.1		6.9	7.5	8.0	9.3	10.3
Solvents	+		1.7		1.7	1.8	1.8	1.8	1.9
Fire Protection	+		1.2		2.1	2.3	2.4	2.5	2.5
Total	**0.3**		**102.7**		**144.9**	**146.8**	**151.3**	**156.1**	**159.1**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Refrigeration/Air Conditioning

The refrigeration and air-conditioning sector includes a wide variety of equipment types that have historically used CFCs or HCFCs. End-uses within this sector include motor vehicle air-conditioning, retail food refrigeration, refrigerated transport (e.g., ship holds, truck trailers, railway freight cars), household refrigeration, residential and small commercial air-conditioning and heat pumps, chillers (large comfort cooling), cold storage facilities, and industrial process refrigeration (e.g., systems used in food processing, chemical, petrochemical, pharmaceutical, oil and gas, and metallurgical industries). As the ODS phaseout has taken effect, most equipment has been retrofitted or replaced to use HFC-based substitutes. Common HFCs in use today in refrigeration/air-conditioning equipment are HFC-134a, R-410A,[84] R-404A, and R-507A.[85] Lower -GWP options such as hydrofluoroolefin (HFO)-1234yf in motor vehicle air-conditioning, R-717 (ammonia) in cold storage and industrial applications, and R-744 (carbon dioxide) and HFC/HFO blends in retail food refrigeration, are also being used. These refrigerants are emitted to the atmosphere during equipment manufacture and operation (as a result of component failure, leaks, and purges), as well as at servicing and disposal events.

Aerosols

Aerosol propellants are used in metered dose inhalers (MDIs) and a variety of personal care products and technical/specialty products (e.g., duster sprays and safety horns). Many pharmaceutical companies that produce MDIs—a type of inhaled therapy used to treat asthma and chronic obstructive pulmonary disease—have replaced the use of CFCs with HFC-propellant alternatives. The earliest ozone-friendly MDIs were produced with HFC-134a, but the industry has started to use HFC-227ea as well. Conversely, since the use of CFC propellants was banned in 1978, most non-medical consumer aerosol products have not transitioned to HFCs, but to “not-in-kind” technologies, such as solid or roll-on deodorants and finger-pump sprays. The transition away from ODS in specialty aerosol products has also led to the introduction of non-fluorocarbon alternatives (e.g., hydrocarbon propellants) in certain applications, in addition to HFC-134a or HFC-152a. Other low-GWP options such as HFO-

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[84] R-410A contains HFC-32 and HFC-125.

[85] R-507A, also called R-507, contains HFC-125 and HFC-143a.

1234ze(E) are being used as well. These propellants are released into the atmosphere as the aerosol products are used.

Foams

Chlorofluorocarbons and HCFCs have traditionally been used as foam blowing agents to produce polyurethane (PU), polystyrene, polyolefin, and phenolic foams, which are used in a wide variety of products and applications. Since the *Montreal Protocol*, flexible PU foams as well as other types of foam, such as polystyrene sheet, polyolefin, and phenolic foam, have transitioned almost completely away from fluorocompounds, into alternatives such as CO_2 and hydrocarbons. The majority of rigid PU foams have transitioned to HFCs—primarily HFC-134a and HFC-245fa. Today, these HFCs are used to produce PU appliance, PU commercial refrigeration, PU spray, and PU panel foams—used in refrigerators, vending machines, roofing, wall insulation, garage doors, and cold storage applications. In addition, HFC-152a, HFC-134a and CO_2 are used to produce polystyrene sheet/board foam, which is used in food packaging and building insulation. Low-GWP fluorinated foam blowing agents in use include HFO-1234ze(E) and HCFO-1233zd(E). Emissions of blowing agents occur when the foam is manufactured as well as during the foam lifetime and at foam disposal, depending on the particular foam type.

Solvents

Chlorofluorocarbons, methyl chloroform (1,1,1-trichloroethane or TCA), and to a lesser extent carbon tetrachloride (CCl_4) were historically used as solvents in a wide range of cleaning applications, including precision, electronics, and metal cleaning. Since their phaseout, metal cleaning end-use applications have primarily transitioned to non-fluorocarbon solvents and not-in-kind processes. The precision and electronics cleaning end-uses have transitioned in part to high-GWP gases, due to their high reliability, excellent compatibility, good stability, low toxicity, and selective solvency. These applications rely on HFC-43-10mee, HFC-365mfc, HFC-245fa, and to a lesser extent, PFCs. Electronics cleaning involves removing flux residue that remains after a soldering operation for printed circuit boards and other contamination-sensitive electronics applications. Precision cleaning may apply to either electronic components or to metal surfaces, and is characterized by products, such as disk drives, gyroscopes, and optical components, that require a high level of cleanliness and generally have complex shapes, small clearances, and other cleaning challenges. The use of solvents yields fugitive emissions of these HFCs and PFCs.

Fire Protection

Fire protection applications include portable fire extinguishers ("streaming" applications) that originally used halon 1211, and total flooding applications that originally used halon 1301, as well as some halon 2402. Since the production and import of virgin halons were banned in the United States in 1994, the halon replacement agent of choice in the streaming sector has been dry chemical, although HFC-236fa is also used to a limited extent. In the total flooding sector, HFC-227ea has emerged as the primary replacement for halon 1301 in applications that require clean agents. Other HFCs, such as HFC-23 and HFC-125, are used in smaller amounts. The majority of HFC-227ea in total flooding systems is used to protect essential electronics, as well as in civil aviation, military mobile weapons systems, oil/gas/other process industries, and merchant shipping. Fluoroketone FK-5-1-12 is also used as a low-GWP option and 2-BTP is being considered. As fire protection equipment is tested or deployed, emissions of HFCs occur.

Methodology

A detailed Vintaging Model of ODS-containing equipment and products was used to estimate the actual—versus potential—emissions of various ODS substitutes, including HFCs and PFCs. The name of the model refers to the fact that it tracks the use and emissions of various compounds for the annual "vintages" of new equipment that enter service in each end-use. The Vintaging Model predicts ODS and ODS substitute use in the United States based on modeled estimates of the quantity of equipment or products sold each year containing these chemicals and the amount of the chemical required to manufacture and/or maintain equipment and products over time. Emissions for each end-use were estimated by applying annual leak rates and release profiles, which account for the lag in emissions from equipment as they leak over time. By aggregating the data for 67 different end-uses, the model produces estimates of annual use and emissions of each compound. Further information on the Vintaging Model is contained in Annex 3.9.

Uncertainty and Time-Series Consistency

Given that emissions of ODS substitutes occur from thousands of different kinds of equipment and from millions of point and mobile sources throughout the United States, emission estimates must be made using analytical tools such as the Vintaging Model or the methods outlined in IPCC (2006). Though the model is more comprehensive than the IPCC default methodology, significant uncertainties still exist with regard to the levels of equipment sales, equipment characteristics, and end-use emissions profiles that were used to estimate annual emissions for the various compounds.

The uncertainty analysis quantifies the level of uncertainty associated with the aggregate emissions across the 67 end-uses in the Vintaging Model. In order to calculate uncertainty, functional forms were developed to simplify some of the complex "vintaging" aspects of some end-use sectors, especially with respect to refrigeration and air-conditioning, and to a lesser degree, fire extinguishing. These sectors calculate emissions based on the entire lifetime of equipment, not just equipment put into commission in the current year, thereby necessitating simplifying equations. The functional forms used variables that included growth rates, emission factors, transition from ODSs, change in charge size as a result of the transition, disposal quantities, disposal emission rates, and either stock for the current year or original ODS consumption. Uncertainty was estimated around each variable within the functional forms based on expert judgment, and a Monte Carlo analysis was performed. The most significant sources of uncertainty for this source category include the emission factors for residential unitary air-conditioners, as well as the percent of non-MDI aerosol propellant that is HFC-152a.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-102. Substitution of ozone depleting substances HFC and PFC emissions were estimated to be between 154.0 and 177.7 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 3.2 percent below to 11.7 percent above the emission estimate of 159.1 MMT CO_2 Eq.

Table 4-102: Approach 2 Quantitative Uncertainty Estimates for HFC and PFC Emissions from ODS Substitutes (MMT CO_2 Eq. and Percent)

Source	Gases	2016 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Substitution of Ozone Depleting Substances	HFCs and PFCs	159.1	154.0	177.7	-3.2%	+11.7%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological approaches were applied to the entire time series to ensure time-series consistency from 1990 through 2016. Details on the emission trends through time are described in more detail in the Methodology section, above.

For more information on the general QA/QC process applied to this source category, consistent with Volume 1, Chapter 6 of the *2006 IPCC Guidelines*, see the QA/QC and Verification Procedures section in the introduction of the IPPU chapter.

Comparison of Reported Consumption to Modeled Consumption of HFCs

Data from EPA's Greenhouse Gas Reporting Program (GHGRP) was also used to perform quality control as a reference scenario check on the modeled emissions from this source category as specified in *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. To do so, consumption patterns demonstrated through data reported under GHGRP Subpart OO—Suppliers of Industrial Greenhouse Gases and Subpart QQ—Importers and Exporters of Fluorinated Greenhouse Gases Contained in Pre-Charged Equipment or Closed-Cell Foams were compared to the modeled demand for new saturated HFCs (excluding HFC-23) used as ODS substitutes from the Vintaging Model.

The collection of data from suppliers of HFCs enables EPA to calculate the reporters' aggregated net supply–the sum of the quantities of chemical produced or imported into the United States less the sum of the quantities of chemical transformed (used as a feedstock in the production of other chemicals), destroyed, or exported from the United States.[86] This allows for a quality control check on emissions from this source because the Vintaging Model uses modeled demand for new chemical as a proxy for total amount supplied, which is similar to net supply, as an input to the emission calculations in the model.

Reported Net Supply (GHGRP Top-Down Estimate)

Under EPA's GHGRP, suppliers (i.e., producers, importers, and exporters) of HFCs under Subpart OO began annually reporting their production, transformation, destruction, imports, and exports to EPA in 2011 (for supply that occurred in 2010) and suppliers of HFCs under Subpart QQ began annually reporting their imports and exports to EPA in 2012 (for supply that occurred in 2011). Beginning in 2015, bulk consumption data for aggregated HFCs reported under Subpart OO were made publicly available under EPA's GHGRP. Data include all saturated HFCs (except HFC-23) reported to EPA across the GHGRP-reporting time series (2010 through 2016). The data include all 26 such saturated HFCs listed in Table A-1 of 40 CFR Part 98, where regulations for EPA's GHGRP are promulgated, though not all species were reported in each reporting year. For the first time in 2016, net imports of HFCs contained in pre-charged equipment or closed-cell foams reported under Subpart QQ were made publicly available under EPA's GHGRP.

Modeled Consumption (Vintaging Model Bottom-Up Estimate)

The Vintaging Model, used to estimate emissions from this source category, calculates chemical demand based on the quantity of equipment and products sold, serviced and retired each year, and the amount of the chemical required to manufacture and/or maintain the equipment and products.[87] It is assumed that the total demand equals the amount supplied by either new production, chemical import, or quantities recovered (usually reclaimed) and placed back on the market. In the Vintaging Model, demand for new chemical, as a proxy for consumption, is calculated as any chemical demand (either for new equipment or for servicing existing equipment) that cannot be met through recycled or recovered material. No distinction is made in the Vintaging Model between whether that need is met through domestic production or imports. To calculate emissions, the Vintaging Model estimates the quantity released from equipment over time. Thus, verifying the Vintaging Model's calculated consumption against GHGRP reported data is one way to check the Vintaging Model's emission estimates.

There are ten saturated HFC species modeled in the Vintaging Model: HFC-23, HFC-32, HFC-125, HFC-134a, HFC-143a, HFC-152a, HFC-227ea, HFC-236fa, HFC-245fa, and HFC-43-10mee. For the purposes of this comparison, only nine HFC species are included (HFC-23 is excluded), to more closely align with the aggregated total reported under EPA's GHGRP. While some amounts of less-used saturated HFCs, including isomers of those included in the Vintaging Model, are reportable under EPA's GHGRP, the data are believed to represent an amount comparable to the modeled estimates as a quality control check.

Comparison Results and Discussion

Comparing the estimates of consumption from these two approaches (i.e., reported and modeled) ultimately supports and improves estimates of emissions, as noted in the *2006 IPCC Guidelines* (which refer to fluorinated greenhouse gas consumption based on supplies as "potential emissions"):

> [W]hen considered along with estimates of actual emissions, the potential emissions approach can assist in validation of completeness of sources covered and as a QC check by comparing total domestic consumption as calculated in this 'potential emissions approach' per compound with the sum of all activity data of the various uses (IPCC 2006).

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[86] Chemical that is exported, transformed, or destroyed—unless otherwise imported back to the United States—will never be emitted in the United States.

[87] The model builds an inventory of the in-use stock of equipment and products and ODSs and HFCs in each of the sub-applications. Emissions are subsequently estimated by applying annual and disposal emission rates to each population of equipment and products.

Table 4-103 and Figure 4-2 compare the net supply of saturated HFCs (excluding HFC-23) in MMT CO_2 Eq. as determined from Subpart OO (supply of HFCs in bulk) and Subpart QQ (supply of HFCs in products and foams) of EPA's GHGRP for the years 2010 through 2016 and the chemical demand as calculated by the Vintaging Model for the same time series.

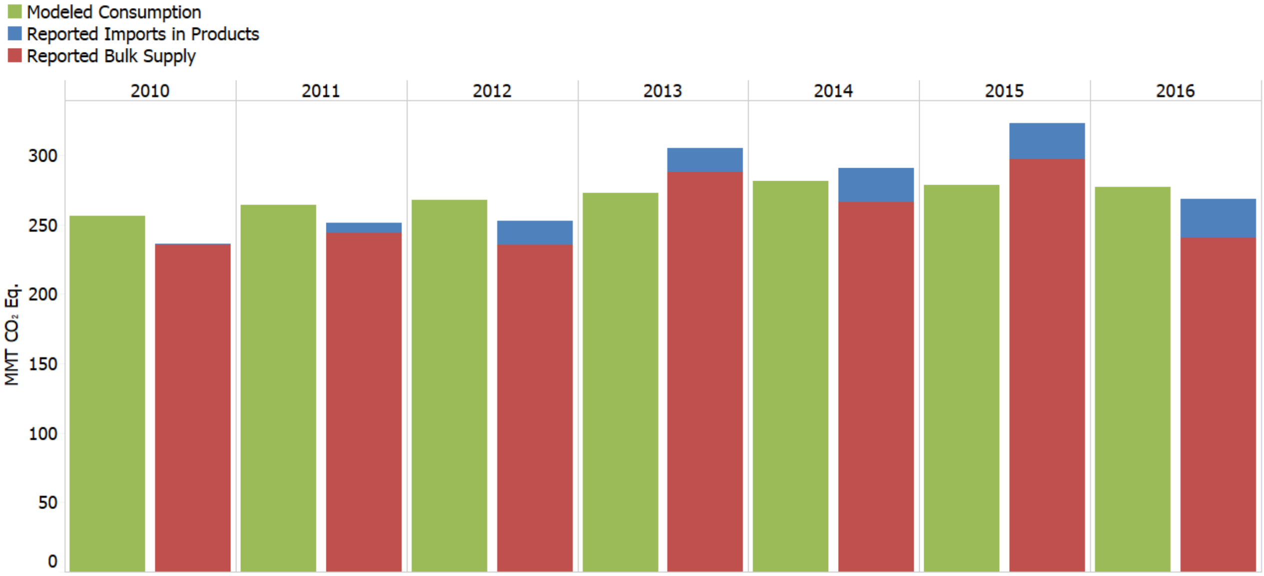
Table 4-103: U.S. HFC Supply (MMT CO_2 Eq.)

	2010	2011	2012	2013	2014	2015	2016
Reported Net Supply (GHGRP)	236	251	253	305	291	323	268
Industrial GHG Suppliers	236	244	235	288	266	297	240
HFCs in Products and Foams	NA	7	18	17	25	26	28
Modeled Supply (Vintaging Model)	256	264	267	272	281	278	277
Percent Difference	**9%**	**5%**	**6%**	**-11%**	**-3%**	**-14%**	**3%**

NA (Not Available)

[a] Importers and exporters of fluorinated gases in products were not required to report 2010 data.

Figure 4-2: U.S. HFC Consumption (MMT CO_2 Eq.)



As shown, the estimates from the Vintaging Model are slightly lower than the GHGRP estimates by an average of 1 percent across the time series (i.e., 2010 through 2016). Potential reasons for these differences include:

- The Vintaging Model includes fewer HFCs than are reported to EPA's GHGRP. However, the additional reported HFCs represent a small fraction of total HFC use for this source category, both in GWP-weighted and unweighted terms, and as such, it is not expected that the additional HFCs reported to EPA are a major driver for the difference between the two sets of estimates. To the extent lower-GWP isomers were used in lieu of the modeled chemicals (e.g., HFC-134 instead of HFC-134a), lower CO_2 Eq. amounts in the GHGRP data compared to the modeled estimates would be expected.
- Because the top-down data are reported at the time of actual production or import and the bottom-up data are calculated at the time of actual placement on the market, there could be a temporal discrepancy when comparing data. Because the GHGRP data generally increases over time (although some year-to-year variations exist) and the Vintaging Model estimates also increase (through 2014), EPA would expect the modeled estimates to be slightly lower than the corresponding GHGRP data due to this temporal effect.
- Under EPA's GHGRP, all facilities that produce HFCs are required to report their quantities, whereas importers or exporters of HFCs or pre-charged equipment and closed-cell foams that contain HFCs are only required to report if either their total imports or their total exports of greenhouse gases are greater than or

equal to 25,000 metric tons of CO_2 Eq. per year. Thus, some imports may not be accounted for in the GHGRP data. On the other hand, some exports might also not be accounted for in this data.

- In some years, imports and exports may be greater than consumption because the excess is being used to increase chemical or equipment stockpiles; in other years, the opposite may hold true. Similarly, relocation of manufacturing facilities or recovery from the recession could contribute to variability in imports or exports. Averaging imports and exports over multiple years can minimize the impact of such fluctuations. For example, when the 2012 and 2013 net additions to the supply are averaged, as shown in Table 4-104, the percent difference between the consumption estimates decreases compared to the 2012-only estimates.

Table 4-104: Averaged U.S. HFC Demand (MMT CO_2 Eq.)

	2010-2011 Avg.	2011-2012 Avg.	2012-2013 Avg.	2013-2014 Avg.	2014-2015 Avg.	2015-2016 Avg.
Reported Net Supply (GHGRP)	244	252	279	298	307	296
Modeled Demand (Vintaging Model)	260	266	270	277	280	277
Percent Difference	**7%**	**5%**	**-3%**	**-7%**	**-9%**	**-6%**

- The Vintaging Model does not reflect the dynamic nature of reported HFC consumption, with significant differences seen in each year. Whereas the Vintaging Model projects a slowly increasing overall demand through 2014, and a slight lowering after that, actual consumption for specific chemicals or equipment may vary over time and could even switch from positive to negative (indicating more chemical exported, transformed, or destroyed than produced or imported in a given year). Furthermore, consumption as calculated in the Vintaging Model is a function of demand not met by disposal recovery. If, in any given year, a significant number of units are disposed, there will be a large amount of additional recovery in that year that can cause an unexpected and not modeled decrease in demand and thus a decrease in consumption. On the other hand, if market, economic, or other factors cause less than expected disposal and recovery, actual supply would decrease, and hence consumption would increase to meet that demand not satisfied by recovered quantities, increasing the GHGRP.
- The Vintaging Model is used to estimate the emissions that occur in the United States. As such, all equipment or products that contain ODS or alternatives, including saturated HFCs, are assumed to consume and emit chemicals equally as like equipment or products originally produced in the United States. The GHGRP data from Subpart OO (industrial greenhouse gas suppliers) includes HFCs produced or imported and used to fill or manufacture products that are then exported from the United States. The Vintaging Model estimates of demand and supply are not meant to incorporate such chemical. Likewise, chemicals may be used outside the United States to create products or charge equipment that is then imported to and used in the United States. The Vintaging Model estimates of demand and supply are meant to capture this chemical, as it will lead to emissions inside the United States. The GHGRP data from Subpart QQ (supply of HFCs in products) accounts for some of these differences; however, the scope of Subpart QQ does not cover all such equipment or products and the chemical contained therein. Depending on whether the United States is a net importer or net exporter of such chemical, this factor may account for some of the difference shown above or might lead to a further discrepancy.

One factor, however, would only lead to modeled estimates to be even higher than the estimates shown and hence for many years higher than GHGRP data:

- Saturated HFCs are also known to be used as a cover gas in the production of magnesium. The Vintaging Model estimates here do not include the amount of HFCs for this use, but rather only the amount for uses that traditionally were served by ODS. Nonetheless, EPA expects this supply not included in the Vintaging Model estimates to be very small compared to the ODS substitute use for the years analyzed. An indication of the different magnitudes of these categories is seen in the fact that the 2016 emissions from that non-modeled source (0.1 MMT CO_2 Eq.) are much smaller than those for the ODS substitute sector (159.1 MMT CO_2 Eq.).

Using a Tier 2 bottom-up modeling methodology to estimate emissions requires assumptions and expert judgment. Comparing the Vintaging Model's estimates to GHGRP-reported estimates, particularly for more widely used chemicals, can help validate the model but it is expected that the model will have limitations. This comparison shows that Vintaging Model consumption estimates are well within the same order of magnitude as the actual consumption data as reported to EPA's GHGRP although the differences in reported net supply and modeled demand are still significant in some of the years. Although it can be difficult to capture the observed market variability, the Vintaging Model is periodically reviewed and updated to ensure that the model reflects the current and future trajectory of ODS and ODS substitutes across all end-uses and the Vintaging Model will continue to be compared to available top-down estimates in order to ensure the model accurately estimates HFC consumption and emissions.

Recalculations Discussion

For the current Inventory, updates to the Vintaging Model were included in response to a peer review conducted on end-uses within the Refrigeration/Air Conditioning and Fire Protection sectors. Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2016. Updates included revisions to stock assumptions for light-duty vehicle and light-duty truck air conditioners, revisions to stock and leak rate assumptions for residential unitary air conditioning, and updates to transitions to alternative refrigerants for road transport refrigeration systems. Fire suppressant transition assumptions for flooding agent fire protection systems were also updated in response to the peer review and comments received during the Public Review comment period for the previous (i.e., 1990 through 2015) Inventory for the Fire Protection sector.

New end-uses representing refrigerated food processing and dispensing equipment and heavy-duty vehicle air conditioners were added to the Refrigeration/Air Conditioning sector. Additionally, the industrial process refrigeration end-use was updated to transition from HCFC-123 to HCFO-1233zd(E) and R-514A in response to upcoming HCFC-123 phaseout requirements under the Montreal Protocol, and, based on direction seen in the industry, some transitions to alternative refrigerants were varied in the centrifugal chillers, retail food, transport refrigeration, and vending machines end-uses.

Together, these updates increased greenhouse gas emissions on average by 0.27 percent between 1990 and 2016.

Planned Improvements

Future improvements to the Vintaging Model are planned for the Refrigeration/Air Conditioning and Fire Protection sectors in response to the peer review.

4.25 Electrical Transmission and Distribution (CRF Source Category 2G1)

The largest use of sulfur hexafluoride (SF_6), both in the United States and internationally, is as an electrical insulator and interrupter in equipment that transmits and distributes electricity (RAND 2004). The gas has been employed by the electric power industry in the United States since the 1950s because of its dielectric strength and arc-quenching characteristics. It is used in gas-insulated substations, circuit breakers, and other switchgear. SF_6 has replaced flammable insulating oils in many applications and allows for more compact substations in dense urban areas.

Fugitive emissions of SF_6 can escape from gas-insulated substations and switchgear through seals, especially from older equipment. The gas can also be released during equipment manufacturing, installation, servicing, and disposal. Emissions of SF_6 from equipment manufacturing and from electrical transmission and distribution systems were estimated to be 4.3 MMT CO_2 Eq. (0.2 kt) in 2016. This quantity represents an 81 percent decrease from the estimate for 1990 (see Table 4-105 and Table 4-106). There are two potential causes for this decrease: a sharp increase in the price of SF_6 during the 1990s and a growing awareness of the magnitude and environmental impact of SF_6 emissions through programs such as EPA's voluntary SF_6 Emission Reduction Partnership for Electric Power

Systems (Partnership) and EPA's GHGRP. Utilities participating in the Partnership have lowered their emission factor (kg SF_6 emitted per kg of nameplate capacity) by more than 85 percent since the Partnership began in 1999. A recent examination of the SF_6 emissions reported by electric power systems to EPA's GHGRP revealed that SF_6 emissions from reporters have decreased by 26 percent from 2011 to 2016,[88] with much of the reduction seen from utilities that are not participants in the Partnership. These utilities may be making relatively large reductions in emissions as they take advantage of relatively large and/or inexpensive emission reduction opportunities (i.e., "low hanging fruit," such as replacing major leaking circuit breakers) that Partners have already taken advantage of under the voluntary program (Ottinger et al. 2014).

Table 4-105: SF_6 Emissions from Electric Power Systems and Electrical Equipment Manufacturers (MMT CO_2 Eq.)

Year	Electric Power Systems	Electrical Equipment Manufacturers	Total
1990	22.8	0.3	23.1
2005	7.7	0.6	8.3
2011	5.3	0.7	6.0
2012	4.4	0.3	4.7
2013	4.1	0.4	4.5
2014	4.3	0.4	4.7
2015	4.0	0.3	4.3
2016	4.1	0.3	4.3

Note: Totals may not sum due to independent rounding.

Table 4-106: SF_6 Emissions from Electric Power Systems and Electrical Equipment Manufacturers (kt)

Year	Emissions
1990	1.0
2005	0.4
2011	0.3
2012	0.2
2013	0.2
2014	0.2
2015	0.2
2016	0.2

Methodology

The estimates of emissions from Electrical Transmission and Distribution are comprised of emissions from electric power systems and emissions from the manufacture of electrical equipment. The methodologies for estimating both sets of emissions are described below.

1990 through 1998 Emissions from Electric Power Systems

Emissions from electric power systems from 1990 through 1998 were estimated based on (1) the emissions estimated for this source category in 1999, which, as discussed in the next section, were based on the emissions reported during the first year of EPA's SF_6 Emission Reduction Partnership for Electric Power Systems

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[88] Analysis of emission trends from the GHGRP is imperfect due to an inconsistent group of reporters year to year.

(Partnership), and (2) the RAND survey of global SF_6 emissions. Because most utilities participating in the Partnership reported emissions only for 1999 through 2011, modeling was used to estimate SF_6 emissions from electric power systems for the years 1990 through 1998. To perform this modeling, U.S. emissions were assumed to follow the same trajectory as global emissions from this source during the 1990 to 1999 period. To estimate global emissions, the RAND survey of global SF_6 sales were used, together with the following equation for estimating emissions, which is derived from the mass-balance equation for chemical emissions (Volume 3, Equation 7.3) in the *2006 IPCC Guidelines*.[89] (Although Equation 7.3 of the *2006 IPCC Guidelines* appears in the discussion of substitutes for ozone-depleting substances, it is applicable to emissions from any long-lived pressurized equipment that is periodically serviced during its lifetime.)

Emissions (kilograms SF_6) = SF_6 purchased to refill existing equipment (kilograms) + nameplate capacity of retiring equipment (kilograms) [90]

Note that the above equation holds whether the gas from retiring equipment is released or recaptured; if the gas is recaptured, it is used to refill existing equipment, thereby lowering the amount of SF_6 purchased by utilities for this purpose.

Gas purchases by utilities and equipment manufacturers from 1961 through 2003 are available from the RAND (2004) survey. To estimate the quantity of SF_6 released or recovered from retiring equipment, the nameplate capacity of retiring equipment in a given year was assumed to equal 81.2 percent of the amount of gas purchased by electrical equipment manufacturers 40 years previous (e.g., in 2000, the nameplate capacity of retiring equipment was assumed to equal 81.2 percent of the gas purchased in 1960). The remaining 18.8 percent was assumed to have been emitted at the time of manufacture. The 18.8 percent emission factor is an average of IPCC default SF_6 emission rates for Europe and Japan for 1995 (IPCC 2006). The 40-year lifetime for electrical equipment is also based on IPCC (2006). The results of the two components of the above equation were then summed to yield estimates of global SF_6 emissions from 1990 through 1999.

U.S. emissions between 1990 and 1999 are assumed to follow the same trajectory as global emissions during this period. To estimate U.S. emissions, global emissions for each year from 1990 through 1998 were divided by the estimated global emissions from 1999. The result was a time series of factors that express each year's global emissions as a multiple of 1999 global emissions. Historical U.S. emissions were estimated by multiplying the factor for each respective year by the estimated U.S. emissions of SF_6 from electric power systems in 1999 (estimated to be 14.3 MMT CO_2 Eq.).

Two factors may affect the relationship between the RAND sales trends and actual global emission trends. One is utilities' inventories of SF_6 in storage containers. When SF_6 prices rise, utilities are likely to deplete internal inventories before purchasing new SF_6 at the higher price, in which case SF_6 sales will fall more quickly than emissions. On the other hand, when SF_6 prices fall, utilities are likely to purchase more SF_6 to rebuild inventories, in which case sales will rise more quickly than emissions. This effect was accounted for by applying 3-year smoothing to utility SF_6 sales data. The other factor that may affect the relationship between the RAND sales trends and actual global emissions is the level of imports from and exports to Russia and China. SF_6 production in these countries is not included in the RAND survey and is not accounted for in any another manner by RAND. However, atmospheric studies confirm that the downward trend in estimated global emissions between 1995 and 1998 was real (see the Uncertainty discussion below).

1999 through 2016 Emissions from Electric Power Systems

Emissions from electric power systems from 1999 to 2016 were estimated based on: (1) reporting from utilities participating in EPA's SF_6 Emission Reduction Partnership for Electric Power Systems (Partners), which began in 1999; (2) reporting from utilities covered by EPA's GHGRP, which began in 2012 for emissions occurring in 2011 (GHGRP-Only Reporters); and (3) the relationship between utilities' reported emissions and their transmission miles as reported in the 2001, 2004, 2007, 2010, 2013, and 2017 Utility Data Institute (UDI) Directories of Electric Power

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[89] Ideally, sales to utilities in the United States between 1990 and 1999 would be used as a model. However, this information was not available. There were only two U.S. manufacturers of SF_6 during this time period, so it would not have been possible to conceal sensitive sales information by aggregation.

[90] Nameplate capacity is defined as the amount of SF_6 within fully charged electrical equipment.

Producers and Distributors (UDI 2001, 2004, 2007, 2010, 2013, and 2017), which was applied to the electric power systems that do not report to EPA (Non-Reporters). (Transmission miles are defined as the miles of lines carrying voltages above 34.5 kV).

Partners

Over the period from 1999 to 2016, Partner utilities, which for inventory purposes are defined as utilities that either currently are or previously have been part of the Partnership,[91] represented 49 percent, on average, of total U.S. transmission miles. Partner utilities estimated their emissions using a Tier 3 utility-level mass balance approach (IPCC 2006). If a Partner utility did not provide data for a particular year, emissions were interpolated between years for which data were available or extrapolated based on Partner-specific transmission mile growth rates. In 2012, many Partners began reporting their emissions (for 2011 and later years) through EPA's GHGRP (discussed further below) rather than through the Partnership. In 2016, approximately 0.2 percent of the total emissions attributed to Partner utilities were reported through Partnership reports. Approximately 92 percent of the total emissions attributed to Partner utilities were reported and verified through EPA's GHGRP. Partners without verified 2016 data accounted for approximately 8 percent of the total emissions attributed to Partner utilities.[92]

GHGRP-Only Reporters

EPA's GHGRP requires users of SF_6 in electric power systems to report emissions if the facility has a total SF_6 nameplate capacity that exceeds 17,820 pounds. (This quantity is the nameplate capacity that would result in annual SF_6 emissions equal to 25,000 metric tons of CO_2 equivalent at the historical emission rate reported under the Partnership.) As under the Partnership, electric power systems that report their SF_6 emissions under EPA's GHGRP are required to use the Tier 3 utility-level mass-balance approach. Many Partners began reporting their emissions through EPA's GHGRP in 2012 (reporting emissions for 2011 and later years) because their nameplate capacity exceeded the reporting threshold. Some Partners who did not report through EPA's GHGRP continued to report through the Partnership.

In addition, many non-Partners began reporting to EPA for the first time through its GHGRP in 2012. Non-Partner emissions reported and verified under EPA's GHGRP were compiled to form a new category of reported data (GHGRP-Only Reporters). GHGRP-Only Reporters accounted for 18 percent of U.S. transmission miles and 21 percent of estimated U.S. emissions from electric power system in 2016.[93]

Non-Reporters

Emissions from Non-Reporters (i.e., utilities other than Partners and GHGRP-Only Reporters) in every year since 1999 were estimated using the results of a regression analysis that correlated emissions from reporting utilities

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[91] Starting in the previous (i.e., 1990 to 2015) Inventory, partners who had reported three years or less of data prior to 2006 were removed. Most of these partners had been removed from the list of current Partners, but remained in the Inventory due to the extrapolation methodology for non-reporting partners.

[92] It should be noted that data reported through EPA's GHGRP must go through a verification process; only data verified as of September 1, 2017 could be used in the emission estimates for the prior year of reporting. For Partners whose GHGRP data was not yet verified, emissions were extrapolated based upon historical Partner-specific transmission mile growth rates, and those Partners are included in the 'non-reporting Partners' category.

For electric power systems, verification involved a series of electronic range, completeness, and algorithm checks for each report submitted. In addition, EPA manually reviewed the reported data and compared each facility's reported transmission miles with the corresponding quantity in the UDI 2017 database (UDI 2017). In the first year of GHGRP reporting, EPA followed up with reporters where the discrepancy between the reported miles and the miles published by UDI was greater than 10 percent, with a goal to improve data quality. Only GHGRP data verified as of September 1, 2017 was included in the emission estimates for 2011, 2012, 2013, 2014, 2015, and 2016.

[93] GHGRP-reported and Partner transmission miles from a number of facilities were equal to zero with non-zero emissions. These facilities emissions were added to the emissions totals for their respective parent companies when identifiable and not included in the regression equation when not identifiable or applicable. Other facilities reported non-zero transmission miles with zero emissions, or zero transmission miles and zero emissions. These facilities were not included in the development of the regression equations (discussed further below). These emissions are already implicitly accounted for in the relationship between transmission miles and emissions.

(using verified data from both Partners and GHGRP-Only Reporters) with their transmission miles.[94] As noted above, non-Partner emissions were reported to the EPA for the first time through its GHGRP in 2012 (representing 2011 emissions). This set of reported data was of particular interest because it provided insight into the emission rate of non-Partners, which previously was assumed to be equal to the historical (1999) emission rate of Partners. Specifically, emissions were estimated for Non-Reporters as follows:

- <u>Non-Reporters, 1999 to 2011:</u> First, the 2011 emission rates (per kg nameplate capacity and per transmission mile) reported by Partners and GHGRP-Only Reporters were reviewed to determine whether there was a statistically significant difference between these two groups. Transmission mileage data for 2011 was reported through GHGRP, with the exception of transmission mileage data for Partners that did not report through GHGRP, which was obtained from UDI. It was determined that there is no statistically significant difference between the emission rates of Partners and GHGRP-Only reporters; therefore, Partner and GHGRP-Only reported data for 2011 were combined to develop regression equations to estimate the emissions of Non-Reporters. Historical emissions from Non-Reporters were estimated by linearly interpolating between the 1999 regression coefficient (based on 1999 Partner data) and the 2011 regression coefficient.

- <u>Non-Reporters, 2012 to Present:</u> It was determined that there continued to be no statistically significant difference between the emission rates reported by Partners and by GHGRP-Only Reporters. Therefore, the emissions data from both groups were combined to develop regression equations for 2012. This was repeated for 2013, 2014, 2015, and 2016 using Partner and GHGRP-Only Reporter data for each year.

    - The 2016 regression equation for reporters was developed based on the emissions reported by a subset of Partner utilities and GHGRP-Only utilities (representing approximately 67 percent of total U.S. transmission miles). The regression equation for 2016 is:

$$\text{Emissions (kg)} = 0.213 \times \text{Transmission Miles}$$

Table 4-107 below shows the percentage of transmission miles covered by reporters (i.e., associated with reported data) and the regression coefficient for 1999 (the first year data was reported), and for 2011 through present (the years with GHGRP reported data). The coefficient increased between 2015 and 2016.

Table 4-107: Transmission Mile Coverage (kg) and Regression Coefficients (Percent)

	1999		2011	2012	2013	2014	2015	2016
Percentage of Miles Covered by Reporters	50%		70%	73%	73%	73%	70%	67%
Regression Coefficient[a]	0.71		0.28	0.24	0.23	0.23	0.21	0.21

[a] Regression coefficient for emissions is calculated utilizing transmission miles as the explanatory variable and emissions as the response variable. The equation utilizes a constant intercept of zero. When calculating the regression coefficient, outliers are also removed from the analysis when the standard residual for that reporter exceeds the value 3.0. In 2016, one reporter was removed as a result of the outlier test.

Data on transmission miles for each Non-Reporter for the years 2000, 2003, 2006, and 2009, 2012, and 2016 were obtained from the 2001, 2004, 2007, 2010, 2013, and 2017 UDI Directories of Electric Power Producers and Distributors, respectively (UDI 2001, 2004, 2007, 2010, 2013, and 2017). The U.S. transmission system grew by over 22,000 miles between 2000 and 2003 yet declined by almost 4,000 miles between 2003 and 2006. Given these fluctuations, periodic increases are assumed to occur gradually. Therefore, transmission mileage was assumed to increase at an annual rate of 1.2 percent between 2000 and 2003 and decrease by 0.20 percent between 2003 and 2006. This growth rate grew to 1.7 percent from 2006 to 2009 as transmission miles increased by more than 33,000 miles. The growth rate for 2009 through 2012 was calculated to be 1.2 percent as transmission miles grew by approximately 24,000 during this time period. Starting in 2012, two growth rates were calculated to differentiate between the growth of transmission miles reported by GHGRP reporters and the growth of transmission miles observed for non-reporters based on the transmission miles included in the UDI database. The annual growth rate for 2012 through 2016 for non-reporters was calculated to be -0.2 percent whereas the growth rate for GHGRP reporters

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[94] In the United States, SF_6 is contained primarily in transmission equipment rated above 34.5 kV.

was calculated to be 1.2 percent. Total transmission miles for both groups grew by approximately 22,000 over this time period.

Total Industry Emissions

As a final step, total electric power system emissions from 1999 through 2016 were determined for each year by summing the Partner reported and estimated emissions (reported data was available through the EPA's SF_6 Emission Reduction Partnership for Electric Power Systems), the GHGRP-Only reported emissions, and the non-reporting utilities' emissions (determined using the regression equations).

1990 through 2016 Emissions from Manufacture of Electrical Equipment

Three different methods were used to estimate 1990 to 2016 emissions from original electrical equipment manufacturers (OEMs).

- OEM emissions from 1990 through 2000 were derived by assuming that manufacturing emissions equaled 10 percent of the quantity of SF_6 provided with new equipment. The 10 percent emission rate is the average of the "ideal" and "realistic" manufacturing emission rates (4 percent and 17 percent, respectively) identified in a paper prepared under the auspices of the International Council on Large Electric Systems (CIGRE) in February 2002 (O'Connell et al. 2002). The quantity of SF_6 provided with new equipment was estimated based on statistics compiled by the National Electrical Manufacturers Association (NEMA). These statistics were provided for 1990 to 2000.
- OEM emissions from 2000 through 2010 were estimated by (1) interpolating between the emission rate estimated for 2000 (10 percent) and an emission rate estimated for 2011 based on reporting by OEMs through the GHGRP (5.8 percent), and (2) estimating the quantities of SF_6 provided with new equipment for 2001 to 2010. The quantities of SF_6 provided with new equipment were estimated using Partner reported data and the total industry SF_6 nameplate capacity estimate (152.1 MMT CO_2 Eq. in 2010). Specifically, the ratio of new nameplate capacity to total nameplate capacity of a subset of Partners for which new nameplate capacity data was available from 1999 to 2010 was calculated. These ratios were then multiplied by the total industry nameplate capacity estimate for each year to derive the amount of SF_6 provided with new equipment for the entire industry. Additionally, to obtain the 2011 emission rate (necessary for estimating 2001 through 2010 emissions), the estimated 2011 emissions (estimated using the third methodology listed below) were divided by the estimated total quantity of SF_6 provided with new equipment in 2011. The 2011 quantity of SF_6 provided with new equipment was estimated in the same way as the 2001 through 2010 quantities.
- OEM emissions from 2011 through 2016 were estimated using the SF_6 emissions from OEMs reporting to the GHGRP, and an assumption that these reported emissions account for a conservative estimate of 50 percent of the total emissions from all U.S. OEMs.

Uncertainty and Time-Series Consistency

To estimate the uncertainty associated with emissions of SF_6 from Electrical Transmission and Distribution, uncertainties associated with four quantities were estimated: (1) emissions from Partners, (2) emissions from GHGRP-Only Reporters, (3) emissions from Non-Reporters, and (4) emissions from manufacturers of electrical equipment. A Monte Carlo analysis was then applied to estimate the overall uncertainty of the emissions estimate.

Total emissions from the SF_6 Emission Reduction Partnership include emissions from both reporting (through the Partnership or EPA's GHGRP) and non-reporting Partners. For reporting Partners, individual Partner-reported SF_6 data was assumed to have an uncertainty of 10 percent. Based on a Monte Carlo analysis, the cumulative uncertainty of all Partner-reported data was estimated to be 5.4 percent. The uncertainty associated with extrapolated or interpolated emissions from non-reporting Partners was assumed to be 20 percent.

For GHGRP-Only Reporters, reported SF_6 data was assumed to have an uncertainty of 20 percent.[95] Based on a Monte Carlo analysis, the cumulative uncertainty of all GHGRP-Only reported data was estimated to be 9.7 percent.

There are two sources of uncertainty associated with the regression equations used to estimate emissions in 2016 from Non-Reporters: (1) uncertainty in the coefficients (as defined by the regression standard error estimate), and (2) the uncertainty in total transmission miles for Non-Reporters. Uncertainties were also estimated regarding (1) estimates of SF_6 emissions from OEMs reporting to EPA's GHGRP, and (2) the assumption on the percent share of OEM emissions from OEMs reporting to EPA's GHGRP.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-108. Electrical Transmission and Distribution SF_6 emissions were estimated to be between 3.8 and 5.0 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 13 percent below and 14 percent above the emission estimate of 4.3 MMT CO_2 Eq.

Table 4-108: Approach 2 Quantitative Uncertainty Estimates for SF_6 Emissions from Electrical Transmission and Distribution (MMT CO_2 Eq. and Percent)

Source	Gas	2016 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to 2016 Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Electrical Transmission and Distribution	SF_6	4.3	3.8	5.0	-13%	+14%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

In addition to the uncertainty quantified above, there is uncertainty associated with using global SF_6 sales data to estimate U.S. emission trends from 1990 through 1999. However, the trend in global emissions implied by sales of SF_6 appears to reflect the trend in global emissions implied by changing SF_6 concentrations in the atmosphere. That is, emissions based on global sales declined by 29 percent between 1995 and 1998 (RAND 2004), and emissions based on atmospheric measurements declined by 17 percent over the same period (Levin et al. 2010).

Several pieces of evidence indicate that U.S. SF_6 emissions were reduced as global emissions were reduced. First, the decreases in sales and emissions coincided with a sharp increase in the price of SF_6 that occurred in the mid-1990s and that affected the United States as well as the rest of the world. A representative from DILO, a major manufacturer of SF_6 recycling equipment, stated that most U.S. utilities began recycling rather than venting SF_6 within two years of the price rise. Finally, the emissions reported by the one U.S. utility that reported its emissions for all the years from 1990 through 1999 under the Partnership showed a downward trend beginning in the mid-1990s.

Methodological approaches were applied to the entire time series to ensure time-series consistency from 1990 through 2016. Details on the emission trends through time are described in more detail in the Methodology section, above.

For more information on the general QA/QC process applied to this source category, consistent with Volume 1, Chapter 6 of the *2006 IPCC Guidelines*, see the QA/QC and Verification Procedures section in the introduction of the IPPU chapter.

Recalculations Discussion

The historical emissions estimated for this source category have undergone some revisions. SF_6 emission estimates for the period 1990 through 2015 were updated relative to the previous report based on revisions to interpolated and

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[95] Uncertainty is assumed to be higher for the GHGRP-Only category, because 2011 is the first year that those utilities have reported to EPA.

extrapolated non-reported Partner data.[96] For the current Inventory, historical estimates for the period 2011 through 2015 were also updated relative to the previous report based on revisions to reported historical data in EPA's GHGRP. One correction was made to a 2015 transmission mile value reported by one GHGRP partner, who reported a value roughly 25 times higher than was reported in 2011 through 2014 and 2016. As a result of this correction, the emissions regression coefficient for 2015 increased compared to the previous coefficient.

For the current Inventory, UDI Platts data was purchased to obtain transmission mile estimates for 2016 estimates. The U.S. transmission mile growth rate used for years 2013 through 2015 was updated to an interpolation between the 2012 and 2016 data, changing the growth rate that was previously used for extrapolating 2013 through 2015 estimates. Additionally, a methodology was implemented for the current Inventory to differentiate between a transmission mile growth rate for GHGRP reporters (GHGRP growth rate) and a transmission mile growth rate for non-reporters based on UDI data for those utilities (UDI growth rate). This was done to derive growth rates that were based on roughly the same populations during the three years. From 2013 to 2015, the UDI growth rate is applied only to utilities that do not report to the GHGRP; GHGRP reporters provide transmission mile estimates during these years, which is a better indication of the actual transmission miles for this population. Additionally, the transmission mile growth rates calculated for GHGRP reporters and non-reporters were found to be significantly different. The impact of this methodology improvement is a more accurate representation of transmission miles between 2013 and 2015. This resulted in a decrease in the overall estimate of transmission miles from 2013 and 2014, and an increase in the estimate of transmission miles in 2015.

In previous Inventories, estimates of emissions from OEMs after 2010, which rely on data obtained from GHGRP subpart SS reporters, only included SF_6 emissions from equipment manufacture and did not account for any reported emissions that occur during the OEM installation of equipment. For the current Inventory, the calculation of SF_6 emissions from OEMs was modified to include SF_6 emissions during equipment installation. The same scaling assumption used to determine U.S. total OEM emissions during manufacture was applied to estimate a U.S. total of OEM emissions from installation. This recalculation slightly increased historical estimates not only for the years when GHGRP data are available (2011 to 2015) but also for years 2001 through 2010 since emissions for these years are estimated by interpolating between the emission rate estimated for 2000 (10 percent) and an emission rate estimated for 2011 based on reporting by OEMs through the GHGRP.

Finally, a correction was made to the calculation of total U.S. nameplate capacity. For the 1999 through 2015 inventory, an additional year (2006) was included in the calculation of emission regression coefficients via extrapolation, though this update was inadvertently not carried to the leak rate calculation, which is used for nameplate capacity. This issue was corrected for the current Inventory, which smoothed the nameplate capacity trend between 1999 and 2011.

As a result of the recalculations, SF_6 emissions from electrical transmission and distribution increased by 3.0 percent for 2015 relative to the previous report. On average, SF_6 emission estimates for the entire time series decreased by approximately 0.1 percent per year.

Planned Improvements

EPA is continuing research to improve the methodology for estimating non-reporter nameplate capacity. The current methodology uses Beginning of Year Nameplate Capacity and the Net Increase in Nameplate Capacity for the GHGRP reporters, which aggregates a small portion of hermetically sealed equipment and high-voltage equipment. More research is needed to determine the impact of removing the Net Increase in Nameplate Capacity. Additionally, the current methodology relies on country-wide emission estimates to calculate Total Nameplate Capacity. This reliance on calculated emission values to estimate nameplate capacity often results in similar trends between the values. EPA is planning to revisit the reasoning behind the current methodology, and to evaluate whether a change should be made to relate nameplate capacity directly to transmission miles.

Due to the GHGRP policy that allows reporters to "off-ramp" from the reporting program when their emissions remain below certain levels for certain periods of time (e.g., below 25,000 MT CO_2 Eq. for five years), the number

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[96] The earlier year estimates within the time series (i.e., 1990 through 1998) were updated based on revisions to the 1999 U.S. emission estimate because emissions for 1990 through 1998 are estimated by multiplying a series of annual factors by the estimated U.S. emissions of SF_6 from electric power systems in 1999 (see Methodology section).

of electric power systems whose reports are used to develop regression coefficients and country-wide emissions estimates is decreasing. While EPA continues to account for emissions from these electric power systems using the estimation method for non-reporters, it is possible that their cessation of reporting could influence the value and/or stability of the emission factors (per transmission mile) that are applied to non-reporters. EPA is planning to explore whether this is the case. If so, EPA is planning to evaluate whether the current methodology for scaling emissions is the best option.

4.26 Nitrous Oxide from Product Uses (CRF Source Category 2G3)

Nitrous oxide (N_2O) is a clear, colorless, oxidizing liquefied gas with a slightly sweet odor which is used in a wide variety of specialized product uses and applications. The amount of N_2O that is actually emitted depends upon the specific product use or application.

There are a total of three N_2O production facilities currently operating in the United States (Ottinger 2014). Nitrous oxide is primarily used in carrier gases with oxygen to administer more potent inhalation anesthetics for general anesthesia, and as an anesthetic in various dental and veterinary applications. The second main use of N_2O is as a propellant in pressure and aerosol products, the largest application being pressure-packaged whipped cream. Small quantities of N_2O also are used in the following applications:

- Oxidizing agent and etchant used in semiconductor manufacturing;
- Oxidizing agent used, with acetylene, in atomic absorption spectrometry;
- Production of sodium azide, which is used to inflate airbags;
- Fuel oxidant in auto racing; and
- Oxidizing agent in blowtorches used by jewelers and others (Heydorn 1997).

Production of N_2O in 2016 was approximately 15 kt (see Table 4-109).

Table 4-109: N_2O Production (kt)

Year	kt
1990	16
2005	15
2012	15
2013	15
2014	15
2015	15
2016	15

Nitrous oxide emissions were 4.2 MMT CO_2 Eq. (14 kt N_2O) in 2016 (see Table 4-110). Production of N_2O stabilized during the 1990s because medical markets had found other substitutes for anesthetics, and more medical procedures were being performed on an outpatient basis using local anesthetics that do not require N_2O. The use of N_2O as a propellant for whipped cream has also stabilized due to the increased popularity of cream products packaged in reusable plastic tubs (Heydorn 1997).

Table 4-110: N_2O Emissions from N_2O Product Usage (MMT CO_2 Eq. and kt)

Year	MMT CO_2 Eq.	kt
1990	4.2	14
2005	4.2	14

2012	4.2	14
2013	4.2	14
2014	4.2	14
2015	4.2	14
2016	4.2	14

Methodology

Emissions from N_2O product uses were estimated using the following equation:

$$E_{pu} = \sum_a (P \times S_a \times ER_a)$$

where,

E_{pu} = N_2O emissions from product uses, metric tons
P = Total U.S. production of N_2O, metric tons
a = specific application
S_a = Share of N_2O usage by application *a*
ER_a = Emission rate for application *a*, percent

The share of total quantity of N_2O usage by end-use represents the share of national N_2O produced that is used by the specific subcategory (e.g., anesthesia, food processing). In 2016, the medical/dental industry used an estimated 86.5 percent of total N_2O produced, followed by food processing propellants at 6.5 percent. All other categories combined used the remainder of the N_2O produced. This subcategory breakdown has changed only slightly over the past decade. For instance, the small share of N_2O usage in the production of sodium azide has declined significantly during the 1990s. Due to the lack of information on the specific time period of the phase-out in this market subcategory, most of the N_2O usage for sodium azide production is assumed to have ceased after 1996, with the majority of its small share of the market assigned to the larger medical/dental consumption subcategory (Heydorn 1997). The N_2O was allocated across the following categories: medical applications, food processing propellant, and sodium azide production (pre-1996). A usage emissions rate was then applied for each sector to estimate the amount of N_2O emitted.

Only the medical/dental and food propellant subcategories were estimated to release emissions into the atmosphere, and therefore these subcategories were the only usage subcategories with emission rates. For the medical/dental subcategory, due to the poor solubility of N_2O in blood and other tissues, none of the N_2O is assumed to be metabolized during anesthesia and quickly leaves the body in exhaled breath. Therefore, an emission factor of 100 percent was used for this subcategory (IPCC 2006). For N_2O used as a propellant in pressurized and aerosol food products, none of the N_2O is reacted during the process and all of the N_2O is emitted to the atmosphere, resulting in an emission factor of 100 percent for this subcategory (IPCC 2006). For the remaining subcategories, all of the N_2O is consumed/reacted during the process, and therefore the emission rate was considered to be zero percent (Tupman 2002).

The 1990 through 1992 N_2O production data were obtained from SRI Consulting's *Nitrous Oxide, North America* report (Heydorn 1997). Nitrous oxide production data for 1993 through 1995 were not available. Production data for 1996 was specified as a range in two data sources (Heydorn 1997; Tupman 2002). In particular, for 1996, Heydorn (1997) estimates N_2O production to range between 13.6 and 18.1 thousand metric tons. Tupman (2003) provided a narrower range (15.9 to 18.1 thousand metric tons) for 1996 that falls within the production bounds described by Heydorn (1997). Tupman (2003) data are considered more industry-specific and current. Therefore, the midpoint of the narrower production range was used to estimate N_2O emissions for years 1993 through 2001 (Tupman 2003). The 2002 and 2003 N_2O production data were obtained from the Compressed Gas Association Nitrous Oxide Fact Sheet and Nitrous Oxide Abuse Hotline (CGA 2002, 2003). These data were also provided as a range. For example, in 2003, CGA (2003) estimates N_2O production to range between 13.6 and 15.9 thousand metric tons. Due to the unavailability of data, production estimates for years 2004 through 2016 were held constant at the 2003 value.

The 1996 share of the total quantity of N_2O used by each subcategory was obtained from SRI Consulting's *Nitrous Oxide, North America* report (Heydorn 1997). The 1990 through 1995 share of total quantity of N_2O used by each subcategory was kept the same as the 1996 number provided by SRI Consulting. The 1997 through 2001 share of total quantity of N_2O usage by sector was obtained from communication with a N_2O industry expert (Tupman 2002). The 2002 and 2003 share of total quantity of N_2O usage by sector was obtained from CGA (2002, 2003). Due to the unavailability of data, the share of total quantity of N_2O usage data for years 2004 through 2016 was assumed to equal the 2003 value. The emissions rate for the food processing propellant industry was obtained from SRI Consulting's Nitrous Oxide, North America report (Heydorn 1997), and confirmed by a N_2O industry expert (Tupman 2002). The emissions rate for all other subcategories was obtained from communication with a N_2O industry expert (Tupman 2002). The emissions rate for the medical/dental subcategory was obtained from the *2006 IPCC Guidelines*.

Uncertainty and Time-Series Consistency

The overall uncertainty associated with the 2016 N_2O emission estimate from N_2O product usage was calculated using the *2006 IPCC Guidelines* (2006) Approach 2 methodology. Uncertainty associated with the parameters used to estimate N_2O emissions include production data, total market share of each end use, and the emission factors applied to each end use, respectively.

The results of this Approach 2 quantitative uncertainty analysis are summarized in Table 4-111. Nitrous oxide emissions from N_2O product usage were estimated to be between 3.2 and 5.2 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 24 percent below to 24 percent above the emission estimate of 4.2 MMT CO_2 Eq.

Table 4-111: Approach 2 Quantitative Uncertainty Estimates for N_2O Emissions from N_2O Product Usage (MMT CO_2 Eq. and Percent)

Source	Gas	2016 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
N_2O from Product Uses	N_2O	4.2	3.2	5.2	-24%	+24%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2016. Details on the emission trends through time are described in more detail in the Methodology section, above.

For more information on the general QA/QC process applied to this source category, consistent with Volume 1, Chapter 6 of the *2006 IPCC Guidelines*, see the QA/QC and Verification Procedures section in the introduction of the IPPU chapter.

Planned Improvements

EPA has recently initiated an evaluation of alternative production statistics for cross-verification and updating time-series activity data, emission factors, assumptions, etc., and a reassessment of N_2O product use subcategories that accurately represent trends. This evaluation includes conducting a literature review of publications and research that may provide additional details on the industry. This work is currently ongoing and thus the results have not been incorporated into the current Inventory report.

Pending additional resources and planned improvement prioritization, EPA may also evaluate production and use cycles, and the potential need to incorporate a time lag between production and ultimate product use and resulting release of N_2O. Additionally, planned improvements include considering imports and exports of N_2O for product uses.

Finally, for future Inventories, EPA will examine data from EPA's GHGRP to improve the emission estimates for the N_2O product use subcategory. Particular attention will be made to ensure aggregated information can be published without disclosing CBI and time-series consistency, as the facility-level reporting data from EPA's GHGRP are not available for all inventory years as required in this Inventory. EPA is still assessing the possibility of incorporating aggregated GHGRP CBI data to estimate emissions; therefore, this planned improvement is still in development and not incorporated in the current Inventory report.

4.27 Industrial Processes and Product Use Sources of Indirect Greenhouse Gases

In addition to the main greenhouse gases addressed above, many industrial processes can result in emissions of various ozone precursors (i.e., indirect greenhouse gases). As some of industrial applications also employ thermal incineration as a control technology, combustion byproducts, such as carbon monoxide (CO) and nitrogen oxides (NO_x), are also reported with this source category. Non-CH_4 volatile organic compounds (NMVOCs), commonly referred to as "hydrocarbons," are the primary gases emitted from most processes employing organic or petroleum based products, and can also result from the product storage and handling. Accidental releases of greenhouse gases associated with product use and handling can constitute major emissions in this category. In the United States, emissions from product use are primarily the result of solvent evaporation, whereby the lighter hydrocarbon molecules in the solvents escape into the atmosphere. The major categories of product uses include: degreasing, graphic arts, surface coating, other industrial uses of solvents (e.g., electronics), dry cleaning, and non-industrial uses (e.g., uses of paint thinner). Product usage in the United States also results in the emission of small amounts of hydrofluorocarbons (HFCs) and hydrofluoroethers (HFEs), which are included under Substitution of Ozone Depleting Substances in this chapter.

Total emissions of NO_x, CO, and NMVOCs from non-energy industrial processes and product use from 1990 to 2016 are reported in Table 4-112.

Table 4-112: NO_x, CO, and NMVOC Emissions from Industrial Processes and Product Use (kt)

Gas/Source	1990	2005	2012	2013	2014	2015	2016
NO_x	**592**	**572**	**443**	**434**	**424**	**424**	**424**
Industrial Processes							
Other Industrial Processes[a]	343	437	315	311	306	306	306
Metals Processing	88	60	65	66	68	68	68
Chemical and Allied Product Manufacturing	152	55	45	44	42	42	42
Storage and Transport	3	15	14	10	5	5	5
Miscellaneous[b]	5	2	3	3	2	2	2
Product Uses							
Surface Coating	1	3	1	1	1	1	1
Graphic Arts	+	0	0	0	0	0	0
Degreasing	+	0	0	0	0	0	0
Dry Cleaning	+	0	0	0	0	0	0
Other Industrial Processes[a]	+	0	0	0	0	0	0
Non-Industrial Processes[c]	+	0	0	0	0	0	0
Other	NA	0	0	0	0	0	0
CO	**4,129**	**1,557**	**1,246**	**1,262**	**1,273**	**1,273**	**1,273**
Industrial Processes							
Metals Processing	2,395	752	647	600	553	553	553
Other Industrial Processes[a]	487	484	388	470	551	551	551
Chemical and Allied Product Manufacturing	1,073	189	140	128	117	117	117
Miscellaneous[b]	101	32	49	48	42	42	42
Storage and Transport	69	97	19	14	9	9	9
Product Uses							
Surface Coating	+	2	2	2	1	1	1
Other Industrial Processes[a]	4	0	0	0	0	0	0
Dry Cleaning	+	0	0	0	0	0	0
Degreasing	+	0	0	0	0	0	0

Graphic Arts	+	0	0	0	0	0	0
Non-Industrial Processes[c]	+	0	0	0	0	0	0
Other	NA	0	0	0	0	0	0
NMVOCs	**7,638**	**5,849**	**3,861**	**3,793**	**3,723**	**3,723**	**3,723**
Industrial Processes							
Storage and Transport	1,352	1,308	837	727	618	618	618
Other Industrial Processes[a]	364	414	306	313	320	320	320
Chemical and Allied Product Manufacturing	575	213	73	70	68	68	68
Metals Processing	111	45	29	28	26	26	26
Miscellaneous[b]	20	17	27	26	23	23	23
Product Uses							
Surface Coating	2,289	1,578	1,061	1,077	1,093	1,093	1,093
Non-Industrial Processes[c]	1,724	1,446	972	987	1,002	1,002	1,002
Degreasing	675	280	189	191	194	194	194
Dry Cleaning	195	230	155	157	160	160	160
Graphic Arts	249	194	130	132	134	134	134
Other Industrial Processes[a]	85	88	59	60	61	61	61
Other	+	36	24	24	25	25	25

+ Does not exceed 0.5 kt

NA (Not Available)

[a] Includes rubber and plastics manufacturing, and other miscellaneous applications.

[b] Miscellaneous includes the following categories: catastrophic/accidental release, other combustion, health services, cooling towers, and fugitive dust. It does not include agricultural fires or slash/prescribed burning, which are accounted for under the Field Burning of Agricultural Residues source.

[c] Includes cutback asphalt, pesticide application adhesives, consumer solvents, and other miscellaneous applications.

Note: Totals may not sum due to independent rounding.

Methodology

Emission estimates for 1990 through 2016 were obtained from data published on the National Emission Inventory (NEI) Air Pollutant Emission Trends web site (EPA 2016), and disaggregated based on EPA (2003). Data were collected for emissions of CO, NO_x, volatile organic compounds (VOCs), and sulfur dioxide (SO_2) from metals processing, chemical manufacturing, other industrial processes, transport and storage, and miscellaneous sources. Emission estimates for 2012 and 2013 for non-electric generating units (EGU) were updated to the most recent available data in EPA (2016). Emission estimates for 2012 and 2013 for non-mobile sources are recalculated emissions by interpolation from 2016 in EPA (2016). Emissions were calculated either for individual source categories or for many categories combined, using basic activity data (e.g., the amount of raw material processed or the amount of solvent purchased) as an indicator of emissions. National activity data were collected for individual categories from various agencies. Depending on the category, these basic activity data may include data on production, fuel deliveries, raw material processed, etc.

Emissions for product use were calculated by aggregating product use data based on information relating to product uses from different applications such as degreasing, graphic arts, etc. Emission factors for each consumption category were then applied to the data to estimate emissions. For example, emissions from surface coatings were mostly due to solvent evaporation as the coatings solidify. By applying the appropriate product-specific emission factors to the amount of products used for surface coatings, an estimate of NMVOC emissions was obtained. Emissions of CO and NO_x under product use result primarily from thermal and catalytic incineration of solvent-laden gas streams from painting booths, printing operations, and oven exhaust.

Activity data were used in conjunction with emission factors, which together relate the quantity of emissions to the activity. Emission factors are generally available from the EPA's *Compilation of Air Pollutant Emission Factors*, AP-42 (EPA 1997). The EPA currently derives the overall emission control efficiency of a source category from a variety of information sources, including published reports, the 1985 National Acid Precipitation and Assessment Program emissions inventory, and other EPA databases.

Uncertainty and Time-Series Consistency

Uncertainties in these estimates are partly due to the accuracy of the emission factors and activity data used. A quantitative uncertainty analysis was not performed.

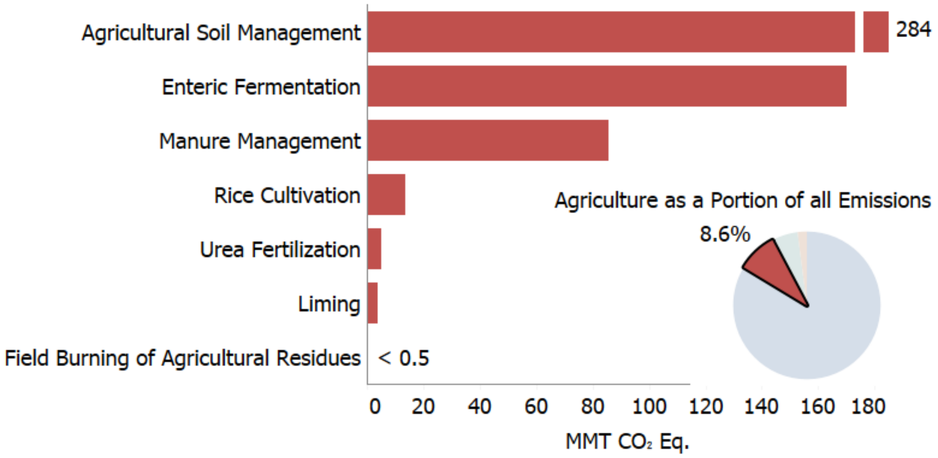
Methodological approaches were applied to the entire time series to ensure time-series consistency from 1990 through 2016. Details on the emission trends through time are described in more detail in the Methodology section, above.

For more information on the general QA/QC process applied to this source category, consistent with Volume 1, Chapter 6 of the *2006 IPCC Guidelines*, see the QA/QC and Verification Procedures section in the introduction of the IPPU chapter.

5. Agriculture

Agricultural activities contribute directly to emissions of greenhouse gases through a variety of processes. This chapter provides an assessment of methane (CH_4) and nitrous oxide (N_2O) emissions from enteric fermentation in domestic livestock, livestock manure management, rice cultivation, agricultural soil management, and field burning of agricultural residues; as well as carbon dioxide (CO_2) emissions from liming and urea fertilization (see Figure 5-1). Additional CO_2, CH_4 and N_2O fluxes from agriculture-related land-use and land-use conversion activities, such as cultivation of cropland, grassland fires and conversion of forest land to cropland, are presented in the Land Use, Land-Use Change, and Forestry (LULUCF) chapter. Carbon dioxide emissions from on-farm energy use are reported in the Energy chapter.

Figure 5-1: 2016 Agriculture Chapter Greenhouse Gas Emission Sources (MMT CO_2 Eq.)



In 2016, the Agriculture sector was responsible for emissions of 562.6 MMT CO_2 Eq.,[1] or 8.6 percent of total U.S. greenhouse gas emissions.[2] Methane emissions from enteric fermentation and manure management represent 25.9 percent and 10.3 percent of total CH_4 emissions from anthropogenic activities, respectively. Of all domestic animal types, beef and dairy cattle were by far the largest emitters of CH_4. Rice cultivation and field burning of agricultural residues were minor sources of CH_4. Emissions of N_2O by agricultural soil management through activities such as fertilizer application and other agricultural practices that increased nitrogen availability in the soil was the largest source of U.S. N_2O emissions, accounting for 76.7 percent. Manure management and field burning of agricultural residues were also small sources of N_2O emissions. Urea fertilization and liming each accounted for 0.1 percent of total CO_2 emissions from anthropogenic activities.

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[1] Following the current reporting requirements under the United Nations Framework Convention on Climate Change (UNFCCC), this Inventory report presents CO_2 equivalent values based on the *IPCC Fourth Assessment Report* (AR4) GWP values. See the Introduction chapter for more information.

[2] Emissions reported in the Agriculture chapter include those from all states, including Hawaii and Alaska; however, U.S. Territories are not included.

Table 5-1 and Table 5-2 present emission estimates for the Agriculture sector. Between 1990 and 2016, CO_2 and CH_4 emissions from agricultural activities increased by 26.5 percent and 15.8 percent, respectively, while N_2O emissions from agricultural activities fluctuated from year to year, but increased by 14.1 percent overall.

Table 5-1: Emissions from Agriculture (MMT CO_2 Eq.)

Gas/Source	1990	2005	2012	2013	2014	2015	2016
CO_2	**7.1**	**7.9**	**10.3**	**8.4**	**8.1**	**8.7**	**9.0**
Urea Fertilization	2.4	3.5	4.3	4.4	4.5	4.9	5.1
Liming	4.7	4.3	6.0	3.9	3.6	3.8	3.9
CH_4	**217.6**	**242.1**	**244.0**	**240.6**	**240.1**	**245.4**	**251.8**
Enteric Fermentation	164.2	168.9	166.7	165.5	164.2	166.5	170.1
Manure Management	37.2	56.3	65.6	63.3	62.9	66.3	67.7
Rice Cultivation	16.0	16.7	11.3	11.5	12.7	12.3	13.7
Field Burning of Agricultural Residues	0.2	0.2	0.3	0.3	0.3	0.3	0.3
N_2O	**264.5**	**270.1**	**265.5**	**294.2**	**291.6**	**312.8**	**301.8**
Agricultural Soil Management	250.5	253.5	247.9	276.6	274.0	295.0	283.6
Manure Management	14.0	16.5	17.5	17.5	17.5	17.7	18.1
Field Burning of Agricultural Residues	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Total	**489.2**	**520.0**	**519.8**	**543.1**	**539.8**	**566.9**	**562.6**

Note: Totals may not sum due to independent rounding.

Table 5-2: Emissions from Agriculture (kt)

Gas/Source	1990	2005	2012	2013	2014	2015	2016
CO_2	**7,084**	**7,854**	**10,259**	**8,350**	**8,147**	**8,665**	**8,961**
Urea Fertilization	2,417	3,504	4,282	4,443	4,538	4,888	5,098
Liming	4,667	4,349	5,978	3,907	3,609	3,777	3,863
CH_4	**8,702**	**9,684**	**9,760**	**9,623**	**9,602**	**9,816**	**10,073**
Enteric Fermentation	6,566	6,755	6,670	6,619	6,567	6,661	6,805
Manure Management	1,486	2,254	2,625	2,530	2,514	2,651	2,709
Rice Cultivation	641	667	453	462	510	493	549
Field Burning of Agricultural Residues	9	8	11	11	11	11	11
N_2O	**888**	**906**	**891**	**987**	**979**	**1,050**	**1,013**
Agricultural Soil Management	840	851	832	928	920	990	952
Manure Management	47	55	59	59	59	59	61
Field Burning of Agricultural Residues	+	+	+	+	+	+	+

+ Does not exceed 0.5 kt.

Note: Totals may not sum due to independent rounding.

Box 5-1: Methodological Approach for Estimating and Reporting U.S. Emissions and Removals

In following the United Nations Framework Convention on Climate Change (UNFCCC) requirement under Article 4.1 to develop and submit national greenhouse gas emission inventories, the emissions and removals presented in this report and this chapter, are organized by source and sink categories and calculated using internationally-accepted methods provided by the Intergovernmental Panel on Climate Change (IPCC) in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories (2006 IPCC Guidelines)*. Additionally, the calculated emissions and removals in a given year for the United States are presented in a common manner in line with the UNFCCC reporting guidelines for the reporting of inventories under this international agreement. The use of consistent methods to calculate emissions and removals by all nations providing their inventories to the UNFCCC ensures that these reports are comparable. The presentation of emissions and removals provided in this Inventory do not preclude alternative examinations, but rather, this Inventory presents emissions and removals in a common format consistent with how countries are to report Inventories under the UNFCCC. The report itself, and this chapter, follows this standardized format, and provides an explanation of the application of methods used to calculate emissions and removals.

Box 5-2: Biennial Inventory Compilation

For the current Inventory (i.e., 1990 through 2016 report), a biennial inventory compilation process has been implemented for the Agriculture and LULUCF chapters. As part of this biennial compilation process, during alternating years, modified approaches will be applied to extend the emissions/removals time series of some Agriculture and LULUCF source and sink categories rather than implementing a full inventory compilation (i.e., updating activity data and running models). In the current Inventory, for each category where these modified approaches for extending the time series have been utilized, the alternative methods have been transparently documented in their respective Methodology sections of the chapter. This biennial compilation schedule has been adopted for the Agriculture and LULUCF chapters in order to conserve and efficiently utilize resources that are needed to implement key improvements. Over the next four to six years, this process will result in more rapid improvements to the Agriculture and LULUCF chapters. The next Inventory (i.e., 1990 through 2017 report) will include a full compilation of the Agriculture and LULUCF chapters along with a number of key improvements.

5.1 Enteric Fermentation (CRF Source Category 3A)

Methane is produced as part of normal digestive processes in animals. During digestion, microbes resident in an animal's digestive system ferment food consumed by the animal. This microbial fermentation process, referred to as enteric fermentation, produces CH_4 as a byproduct, which can be exhaled or eructated by the animal. The amount of CH_4 produced and emitted by an individual animal depends primarily upon the animal's digestive system, and the amount and type of feed it consumes.

Ruminant animals (e.g., cattle, buffalo, sheep, goats, and camels) are the major emitters of CH_4 because of their unique digestive system. Ruminants possess a rumen, or large "fore-stomach," in which microbial fermentation breaks down the feed they consume into products that can be absorbed and metabolized. The microbial fermentation that occurs in the rumen enables them to digest coarse plant material that non-ruminant animals cannot. Ruminant animals, consequently, have the highest CH_4 emissions per unit of body mass among all animal types.

Non-ruminant animals (e.g., swine, horses, and mules and asses) also produce CH_4 emissions through enteric fermentation, although this microbial fermentation occurs in the large intestine. These non-ruminants emit significantly less CH_4 on a per-animal-mass basis than ruminants because the capacity of the large intestine to produce CH_4 is lower.

In addition to the type of digestive system, an animal's feed quality and feed intake also affect CH_4 emissions. In general, lower feed quality and/or higher feed intake leads to higher CH_4 emissions. Feed intake is positively correlated to animal size, growth rate, level of activity and production (e.g., milk production, wool growth, pregnancy, or work). Therefore, feed intake varies among animal types as well as among different management practices for individual animal types (e.g., animals in feedlots or grazing on pasture).

Methane emission estimates from enteric fermentation are provided in Table 5-3 and Table 5-4. Total livestock CH_4 emissions in 2016 were 170.1 MMT CO_2 Eq. (6,805 kt). Beef cattle remain the largest contributor of CH_4 emissions from enteric fermentation, accounting for 71 percent in 2016. Emissions from dairy cattle in 2016 accounted for 25 percent, and the remaining emissions were from horses, sheep, swine, goats, American bison, mules and asses.

Table 5-3: CH_4 Emissions from Enteric Fermentation (MMT CO_2 Eq.)

Livestock Type	1990		2005		2012	2013	2014	2015	2016
Beef Cattle	119.1		125.2		119.1	118.0	116.5	118.1	121.3
Dairy Cattle	39.4		37.6		41.7	41.6	42.0	42.6	42.9
Swine	2.0		2.3		2.5	2.5	2.4	2.6	2.6
Horses	1.0		1.7		1.6	1.6	1.6	1.5	1.5
Sheep	2.3		1.2		1.1	1.1	1.0	1.1	1.1
Goats	0.3		0.4		0.3	0.3	0.3	0.3	0.3
American Bison	0.1		0.4		0.3	0.3	0.3	0.3	0.3
Mules and Asses	+		0.1		0.1	0.1	0.1	0.1	0.1
Total	**164.2**		**168.9**		**166.7**	**165.5**	**164.2**	**166.5**	**170.1**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table 5-4: CH_4 Emissions from Enteric Fermentation (kt)

Livestock Type	1990		2005		2012	2013	2014	2015	2016
Beef Cattle	4,763		5,007		4,763	4,722	4,660	4,724	4,853
Dairy Cattle	1,574		1,503		1,670	1,664	1,679	1,706	1,715
Swine	81		92		100	98	96	102	105
Horses	40		70		65	64	62	61	62
Sheep	91		49		43	43	42	42	42
Goats	13		14		13	13	12	12	13
American Bison	4		17		13	13	12	12	11
Mules and Asses	1		2		3	3	3	3	3
Total	**6,566**		**6,755**		**6,670**	**6,619**	**6,567**	**6,661**	**6,805**

Note: Totals may not sum due to independent rounding.

From 1990 to 2016, emissions from enteric fermentation have increased by 3.6 percent. While emissions generally follow trends in cattle populations, over the long term there are exceptions as population decreases have been coupled with both production increases and minor decreases. For example, beef cattle emissions increased 1.9 percent from 1990 to 2016, while beef cattle populations actually declined by 3.7 percent and beef production increased (USDA 2016), and while dairy cattle emissions increased 8.9 percent over the entire time series, the population has declined by 2.1 percent and milk production increased 54 percent (USDA 2016). This trend indicates that while emission factors per head are increasing, emission factors per unit of product are going down.

Generally, from 1990 to 1995 emissions from beef cattle increased and then decreased from 1996 to 2004. These trends were mainly due to fluctuations in beef cattle populations and increased digestibility of feed for feedlot cattle. Beef cattle emissions generally increased from 2004 to 2007, as beef cattle populations underwent increases and an extensive literature review indicated a trend toward a decrease in feed digestibility for those years. Beef cattle emissions decreased again from 2007 to 2014, as populations again decreased, but increased in 2015 and 2016, consistent with another increase in population over those same years. Emissions from dairy cattle generally trended downward from 1990 to 2004, along with an overall dairy cattle population decline during the same period. Similar to beef cattle, dairy cattle emissions rose from 2004 to 2007 due to population increases and a decrease in feed digestibility (based on an analysis of more than 350 dairy cow diets). Dairy cattle emissions have continued to trend upward since 2007, in line with dairy cattle population increases. Regarding trends in other animals, populations of sheep have steadily declined, with an overall decrease of 53 percent since 1990. Horse populations are 56 percent greater than they were in 1990, but their numbers have been declining by about 2 percent annually since 2007. Goat populations increased by about 20 percent through 2007, steadily decreased through 2015, then jumped by 13 percent from 2015 to 2016. Swine populations have trended upward through most of the time series, increasing 19 percent from 1990 to 2016. The population of American bison nearly tripled over the 1990 to 2016 time period, while mules and asses have more than quadrupled.

Methodology

Livestock enteric fermentation emission estimate methodologies fall into two categories: cattle and other domesticated animals. Cattle, due to their large population, large size, and particular digestive characteristics, account for the majority of enteric fermentation CH_4 emissions from livestock in the United States. A more detailed methodology (i.e., IPCC Tier 2) was therefore applied to estimate emissions for all cattle. Emission estimates for other domesticated animals (horses, sheep, swine, goats, American bison, and mules and asses) were handled using a less detailed approach (i.e., IPCC Tier 1).

While the large diversity of animal management practices cannot be precisely characterized and evaluated, significant scientific literature exists that provides the necessary data to estimate cattle emissions using the IPCC Tier 2 approach. The Cattle Enteric Fermentation Model (CEFM), developed by EPA and used to estimate cattle CH_4 emissions from enteric fermentation, incorporates this information and other analyses of livestock population, feeding practices, and production characteristics. For the current Inventory, CEFM results for 1990 through 2015 were carried over from the 1990 to 2015 Inventory (i.e., 2017 Inventory submission), and a simplified approach was used to estimate 2016 enteric emissions from cattle.

1990 to 2015 Inventory Methodology for Cattle

National cattle population statistics were disaggregated into the following cattle sub-populations:

- Dairy Cattle
    - Calves
    - Heifer Replacements
    - Cows
- Beef Cattle
    - Calves
    - Heifer Replacements
    - Heifer and Steer Stockers
    - Animals in Feedlots (Heifers and Steer)
    - Cows
    - Bulls

Calf birth rates, end-of-year population statistics, detailed feedlot placement information, and slaughter weight data were used to create a transition matrix that models cohorts of individual animal types and their specific emission profiles. The key variables tracked for each of the cattle population categories are described in Annex 3.10. These variables include performance factors such as pregnancy and lactation as well as average weights and weight gain. Annual cattle population data were obtained from the U.S. Department of Agriculture's (USDA) National Agricultural Statistics Service (NASS) *QuickStats* database (USDA 2016).

Diet characteristics were estimated by region for dairy, grazing beef, and feedlot beef cattle. These diet characteristics were used to calculate digestible energy (DE) values (expressed as the percent of gross energy intake digested by the animal) and CH_4 conversion rates (Y_m) (expressed as the fraction of gross energy converted to CH_4) for each regional population category. The IPCC recommends Y_m ranges of 3.0±1.0 percent for feedlot cattle and 6.5±1.0 percent for other well-fed cattle consuming temperate-climate feed types (IPCC 2006). Given the availability of detailed diet information for different regions and animal types in the United States, DE and Y_m values unique to the United States were developed. The diet characterizations and estimation of DE and Y_m values were based on information from state agricultural extension specialists, a review of published forage quality studies and scientific literature, expert opinion, and modeling of animal physiology.

The diet characteristics for dairy cattle were based on Donovan (1999) and an extensive review of nearly 20 years of literature from 1990 through 2009. Estimates of DE were national averages based on the feed components of the diets observed in the literature for the following year groupings: 1990 through 1993, 1994 through 1998, 1999 through 2003, 2004 through 2006, 2007, and 2008 onward.[3] Base year Y_m values by region were estimated using Donovan (1999). As described in ERG (2016), a ruminant digestion model (COWPOLL, as selected in Kebreab et al. 2008) was used to evaluate Y_m for each diet evaluated from the literature, and a function was developed to adjust regional values over time based on the national trend. Dairy replacement heifer diet assumptions were based on the observed relationship in the literature between dairy cow and dairy heifer diet characteristics.

For feedlot animals, the DE and Y_m values used for 1990 were recommended by Johnson (1999). Values for DE and Y_m for 1991 through 1999 were linearly extrapolated based on the 1990 and 2000 data. DE and Y_m values for 2000 onwards were based on survey data in Galyean and Gleghorn (2001) and Vasconcelos and Galyean (2007).

For grazing beef cattle, Y_m values were based on Johnson (2002), DE values for 1990 through 2006 were based on specific diet components estimated from Donovan (1999), and DE values from 2007 onwards were developed from an analysis by Archibeque (2011), based on diet information in Preston (2010) and USDA-APHIS:VS (2010). Weight and weight gains for cattle were estimated from Holstein (2010), Doren et al. (1989), Enns (2008), Lippke et al. (2000), Pinchack et al. (2004), Platter et al. (2003), Skogerboe et al. (2000), and expert opinion. See Annex 3.10 for more details on the method used to characterize cattle diets and weights in the United States.

Calves younger than 4 months are not included in emission estimates because calves consume mainly milk and the IPCC recommends the use of a Y_m of zero for all juveniles consuming only milk. Diets for calves aged 4 to 6 months are assumed to go through a gradual weaning from milk decreasing to 75 percent at 4 months, 50 percent at age 5 months, and 25 percent at age 6 months. The portion of the diet made up with milk still results in zero emissions. For the remainder of the diet, beef calf DE and Y_m are set equivalent to those of beef replacement heifers, while dairy calf DE is set equal to that of dairy replacement heifers and dairy calf Y_m is provided at 4 and 7 months of age by Soliva (2006). Estimates of Y_m for 5 and 6 month old dairy calves are linearly interpolated from the values provided for 4 and 7 months.

To estimate CH_4 emissions, the population was divided into state, age, sub-type (i.e., dairy cows and replacements, beef cows and replacements, heifer and steer stockers, heifers and steers in feedlots, bulls, beef calves 4 to 6 months, and dairy calves 4 to 6 months), and production (i.e., pregnant, lactating) groupings to more fully capture differences in CH_4 emissions from these animal types. The transition matrix was used to simulate the age and weight structure of each sub-type on a monthly basis in order to more accurately reflect the fluctuations that occur throughout the year. Cattle diet characteristics were then used in conjunction with Tier 2 equations from IPCC (2006) to produce CH_4 emission factors for the following cattle types: dairy cows, beef cows, dairy replacements, beef replacements, steer stockers, heifer stockers, steer feedlot animals, heifer feedlot animals, bulls, and calves. To estimate emissions from cattle, monthly population data from the transition matrix were multiplied by the calculated emission factor for each cattle type. More details are provided in Annex 3.10.

2016 Inventory Methodology for Cattle

As noted above, a simplified approach for cattle enteric emissions was used in lieu of the CEFM for 2016. First, 2016 populations for each of the CEFM cattle sub-populations were estimated, then these populations were multiplied by the corresponding implied emission factors developed from the CEFM for the previous Inventory year. Dairy cow, beef cow, and bull populations for 2016 were based on data directly from the USDA-NASS *QuickStats* database (USDA 2017). Because the remaining CEFM cattle sub-population categories do not correspond exactly to the remaining *QuickStats* cattle categories, 2016 populations for these categories were estimated by extrapolating the 2015 populations based on percent changes from 2015 to 2016 in similar *QuickStats* categories, consistent with Volume 1, Chapter 5 of the *2006 IPCC Guidelines* on time-series consistency. Table 5-5 lists the *QuickStats* categories used to estimate the percent change in population for each of the CEFM categories.

Table 5-5: Cattle Sub-Population Categories for 2016 Population Estimates

CEFM Cattle Category	USDA-NASS *Quickstats* Cattle Category
Dairy Calves	Cattle, Calves
Dairy Cows	Cattle, Cows, Milk
Dairy Replacements 7-11 months	Cattle, Heifers, GE 500 lbs, Milk Replacement

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[3] Due to inconsistencies in the 2003 literature values, the 2002 values were used for 2003, as well.

Dairy Replacements 12-23 months	Cattle, Heifers, GE 500 lbs, Milk Replacement
Bulls	Cattle, Bulls, GE 500 lbs
Beef Calves	Cattle, Calves
Beef Cows	Cattle, Cows, Beef
Beef Replacements 7-11 months	Cattle, Heifers, GE 500 lbs, Beef Replacement
Beef Replacements 12-23 months	Cattle, Heifers, GE 500 lbs, Beef Replacement
Steer Stockers	Cattle, Steers, GE 500 lbs
Heifer Stockers	Cattle, Heifers, GE 500 lbs, (Excl. Replacement)
Steer Feedlot	Cattle, On Feed
Heifer Feedlot	Cattle, On Feed

Non-Cattle Livestock

Emission estimates for other animal types were based on average emission factors representative of entire populations of each animal type. Methane emissions from these animals accounted for a minor portion of total CH_4 emissions from livestock in the United States from 1990 through 2016. Additionally, the variability in emission factors for each of these other animal types (e.g., variability by age, production system, and feeding practice within each animal type) is less than that for cattle.

Annual livestock population data for 1990 to 2015 for sheep; swine; goats; horses; mules and asses; and American bison were obtained for available years from USDA-NASS (USDA 2016). Horse, goat and mule and ass population data were available for 1987, 1992, 1997, 2002, 2007, and 2012 (USDA 1992, 1997, 2016); the remaining years between 1990 and 2015 were interpolated and extrapolated from the available estimates (with the exception of goat populations being held constant between 1990 and 1992). American bison population estimates were available from USDA for 2002, 2007, and 2012 (USDA 2016) and from the National Bison Association (1999) for 1990 through 1999. Additional years were based on observed trends from the National Bison Association (1999), interpolation between known data points, and extrapolation beyond 2012, as described in more detail in Annex 3.10. For the 2016 Inventory simplified approach, values for 1990 through 2015 remained the same as the 1990 through 2015 Inventory. For 2016 populations, sheep and swine population data were obtained from USDA-NASS (USDA 2017). The 2016 populations for the other animal groups were extrapolated based on 1990 through 2015 values.

Methane emissions from sheep, goats, swine, horses, American bison, and mules and asses were estimated by using emission factors utilized in Crutzen et al. (1986, cited in IPCC 2006). These emission factors are representative of typical animal sizes, feed intakes, and feed characteristics in developed countries. For American bison the emission factor for buffalo was used and adjusted based on the ratio of live weights to the 0.75 power. The methodology is the same as that recommended by IPCC (2006).

See Annex 3.10 for more detailed information on the methodology and data used to calculate CH_4 emissions from enteric fermentation.

Uncertainty and Time-Series Consistency

A quantitative uncertainty analysis for this source category was performed using the IPCC-recommended Approach 2 uncertainty estimation methodology based on a Monte Carlo Stochastic Simulation technique as described in ICF (2003). These uncertainty estimates were developed for the 1990 through 2001 Inventory (i.e., 2003 submission to the UNFCCC). There have been no significant changes to the methodology since that time; consequently, these uncertainty estimates were directly applied to the 2016 emission estimates in this Inventory.

A total of 185 primary input variables (177 for cattle and 8 for non-cattle) were identified as key input variables for the uncertainty analysis. A normal distribution was assumed for almost all activity- and emission factor-related input variables. Triangular distributions were assigned to three input variables (specifically, cow-birth ratios for the three most recent years included in the 2001 model run) to ensure only positive values would be simulated. For some key input variables, the uncertainty ranges around their estimates (used for inventory estimation) were collected from published documents and other public sources; others were based on expert opinion and best estimates. In addition, both endogenous and exogenous correlations between selected primary input variables were modeled. The exogenous correlation coefficients between the probability distributions of selected activity-related variables were developed through expert judgment.

The uncertainty ranges associated with the activity data-related input variables were plus or minus 10 percent or lower. However, for many emission factor-related input variables, the lower- and/or the upper-bound uncertainty estimates were over 20 percent. The results of the quantitative uncertainty analysis are summarized in Table 5-6. Based on this analysis, enteric fermentation CH_4 emissions in 2016 were estimated to be between 151.4 and 200.7 MMT CO_2 Eq. at a 95 percent confidence level, which indicates a range of 11 percent below to 18 percent above the 2016 emission estimate of 170.1 MMT CO_2 Eq. Among the individual cattle sub-source categories, beef cattle account for the largest amount of CH_4 emissions, as well as the largest degree of uncertainty in the emission estimates—due mainly to the difficulty in estimating the diet characteristics for grazing members of this animal group. Among non-cattle, horses represent the largest percent of uncertainty in the previous uncertainty analysis because the Food and Agricultural Organization of the United Nations (FAO) population estimates used for horses at that time had a higher degree of uncertainty than for the USDA population estimates used for swine, goats, and sheep. The horse populations are now from the same USDA source as the other animal types, and therefore the uncertainty range around horses is likely overestimated. Cattle calves, American bison, mules and asses were excluded from the initial uncertainty estimate because they were not included in emission estimates at that time.

Table 5-6: Approach 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Enteric Fermentation (MMT CO_2 Eq. and Percent)

Source	Gas	2016 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a, b, c] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Enteric Fermentation	CH_4	170.1	151.4	200.7	-11%	+18%

[a] Range of emissions estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

[b] Note that the relative uncertainty range was estimated with respect to the 2001 emission estimates from the 2003 submission and applied to the 2016 estimates.

[c] The overall uncertainty calculated in 2003, and applied to the 2016 emission estimate, did not include uncertainty estimates for calves, American bison, and mules and asses. Additionally, for bulls the emissions estimate was based on the Tier 1 methodology. Since bull emissions are now estimated using the Tier 2 method, the uncertainty surrounding their estimates is likely lower than indicated by the previous uncertainty analysis.

Details on the emission trends through time are described in more detail in the Methodology section.

QA/QC and Verification

In order to ensure the quality of the emission estimates from enteric fermentation, the IPCC Tier 1 and Tier 2 Quality Assurance/Quality Control (QA/QC) procedures were implemented consistent with the U.S. QA/QC plan (EPA 2002). Tier 2 QA procedures included independent review of emission estimate methodologies from previous inventories. Over the past few years, particular importance has been placed on harmonizing the data exchange between the enteric fermentation and manure management source categories. The current Inventory now utilizes the transition matrix from the CEFM for estimating cattle populations and weights for both source categories, and the CEFM is used to output volatile solids and nitrogen excretion estimates using the diet assumptions in the model in conjunction with the energy balance equations from the IPCC (2006). This approach facilitates the QA/QC process for both of these source categories.

Recalculations Discussion

No recalculations were performed for the 1990 to 2015 estimates. The 2016 estimates were developed using a simplified approach, as noted earlier in the chapter.

Planned Improvements

Continued research and regular updates are necessary to maintain an emissions inventory that reflects the current base of knowledge. Depending upon the outcome of ongoing investigations, future improvements for enteric fermentation could include some of the following options:

- Further research to improve the estimation of dry matter intake (as gross energy intake) using data from appropriate production systems;
- Updating input variables that are from older data sources, such as beef births by month and beef cow lactation rates;
- Investigation of the availability of annual data for the DE, Y_m, and crude protein values of specific diet and feed components for grazing and feedlot animals;
- Further investigation on additional sources or methodologies for estimating DE for dairy cattle, given the many challenges in characterizing dairy cattle diets;
- Further evaluation of the assumptions about weights and weight gains for beef cows, such that trends beyond 2007 are updated, rather than held constant;
- Further evaluation of the estimated weight for dairy cows (i.e., 1,500 lbs) that is based solely on Holstein cows as mature dairy cow weight is likely slightly overestimated, based on knowledge of the breeds of dairy cows in the United States;
- Potentially updating to a Tier 2 methodology for other animal types (i.e., sheep, swine, goats, horses);
- Investigation of methodologies and emission factors for including enteric fermentation emission estimates from poultry;
- Comparison of the current CEFM processing of animal population data to estimates developed using annual average populations to determine if the model could be simplified to use annual population data; and
- Recent changes that have been implemented to the CEFM warrant an assessment of the current uncertainty analysis; therefore, a revision of the quantitative uncertainty surrounding emission estimates from this source category will be initiated.

5.2 Manure Management (CRF Source Category 3B)

The treatment, storage, and transportation of livestock manure can produce anthropogenic CH_4 and N_2O emissions. Methane is produced by the anaerobic decomposition of manure and nitrous oxide is produced from direct and indirect pathways through the processes of nitrification and denitrification; in addition, there are many underlying factors that can affect these resulting emissions from manure management, as described below.

When livestock or poultry manure are stored or treated in systems that promote anaerobic conditions (e.g., as a liquid/slurry in lagoons, ponds, tanks, or pits), the decomposition of the volatile solids component in the manure tends to produce CH_4. When manure is handled as a solid (e.g., in stacks or drylots) or deposited on pasture, range, or paddock lands, it tends to decompose aerobically and produce little or no CH_4. Ambient temperature, moisture, and manure storage or residency time affect the amount of CH_4 produced because they influence the growth of the bacteria responsible for CH_4 formation. For non-liquid-based manure systems, moist conditions (which are a function of rainfall and humidity) can promote CH_4 production. Manure composition, which varies by animal diet, growth rate, and type, including the animal’s digestive system, also affects the amount of CH_4 produced. In general, the greater the energy content of the feed, the greater the potential for CH_4 emissions. However, some higher-energy feeds also are more digestible than lower quality forages, which can result in less overall waste excreted from the animal.

As previously stated, nitrous oxide emissions are produced through both direct and indirect pathways. Direct N_2O emissions are produced as part of the nitrogen (N) cycle through the nitrification and denitrification of the organic N in livestock dung and urine.[4] There are two pathways for indirect N_2O emissions. The first is the result of the volatilization of N in manure (as NH_3 and NO_x) and the subsequent deposition of these gases and their products (NH_4^+ and NO_3^-) onto soils and the surface of lakes and other waters. The second pathway is the runoff and leaching of N from manure to the groundwater below, in riparian zones receiving drain or runoff water, or in the ditches, streams, rivers, and estuaries into which the land drainage water eventually flows.

The production of direct N_2O emissions from livestock manure depends on the composition of the manure and urine, the type of bacteria involved in the process, and the amount of oxygen and liquid in the manure system. For direct N_2O emissions to occur, the manure must first be handled aerobically where ammonia (NH_3) or organic N is converted to nitrates and nitrites (nitrification), and then handled anaerobically where the nitrates and nitrites are reduced to dinitrogen gas (N_2), with intermediate production of N_2O and nitric oxide (NO) (denitrification) (Groffman et al. 2000). These emissions are most likely to occur in dry manure handling systems that have aerobic conditions, but that also contain pockets of anaerobic conditions due to saturation. A very small portion of the total N excreted is expected to convert to N_2O in the waste management system (WMS). Indirect N_2O emissions are produced when nitrogen is lost from the system through volatilization (as NH_3 or NO_x) or through runoff and leaching. The vast majority of volatilization losses from these operations are NH_3. Although there are also some small losses of NO_x, there are no quantified estimates available for use, so losses due to volatilization are only based on NH_3 loss factors. Runoff losses would be expected from operations that house animals or store manure in a manner that is exposed to weather. Runoff losses are also specific to the type of animal housed on the operation due to differences in manure characteristics. Little information is known about leaching from manure management systems as most research focuses on leaching from land application systems. Since leaching losses are expected to be minimal, leaching losses are coupled with runoff losses and the runoff/leaching estimate provided in this chapter does not account for any leaching losses.

Estimates of CH_4 emissions from manure management in 2016 were 67.7 MMT CO_2 Eq. (2,709 kt); in 1990, emissions were 37.2 MMT CO_2 Eq. (1,486 kt). This represents an 82 percent increase in emissions from 1990. Emissions increased on average by 1.1 MMT CO_2 Eq. (3.0 percent) annually over this period. The majority of this increase is due to swine and dairy cow manure, where emissions increased 63 and 140 percent, respectively. From 2015 to 2016, there was a 2.2 percent increase in total CH_4 emissions from manure management, due to an increase in animal populations.

Although the majority of managed manure in the United States is handled as a solid, producing little CH_4, the general trend in manure management, particularly for dairy cattle and swine (which are both shifting towards larger facilities), is one of increasing use of liquid systems. Also, new regulations controlling the application of manure nutrients to land have shifted manure management practices at smaller dairies from daily spread systems to storage and management of the manure on site. In many cases, manure management systems with the most substantial methane emissions are those associated with confined animal management operations where manure is handled in liquid-based systems. Nitrous oxide emissions from manure management vary significantly between the types of management system used and can also result in indirect emissions due to other forms of nitrogen loss from the system (IPCC 2006).

While national dairy animal populations have generally been decreasing since 1990, some states have seen increases in their dairy cattle populations as the industry becomes more concentrated in certain areas of the country and the number of animals contained on each facility increases. These areas of concentration, such as California, New Mexico, and Idaho, tend to utilize more liquid-based systems to manage (flush or scrape) and store manure. Thus, the shift toward larger dairy cattle and swine facilities has translated into an increasing use of liquid manure management systems, which have higher potential CH_4 emissions than dry systems. This significant shift in both the dairy cattle and swine industries was accounted for by incorporating state and WMS-specific CH_4 conversion factor

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[4] Direct and indirect N_2O emissions from dung and urine spread onto fields either directly as daily spread or after it is removed from manure management systems (i.e., lagoon, pit, etc.) and from livestock dung and urine deposited on pasture, range, or paddock lands are accounted for and discussed in the Agricultural Soil Management source category within the Agriculture sector.

(MCF) values in combination with the 1992, 1997, 2002, 2007 and 2012 farm-size distribution data reported in the U.S. Department of Agriculture (USDA) *Census of Agriculture* (USDA 2016d).

In 2016, total N_2O emissions from manure management were estimated to be 18.1 MMT CO_2 Eq. (61 kt); in 1990, emissions were 14.0 MMT CO_2 Eq. (47 kt). These values include both direct and indirect N_2O emissions from manure management. Nitrous oxide emissions have remained fairly steady since 1990. Small changes in N_2O emissions from individual animal groups exhibit the same trends as the animal group populations, with the overall net effect that N_2O emissions showed a 30 percent increase from 1990 to 2016 and a 1.1 percent increase from 2015 through 2016. Overall shifts toward liquid systems have driven down the emissions per unit of nitrogen excreted as dry manure handling systems have greater aerobic conditions that promote N_2O emissions.

Table 5-7 and Table 5-8 provide estimates of CH_4 and N_2O emissions from manure management by animal category.

Table 5-7: CH_4 and N_2O Emissions from Manure Management (MMT CO_2 Eq.)

Gas/Animal Type	1990	2005	2012	2013	2014	2015	2016
CH_4[a]	**37.2**	**56.3**	**65.6**	**63.3**	**62.9**	**66.3**	**67.7**
Dairy Cattle	14.7	26.4	34.3	33.4	34.0	34.8	35.3
Beef Cattle	3.1	3.3	3.2	3.0	3.0	3.1	3.2
Swine	15.6	22.9	24.5	23.2	22.2	24.6	25.4
Sheep	0.2	0.1	0.1	0.1	0.1	0.1	0.1
Goats	+	+	+	+	+	+	+
Poultry	3.3	3.2	3.2	3.2	3.3	3.4	3.5
Horses	0.2	0.3	0.2	0.2	0.2	0.2	0.2
American Bison	+	+	+	+	+	+	+
Mules and Asses	+	+	+	+	+	+	+
N_2O[b]	**14.0**	**16.5**	**17.5**	**17.5**	**17.5**	**17.7**	**18.1**
Dairy Cattle	5.3	5.6	5.9	5.9	5.9	6.1	6.1
Beef Cattle	5.9	7.2	7.7	7.7	7.8	7.7	7.9
Swine	1.2	1.7	1.9	1.9	1.8	2.0	2.0
Sheep	0.1	0.3	0.3	0.3	0.3	0.3	0.3
Goats	+	+	+	+	+	+	+
Poultry	1.4	1.6	1.6	1.6	1.6	1.6	1.6
Horses	0.1	0.1	0.1	0.1	0.1	0.1	0.1
American Bison[c]	NA	NA	NA	NA	NA	NA	NA
Mules and Asses	+	+	+	+	+	+	+
Total	**51.1**	**72.9**	**83.2**	**80.8**	**80.4**	**84.0**	**85.9**

+ Does not exceed 0.05 MMT CO_2 Eq.

NA (Not Available)

[a] Accounts for CH_4 reductions due to capture and destruction of CH_4 at facilities using anaerobic digesters.

[b] Includes both direct and indirect N_2O emissions.

[c] There are no American bison N_2O emissions from managed systems.

Notes: Totals may not sum due to independent rounding. American bison are maintained entirely on unmanaged WMS.

Table 5-8: CH_4 and N_2O Emissions from Manure Management (kt)

Gas/Animal Type	1990	2005	2012	2013	2014	2015	2016
CH_4[a]	**1,486**	**2,254**	**2,625**	**2,530**	**2,514**	**2,651**	**2,709**
Dairy Cattle	590	1,057	1,373	1,338	1,361	1,391	1,413
Beef Cattle	126	133	128	121	120	126	130
Swine	622	916	982	930	890	985	1,014
Sheep	7	3	3	3	3	3	3
Goats	1	1	1	1	1	1	1
Poultry	131	129	128	128	131	135	138
Horses	9	12	10	9	9	9	9
American Bison	+	+	+	+	+	+	+

Mules and Asses	+	+	+	+	+	+	+
N_2O^b	**47**	**55**	**59**	**59**	**59**	**59**	**61**
Dairy Cattle	18	19	20	20	20	20	21
Beef Cattle	20	24	26	26	26	26	27
Swine	4	6	6	6	6	7	7
Sheep	+	1	1	1	1	1	1
Goats	+	+	+	+	+	+	+
Poultry	5	5	5	5	5	5	5
Horses	+	+	+	+	+	+	+
American Bison[c]	NA	NA	NA	NA	NA	NA	NA
Mules and Asses	+	+	+	+	+	+	+

+ Does not exceed 0.5 kt.

NA (Not available)

[a] Accounts for CH_4 reductions due to capture and destruction of CH_4 at facilities using anaerobic digesters.

[b] Includes both direct and indirect N_2O emissions.

[c] There are no American bison N_2O emissions from managed systems.

Notes: Totals may not sum due to independent rounding. American bison are maintained entirely on unmanaged WMS.

Methodology

The methodologies presented in IPCC (2006) form the basis of the CH_4 and N_2O emission estimates for each animal type. This section presents a summary of the methodologies used to estimate CH_4 and N_2O emissions from manure management. For the current Inventory, results for 1990 through 2015 were carried over from the 1990 to 2015 Inventory (i.e., 2017 submission) and a simplified approach was used to estimate manure management emissions for 2016. See Annex 3.11 for more detailed information on the methodology and data used to calculate CH_4 and N_2O emissions from manure management.

Methane Calculation Methods

The following inputs were used in the calculation of manure management CH_4 emissions for 1990 through 2015:

- Animal population data (by animal type and state);
- Typical animal mass (TAM) data (by animal type);
- Portion of manure managed in each WMS, by state and animal type;
- Volatile solids (VS) production rate (by animal type and state or United States);
- Methane producing potential (B_o) of the volatile solids (by animal type); and
- Methane conversion factors (MCF), the extent to which the CH_4 producing potential is realized for each type of WMS (by state and manure management system, including the impacts of any biogas collection efforts).

Methane emissions were estimated by first determining activity data, including animal population, TAM, WMS usage, and waste characteristics. The activity data sources are described below:

- Annual animal population data for 1990 through 2015 for all livestock types, except goats, horses, mules and asses, and American bison were obtained from the USDA-NASS. For cattle, the USDA populations were utilized in conjunction with birth rates, detailed feedlot placement information, and slaughter weight data to create the transition matrix in the Cattle Enteric Fermentation Model (CEFM) that models cohorts of individual animal types and their specific emission profiles. The key variables tracked for each of the cattle population categories are described in Section 5.1 and in more detail in Annex 3.10. Goat population data for 1992, 1997, 2002, 2007, and 2012; horse and mule and ass population data for 1987, 1992, 1997, 2002, 2007, and 2012; and American bison population for 2002, 2007 and 2012 were obtained from the *Census of Agriculture* (USDA 2014a). American bison population data for 1990 through 1999 were obtained from the National Bison Association (1999).

- The TAM is an annual average weight that was obtained for animal types other than cattle from information in USDA's *Agricultural Waste Management Field Handbook* (USDA 1996), the American

Society of Agricultural Engineers, Standard D384.1 (ASAE 1998) and others (Meagher 1986; EPA 1992; Safley 2000; ERG 2003b; IPCC 2006; ERG 2010a). For a description of the TAM used for cattle, see Annex 3.10.

- WMS usage was estimated for swine and dairy cattle for different farm size categories using state and regional data from USDA (USDA APHIS 1996; Bush 1998; Ott 2000; USDA 2016d) and EPA (ERG 2000a; EPA 2002a and 2002b). For beef cattle and poultry, manure management system usage data were not tied to farm size but were based on other data sources (ERG 2000a; USDA APHIS 2000; UEP 1999). For other animal types, manure management system usage was based on previous estimates (EPA 1992). American bison WMS usage was assumed to be the same as not on feed (NOF) cattle, while mules and asses were assumed to be the same as horses.
- VS production rates for all cattle except for calves were calculated by head for each state and animal type in the CEFM. VS production rates by animal mass for all other animals were determined using data from USDA's *Agricultural Waste Management Field Handbook* (USDA 1996 and 2008; ERG 2010b and 2010c) and data that was not available in the most recent *Handbook* were obtained from the American Society of Agricultural Engineers, Standard D384.1 (ASAE 1998) or the *2006 IPCC Guidelines* (IPCC 2006). American bison VS production was assumed to be the same as NOF bulls.
- The maximum CH_4-producing capacity of the VS (B_o) was determined for each animal type based on literature values (Morris 1976; Bryant et al. 1976; Hashimoto 1981; Hashimoto 1984; EPA 1992; Hill 1982; Hill 1984).
- MCFs for dry systems were set equal to default IPCC factors based on state climate for each year (IPCC 2006). MCFs for liquid/slurry, anaerobic lagoon, and deep pit systems were calculated based on the forecast performance of biological systems relative to temperature changes as predicted in the van't Hoff-Arrhenius equation which is consistent with IPCC (2006) Tier 2 methodology.
- Data from anaerobic digestion systems with CH_4 capture and combustion were obtained from the EPA AgSTAR Program, including information presented in the *AgSTAR Digest* (EPA 2000, 2003, 2006) and the AgSTAR project database (EPA 2016). Anaerobic digester emissions were calculated based on estimated methane production and collection and destruction efficiency assumptions (ERG 2008).
- For all cattle except for calves, the estimated amount of VS (kg per animal-year) managed in each WMS for each animal type, state, and year were taken from the CEFM, assuming American bison VS production to be the same as NOF bulls. For animals other than cattle, the annual amount of VS (kg per year) from manure excreted in each WMS was calculated for each animal type, state, and year. This calculation multiplied the animal population (head) by the VS excretion rate (kg VS per 1,000 kg animal mass per day), the TAM (kg animal mass per head) divided by 1,000, the WMS distribution (percent), and the number of days per year (365.25).

The estimated amount of VS managed in each WMS was used to estimate the CH_4 emissions (kg CH_4 per year) from each WMS. The amount of VS (kg per year) were multiplied by the maximum CH_4 producing capacity of the VS (B_o) (m^3 CH_4 per kg VS), the MCF for that WMS (percent), and the density of CH_4 (kg CH_4 per m^3 CH_4). The CH_4 emissions for each WMS, state, and animal type were summed to determine the total U.S. CH_4 emissions.

The following approach was used in the calculation of manure management CH_4 emissions for 2016:

National-level population data for cattle, poultry, and swine animal types were downloaded from USDA-NASS Quickstats. National-level population data for goats, horses, bison, mules, and asses were extrapolated based on the 1990 through 2015 population values. The national populations were then multiplied by the animal-specific 2015 implied emission factors[5] for CH_4 to calculate national-level 2016 CH_4 emissions estimates. These methods were

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[5] An implied emission factor is defined as emissions divided by the relevant measure of activity; The implied emission factors is equal to emissions per activity data unit. For source/sink categories that are composed of several subcategories, the emissions and activity data are summed up across all subcategories. Hence, the implied emission factors are generally not equivalent to the emission factors used to calculate emission estimates, but are average values that could be used, with caution, in data comparisons (UNFCCC 2017).

utilized in order to maintain time-series consistency as referenced in Volume 1, Chapter 5 of the *2006 IPCC Guidelines*.

Nitrous Oxide Calculation Methods

The following inputs were used in the calculation of direct and indirect manure management N_2O emissions for 1990 through 2015:

- Animal population data (by animal type and state);
- TAM data (by animal type);
- Portion of manure managed in each WMS (by state and animal type);
- Total Kjeldahl N excretion rate (Nex);
- Direct N_2O emission factor (EF_{WMS});
- Indirect N_2O emission factor for volatilization ($EF_{volatilization}$);
- Indirect N_2O emission factor for runoff and leaching ($EF_{runoff/leach}$);
- Fraction of N loss from volatilization of NH_3 and NO_x ($Frac_{gas}$); and
- Fraction of N loss from runoff and leaching ($Frac_{runoff/leach}$).

Nitrous oxide emissions were estimated by first determining activity data, including animal population, TAM, WMS usage, and waste characteristics. The activity data sources (except for population, TAM, and WMS, which were described above) are described below:

- Nex rates for all cattle except for calves were calculated by head for each state and animal type in the CEFM. Nex rates by animal mass for all other animals were determined using data from USDA's *Agricultural Waste Management Field Handbook* (USDA 1996 and 2008; ERG 2010b and 2010c) and data from the American Society of Agricultural Engineers, Standard D384.1 (ASAE 1998) and IPCC (2006). American bison Nex rates were assumed to be the same as NOF bulls.[6]
- All N_2O emission factors (direct and indirect) were taken from IPCC (2006). These data are appropriate because they were developed using U.S. data.
- Country-specific estimates for the fraction of N loss from volatilization ($Frac_{gas}$) and runoff and leaching ($Frac_{runoff/leach}$) were developed. $Frac_{gas}$ values were based on WMS-specific volatilization values as estimated from EPA's *National Emission Inventory - Ammonia Emissions from Animal Agriculture Operations* (EPA 2005). $Frac_{runoff/leaching}$ values were based on regional cattle runoff data from EPA's Office of Water (EPA 2002b; see Annex 3.11).

To estimate N_2O emissions for cattle (except for calves), the estimated amount of N excreted (kg per animal-year) that is managed in each WMS for each animal type, state, and year were taken from the CEFM. For calves and other animals, the amount of N excreted (kg per year) in manure in each WMS for each animal type, state, and year was calculated. The population (head) for each state and animal was multiplied by TAM (kg animal mass per head) divided by 1,000, the nitrogen excretion rate (Nex, in kg N per 1,000 kg animal mass per day), WMS distribution (percent), and the number of days per year.

Direct N_2O emissions were calculated by multiplying the amount of N excreted (kg per year) in each WMS by the N_2O direct emission factor for that WMS (EF_{WMS}, in kg N_2O-N per kg N) and the conversion factor of N_2O-N to N_2O. These emissions were summed over state, animal, and WMS to determine the total direct N_2O emissions (kg of N_2O per year).

Next, indirect N_2O emissions from volatilization (kg N_2O per year) were calculated by multiplying the amount of N excreted (kg per year) in each WMS by the fraction of N lost through volatilization ($Frac_{tas}$) divided by 100, the emission factor for volatilization ($EF_{volatilization}$, in kg N_2O per kg N), and the conversion factor of N_2O-N to N_2O. Indirect N_2O emissions from runoff and leaching (kg N_2O per year) were then calculated by multiplying the amount

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[6] The N_2O emissions from N excreted (Nex) by American bison on grazing lands are accounted for and discussed in the Agricultural Soil Management source category and included under pasture, range and paddock (PRP) emissions. Because American bison are maintained entirely on unmanaged WMS and N_2O emissions from unmanaged WMS are not included in the Manure Management source category, there are no N_2O emissions from American bison included in the Manure Management source category.

of N excreted (kg per year) in each WMS by the fraction of N lost through runoff and leaching ($Frac_{runoff/leach}$) divided by 100, and the emission factor for runoff and leaching ($EF_{runoff/leach}$, in kg N_2O per kg N), and the conversion factor of N_2O-N to N_2O. The indirect N_2O emissions from volatilization and runoff and leaching were summed to determine the total indirect N_2O emissions.

Following these steps, direct and indirect N_2O emissions were summed to determine total N_2O emissions (kg N_2O per year) for the years 1990 to 2015.

The following approach was used in the calculation of manure management N_2O emissions for 2016:

National-level population data for cattle, poultry, and swine animal types were downloaded from USDA-NASS Quickstats. National-level population data for goats, horses, bison, mules, and asses were extrapolated based on the 1990 through 2015 population values. The national populations were then multiplied by the animal-specific 2015 implied emission factors for N_2O (combines both direct and indirect N_2O) to calculate national-level 2016 N_2O emissions estimates. These methods were utilized in order to maintain time-series consistency as referenced in Volume 1, Chapter 5 of the *2006 IPCC Guidelines*.

Uncertainty and Time-Series Consistency

An analysis (ERG 2003a) was conducted for the manure management emission estimates presented in the 1990 through 2001 Inventory (i.e., 2003 submission to the UNFCCC) to determine the uncertainty associated with estimating CH_4 and N_2O emissions from livestock manure management. The quantitative uncertainty analysis for this source category was performed in 2002 through the IPCC-recommended Approach 2 uncertainty estimation methodology, the Monte Carlo Stochastic Simulation technique. The uncertainty analysis was developed based on the methods used to estimate CH_4 and N_2O emissions from manure management systems. A normal probability distribution was assumed for each source data category. The series of equations used were condensed into a single equation for each animal type and state. The equations for each animal group contained four to five variables around which the uncertainty analysis was performed for each state. These uncertainty estimates were directly applied to the 2016 emission estimates as there have not been significant changes in the methodology since that time.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 5-9. Manure management CH_4 emissions in 2016 were estimated to be between 55.5 and 81.3 MMT CO_2 Eq. at a 95 percent confidence level, which indicates a range of 18 percent below to 20 percent above the actual 2016 emission estimate of 67.7 MMT CO_2 Eq. At the 95 percent confidence level, N_2O emissions were estimated to be between 15.2 and 22.5 MMT CO_2 Eq. (or approximately 16 percent below and 24 percent above the actual 2016 emission estimate of 18.1 MMT CO_2 Eq.).

Table 5-9: Approach 2 Quantitative Uncertainty Estimates for CH_4 and N_2O (Direct and Indirect) Emissions from Manure Management (MMT CO_2 Eq. and Percent)

Source	Gas	2016 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Manure Management	CH_4	67.7	55.5	81.3	-18%	20%
Manure Management	N_2O	18.1	15.2	22.5	-16%	24%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

QA/QC and Verification

Tier 1 and Tier 2 QA/QC activities were conducted consistent with the U.S. QA/QC plan. Tier 2 activities focused on comparing estimates for the previous and current Inventories for N_2O emissions from managed systems and CH_4 emissions from livestock manure. All errors identified were corrected. Order of magnitude checks were also conducted, and corrections made where needed.

Time-series data, including population, are validated by experts to ensure they are representative of the best available U.S.-specific data. The U.S.-specific values for TAM, Nex, VS, B_o, and MCF were also compared to the

IPCC default values and validated by experts. Although significant differences exist in some instances, these differences are due to the use of U.S.-specific data and the differences in U.S. agriculture as compared to other countries. The U.S. manure management emission estimates use the most reliable country-specific data, which are more representative of U.S. animals and systems than the IPCC (2006) default values.

For additional verification of the 1990 to 2015 estimates, the implied CH_4 emission factors for manure management (kg of CH_4 per head per year) were compared against the default IPCC (2006) values.[7] Table 5-10 presents the implied emission factors of kg of CH_4 per head per year used for the manure management emission estimates as well as the IPCC (2006) default emission factors. The 2015 U.S. implied emission factors fall within the range of the IPCC (2006) default values, except in the case of sheep, goats, and some years for horses and dairy cattle. The U.S. implied emission factors are greater than the IPCC (2006) default value for those animals due to the use of U.S.-specific data for typical animal mass and VS excretion. There is an increase in implied emission factors for dairy cattle and swine across the time series. This increase reflects the dairy cattle and swine industry trend towards larger farm sizes; large farms are more likely to manage manure as a liquid and therefore produce more CH_4 emissions.

Table 5-10: IPCC (2006) Implied Emission Factor Default Values Compared with Calculated Values for CH_4 from Manure Management (kg/head/year)

Animal Type	IPCC Default CH_4 Emission Factors (kg/head/year)	Implied CH_4 Emission Factors (kg/head/year)						
		1990	2005	2011	2012	2013	2014	2015
Dairy Cattle	48-112	30.2	59.4	70.3	73.9	72.3	73.4	74.0
Beef Cattle	1-2	1.5	1.6	1.7	1.7	1.6	1.6	1.7
Swine	10-45	11.5	15.0	14.5	14.8	14.2	13.8	14.5
Sheep	0.19-0.37	0.6	0.6	0.5	0.5	0.5	0.5	0.5
Goats	0.13-0.26	0.4	0.3	0.3	0.3	0.3	0.3	0.3
Poultry	0.02-1.4	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Horses	1.56-3.13	4.3	3.1	2.6	2.7	2.5	2.5	2.6
American Bison	NA	1.8	2.0	2.1	2.1	2.0	2.0	2.1
Mules and Asses	0.76-1.14	0.9	1.0	1.0	1.0	0.9	0.9	1.0

Note: CH_4 implied emission factors were not calculated for 2016 due to the simplified emissions estimation approach used to estimate emissions for that year.

In addition, default IPCC (2006) emission factors for N_2O were compared to the U.S. Inventory implied N_2O emission factors. Default N_2O emission factors from the *2006 IPCC Guidelines* were used to estimate N_2O emission from each WMS in conjunction with U.S.-specific Nex values. The implied emission factors differed from the U.S. Inventory values due to the use of U.S.-specific Nex values and differences in populations present in each WMS throughout the time series.

Recalculations Discussion

No recalculations were performed for the 1990 to 2015 estimates. The 2016 estimates were developed using a simplified approach, as noted in the Methodology section of this chapter.

Planned Improvements

During the Public Review period of the current Inventory (i.e., 1990 through 2016), EPA received comment on various aspects of the manure management inventory, including recommended improvements to clarify the scope of the manure management sector and better align terminology with those used within the industry (e.g., clarifying "managed" versus "unmanaged"), as well as comments to update data and methods which reiterated those improvements already identified by EPA and listed below. EPA notes that potential data sources (such as the USDA Agricultural Resource Management Survey) for updated WMS distribution estimates have been obtained and

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[7] CH_4 implied emission factors were not calculated for 2016 due to the simplified emissions estimation approach used to estimate emissions for that year.

discussed with USDA. EPA is working with USDA to review these data sources for potential implementation in future Inventory reports. EPA also notes that many of these improvements, identified below, are major updates and may take multiple years to implement in full, but will add clarity to improve the transparency of future inventories.

In addition, EPA may pursue the following improvements in future Inventory years:

- Implement a methodology to calculate monthly emissions estimates to present data that show seasonal changes in emissions from each WMS.
- Revise the anaerobic digestion estimates to estimate CH_4 emissions reductions due to the use of anaerobic digesters (the Inventory currently estimates only emissions from anaerobic digestion systems).
- Update the B_0 data used in the Inventory, which are dated.
- Compare CH_4 and N_2O emission estimates with estimates from other models and more recent studies and compare the results to the Inventory, such as USDA's Dairy Gas Emissions Model.
- Compare manure management emission estimates with on-farm WMS measurement data to identify opportunities for improved estimates.
- Improve collaboration with the Enteric Fermentation source category estimates. For future inventories, it may be beneficial to have the CEFM and Manure Management calculations in the same model, as they rely on much of the same activity data and they depend on each other's outputs to properly calculation emissions.
- Changes that have been implemented to the CH_4 and N_2O estimates warrant an assessment of the current uncertainty analysis; therefore, a revision of the quantitative uncertainty surrounding emission estimates from this source will be initiated.

5.3 Rice Cultivation (CRF Source Category 3C)

Most of the world's rice is grown on flooded fields (Baicich 2013), and flooding creates anaerobic conditions that foster CH_4 production through a process known as methanogenesis. Approximately 60 to 90 percent of the CH_4 produced by methanogenic bacteria is oxidized in the soil and converted to CO_2 by methanotrophic bacteria. The remainder is emitted to the atmosphere (Holzapfel-Pschorn et al. 1985; Sass et al. 1990) or transported as dissolved CH_4 into groundwater and waterways (Neue et al. 1997). Methane is transported to the atmosphere primarily through the rice plants, but some CH_4 also escapes via ebullition (i.e., bubbling through the water) and to a much lesser extent by diffusion through the water (van Bodegom et al. 2001).

Water management is arguably the most important factor affecting CH_4 emissions, and improved water management has the largest potential to mitigate emissions (Yan et al. 2009). Upland rice fields are not flooded, and therefore do not produce CH_4, but large amounts of CH_4 can be emitted in continuously irrigated fields, which is the most common practices in the United States (USDA 2012). Single or multiple aeration events with drainage of a field during the growing season can significantly reduce these emissions (Wassmann et al. 2000a), but drainage may also increase N_2O emissions. Deepwater rice fields (i.e., fields with flooding depths greater than one meter, such as natural wetlands) tend to have less living stems reaching the soil, thus reducing the amount of CH_4 transport to the atmosphere through the plant compared to shallow-flooded systems (Sass 2001).

Other management practices also influence CH_4 emissions from flooded rice fields including rice residue straw management and application of organic amendments, in addition to cultivar selection due to differences in the amount of root exudates[8] among rice varieties (Neue et al. 1997). These practices influence the amount of organic matter available for methanogenesis, and some practices, such as mulching rice straw or composting organic amendments, can reduce the amount of labile carbon and limit CH_4 emissions (Wassmann et al. 2000b). Fertilization practices also influences CH_4 emissions, particularly the use of fertilizers with sulfate (Wassmann et al. 2000b; Linquist et al. 2012). Other environmental variables also impact the methanogenesis process such as soil temperature and soil type. Soil temperature is an important factor regulating the activity of methanogenic bacteria

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[8] The roots of rice plants add organic material to the soil through a process called "root exudation." Root exudation is thought to enhance decomposition of the soil organic matter and release nutrients that the plant can absorb and use to stimulate more production. The amount of root exudate produced by a rice plant over a growing season varies among rice varieties.

which in turn affects the rate of CH_4 production. Soil texture influences decomposition of soil organic matter, but is also thought to have an impact on oxidation of CH_4 in the soil (Sass et al. 1994).

Rice is currently cultivated in twelve states, including Arkansas, California, Florida, Illinois, Kentucky, Louisiana, Minnesota, Mississippi, Missouri, New York, South Carolina, Tennessee and Texas. Soil types, rice varieties, and cultivation practices vary across the United States, but most farmers apply fertilizers and do not harvest crop residues. In addition, a second, ratoon rice crop is sometimes grown in the Southeast. Ratoon crops are produced from regrowth of the stubble remaining after the harvest of the first rice crop. Methane emissions from ratoon crops are higher than those from the primary crops due to the increased amount of labile organic matter available for anaerobic decomposition in the form of relatively fresh crop residue straw. Emissions tend to be higher in rice fields if the residues have been in the field for less than 30 days before planting the next rice crop (Lindau and Bollich 1993; IPCC 2006; Wang et al. 2013). While a combination of Tier 1 and 3 methods are used to estimate CH_4 emissions from rice cultivation across most of the time series, a surrogate data method has been applied to estimate national emissions in the last few years of this Inventory. National emission estimates based on surrogate data will be recalculated in a future Inventory using the Tier 1 and 3 methods.

Overall, rice cultivation is a minor source of CH_4 emissions in the United States relative to other source categories (see Table 5-11, Table 5-12, and Figure 5-2). The majority of emission occur in Arkansas, California, Louisiana and Texas. In 2016, CH_4 emissions from rice cultivation were 13.7 MMT CO_2 Eq. (549 kt). Annual emissions fluctuate between 1990 and 2016, and emissions in 2016 represented a 14 percent decrease compared to 1990. Variation in emissions is largely due to differences in the amount of rice harvested areas over time, which has been decreasing over the past two decades.

Table 5-11: CH_4 Emissions from Rice Cultivation (MMT CO_2 Eq.)

State	1990		2005		2012	2013	2014	2015	2016
Arkansas	3.3		4.7		3.8	NE	NE	NE	NE
California	2.0		2.1		2.0	NE	NE	NE	NE
Florida	+		0.1		+	NE	NE	NE	NE
Illinois	+		+		+	NE	NE	NE	NE
Kentucky	+		+		+	NE	NE	NE	NE
Louisiana	6.1		6.5		3.9	NE	NE	NE	NE
Minnesota	+		+		+	NE	NE	NE	NE
Mississippi	0.6		0.6		0.5	NE	NE	NE	NE
Missouri	0.3		0.6		0.3	NE	NE	NE	NE
New York	+		+		+	NE	NE	NE	NE
South Carolina	+		+		+	NE	NE	NE	NE
Tennessee	+		+		+	NE	NE	NE	NE
Texas	3.7		2.1		0.9	NE	NE	NE	NE
Total	**16.0**		**16.7**		**11.3**	**11.5**	**12.7**	**12.3**	**13.7**

+ Does not exceed 0.05 MMT CO_2 Eq.

NE (Not Estimated). State-level emissions are not estimated for 2013 through 2016 Inventory, and national emissions are determined using a surrogate data method.

Note: Totals may not sum due to independent rounding.

Table 5-12: CH_4 Emissions from Rice Cultivation (kt)

State	1990		2005		2012	2013	2014	2015	2016
Arkansas	132		188		151	NE	NE	NE	NE
California	81		82		81	NE	NE	NE	NE
Florida	+		3		+	NE	NE	NE	NE
Illinois	+		+		+	NE	NE	NE	NE
Kentucky	+		+		+	NE	NE	NE	NE
Louisiana	246		261		156	NE	NE	NE	NE
Minnesota	1		2		1	NE	NE	NE	NE
Mississippi	23		23		19	NE	NE	NE	NE
Missouri	12		22		12	NE	NE	NE	NE
New York	+		+		+	NE	NE	NE	NE
South Carolina	+		+		+	NE	NE	NE	NE
Tennessee	+		+		+	NE	NE	NE	NE

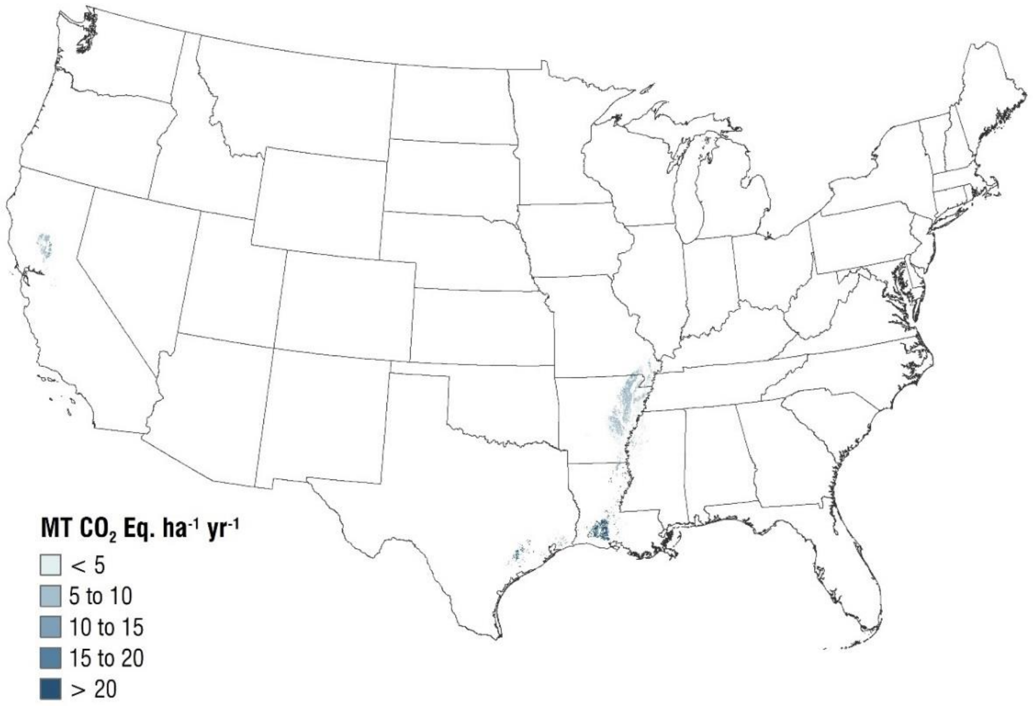
Texas	146		86		34	NE	NE	NE	NE
Total	**641**		**667**		**453**	**462**	**510**	**493**	**549**

+ Does not exceed 0.5 kt.

NE (Not Estimated). State-level emissions are not estimated for 2013 through 2016 Inventory, and national emissions are determined using a surrogate data method.

Note: Totals may not sum due to independent rounding.

Figure 5-2: Annual CH_4 Emissions from Rice Cultivation, 2012 (MMT CO_2 Eq./Year)



Note: Only national-scale emissions are estimated for 2013 through 2016 in this Inventory using the surrogate data method described in the Methodology section, therefore the fine-scale emission patterns in this map are based on the previous Inventory.

Methodology

The methodology used to estimate CH_4 emissions from rice cultivation is based on a combination of IPCC Tier 1 and 3 approaches. The Tier 3 method utilizes a process-based model (DAYCENT) to estimate CH_4 emissions from rice cultivation (Cheng et al. 2013), and has been tested in the United States (see Annex 3.12) and Asia (Cheng et al. 2013, 2014). The model simulates hydrological conditions and thermal regimes, organic matter decomposition, root exudation, rice plant growth and its influence on oxidation of CH_4, as well as CH_4 transport through the plant and via ebullition (Cheng et al. 2013). The method simulates the influence of organic amendments and rice straw management on methanogenesis in the flooded soils. In addition to CH_4 emissions, DAYCENT simulates soil C stock changes and N_2O emissions (Parton et al. 1987 and 1998; Del Grosso et al. 2010), and allows for a seamless set of simulations for crop rotations that include both rice and non-rice crops.

The Tier 1 method is applied to estimate CH_4 emissions from rice when grown in rotation with crops that are not simulated by DAYCENT, such as vegetables and perennial/horticultural crops. The Tier 1 method is also used for areas converted between agriculture (i.e., cropland and grassland) and other land uses, such as forest land, wetland, and settlements. In addition, the Tier 1 method is used to estimate CH_4 emissions from organic soils (i.e., Histosols) and from areas with very gravelly, cobbly, or shaley soils (greater than 35 percent by volume). The Tier 3 method using DAYCENT has not been fully tested for estimating emissions associated with these crops and rotations, land uses, as well as organic soils or cobbly, gravelly, and shaley mineral soils.

The Tier 1 method for estimating CH_4 emissions from rice production utilizes a default base emission rate and scaling factors (IPCC 2006). The base emission factor represents emissions for continuously flooded fields with no organic amendments. Scaling factors are used to adjust for water management and organic amendments that differ from continuous flooding with no organic amendments. The method accounts for pre-season and growing season flooding; types and amounts of organic amendments; and the number of rice production seasons within a single year (i.e., single cropping, ratooning, etc.). The Tier 1 analysis is implemented in the Agriculture and Land Use National Greenhouse Gas Inventory (ALU) software (Ogle et al. 2016).[9]

Rice cultivation areas are based on cropping and land use histories recorded in the USDA National Resources Inventory (NRI) survey (USDA-NRCS 2015). The NRI is a statistically-based sample of all non-federal land, and includes 380,956 survey points of which 1,588 are in locations with rice cultivation at the end of the NRI time series. The Tier 3 method is used to estimate CH_4 emissions from 1,393 of the NRI survey locations, and the remaining 195 survey locations are estimated with the Tier 1 method. Each NRI survey point is associated with an "expansion factor" that allows scaling of CH_4 emissions from NRI points to the entire country (i.e., each expansion factor represents the amount of area with the same land-use/management history as the sample point). Land-use and some management information in the NRI (e.g., crop type, soil attributes, and irrigation) were collected on a 5-year cycle beginning in 1982, along with cropping rotation data in 4 out of 5 years for each 5-year time period (i.e., 1979 to 1982, 1984 to 1987, 1989 to 1992, and 1994 to 1997). The NRI program began collecting annual data in 1998, with data currently available through 2012 (USDA-NRCS 2015). The current Inventory only uses NRI data through 2012 because newer data are not available, but will be incorporated when additional years of data are released by USDA-NRCS. The harvested rice areas in each state are presented in Table 5-13.

Table 5-13: Rice Area Harvested (1,000 Hectares)

State/Crop	1990	2005	2012	2013	2014	2015	2016
Arkansas	599	796	613	NE	NE	NE	NE
California	248	247	244	NE	NE	NE	NE
Florida	0	11	0	NE	NE	NE	NE
Illinois	0	0	0	NE	NE	NE	NE
Kentucky	0	0	0	NE	NE	NE	NE
Louisiana	380	402	226	NE	NE	NE	NE
Minnesota	4	10	6	NE	NE	NE	NE
Mississippi	119	115	92	NE	NE	NE	NE
Missouri	47	93	46	NE	NE	NE	NE
New York	1	0	0	NE	NE	NE	NE
South Carolina	0	0	0	NE	NE	NE	NE
Tennessee	0	1	0	NE	NE	NE	NE
Texas	300	150	66	NE	NE	NE	NE
Total	**1,698**	**1,826**	**1,292**	**NE**	**NE**	**NE**	**NE**

NE (Not Estimated).

Notes: Totals may not sum due to independent rounding. States are included if NRI reports an area of rice production in the state at any time between 1990 and 2012. Rice harvested area data have not been compiled for 2013 to 2016.

The Southeastern states have sufficient growing periods for a ratoon crop in some years. For example, in Arkansas, the length of growing season is occasionally sufficient for ratoon crops on an average of 1 percent of the rice fields. No data are available about ratoon crops in Missouri or Mississippi, and the average amount of ratooning in Arkansas was assigned to these states. Ratoon cropping occurs much more frequently in Louisiana (LSU 2015 for years 2000 through 2013, 2015) and Texas (TAMU 2015 for years 1993 through 2014), averaging 32 percent and 45 percent of rice acres planted, respectively. Florida also has a large fraction of area with a ratoon crop (49 percent).

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[9] See <http://www.nrel.colostate.edu/projects/ALUsoftware/>.

Ratoon rice crops are not grown in California. Ratooned crop area as a percent of primary crop area is presented in Table 5-14.

Table 5-14: Average Ratooned Area as Percent of Primary Growth Area (Percent)

State	1990-2012
Arkansas[a]	1%
California	0%
Florida[b]	49%
Louisiana[c]	32%
Mississippi[a]	1%
Missouri[a]	0%
Texas[d]	45%

[a] Arkansas: *1990–2000* (Slaton 1999 through 2001); *2001–2011* (Wilson 2002 through 2007, 2009 through 2012); *2012–2013* (Hardke 2013, 2014).

[b] Florida - Ratoon: *1990–2000* (Schueneman 1997, 1999 through 2001); *2001* (Deren 2002); *2002–2003* (Kirstein 2003 through 2004, 2006); *2004* (Cantens 2004 through 2005); *2005–2013* (Gonzalez 2007 through 2014)

[c] Louisiana: *1990–2013* (Linscombe 1999, 2001 through 2014).

[d] Texas: *1990–2002* (Klosterboer 1997, 1999 through 2003); *2003–2004* (Stansel 2004 through 2005); *2005* (Texas Agricultural Experiment Station 2006); *2006–2013* (Texas Agricultural Experiment Station 2007 through 2014).

While rice crop production in the United States includes a minor amount of land with mid-season drainage or alternate wet-dry periods, the majority of rice growers use continuously flooded water management systems (Hardke 2015; UCCE 2015; Hollier 1999; Way et al. 2014). Therefore, continuous flooding was assumed in the DAYCENT simulations and the Tier 1 method. Variation in flooding can be incorporated in future Inventories if water management data are collected.

Winter flooding is another key practice associated with water management in rice fields, and the impact of winter flooding on CH_4 emissions is addressed in the Tier 3 and Tier 1 analyses. Flooding is used to prepare fields for the next growing season, and to create waterfowl habitat (Young 2013; Miller et al. 2010; Fleskes et al. 2005). Fitzgerald et al. (2000) suggests that as much as 50 percent of the annual emissions may occur during the winter flood. Winter flooding is a common practice with an average of 34 percent of fields managed with winter flooding in California (Miller et al. 2010; Fleskes et al. 2005), and approximately 21 percent of the fields managed with winter flooding in Arkansas (Wilson and Branson 2005 and 2006; Wilson and Runsick 2007 and 2008; Wilson et al. 2009 and 2010; Hardke and Wilson 2013 and 2014; Hardke 2015). No data are available on winter flooding for Texas, Louisiana, Florida, Missouri, or Mississippi. For these states, the average amount of flooding is assumed to be similar to Arkansas. In addition, the amount of flooding is assumed to be relatively constant over the Inventory time period.

A surrogate data method is used to estimate emissions for the land area associated with the Tier 3 method for 2013 to 2016, and for the land areas associated with the Tier 1 method for 2016. Specifically, a linear regression model with autoregressive moving-average (ARMA) errors was used to estimate the relationship between the surrogate data and the 1990 through 2012 emissions data that was derived using the Tier 1 and 3 methods (Brockwell and Davis 2016). Surrogate data for this model are based on rice commodity statistics from USDA-NASS.[10] See Box 5-3 for more information about the surrogate data method.

Box 5-3: Surrogate Data Method

An approach to extend the time series is needed to estimate emissions from Rice cultivation because the Inventory is only fully re-compiled every two years for the Agriculture, Forestry, and Other Land Use (AFOLU) sector as part of the biennial update reporting process, and even in years that the Inventory is fully re-compiled, there are typically gaps at the end of the time series. This is mainly due to the fact that the National Resources Inventory (NRI) does not release data every year, and the NRI is a key data source for estimating greenhouse gas emissions.

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[10] See <https://quickstats.nass.usda.gov/>.

A surrogate data method has been selected to impute missing emissions at the end of the time series. A linear regression model with autoregressive moving-average (ARMA) errors (Brockwell and Davis, 2016) is used to estimate the relationship between the surrogate data and the observed 1990 to 2012 emissions data that has been compiled using the inventory methods described in this section. The model to extend the time series is given by

$$Y=X\beta+\varepsilon,$$

where Y is the response variable (e.g., soil organic carbon), $X\beta$ contains specific surrogate data depending on the response variable, and ε is the remaining unexplained error. EPA tested models with a variety of surrogate data, including commodity statistics, weather data, or other relevant information. Parameters are estimated from the observed data for 1990 to 2012 using standard statistical techniques, and these estimates are used to predict the missing emissions data for 2013 to 2016.

A critical issue in using splicing methods in general, is to adequately account for the additional uncertainty introduced by predicting emissions with related information without compiling the full inventory. For example, predicting CH_4 emissions will increase the total variation in the emission estimates for these specific years, compared to those years in which the full inventory is compiled. This added uncertainty is quantified within the model framework using a Monte Carlo approach. The approach requires estimating parameters for results in each Monte Carlo simulation for the full inventory (i.e., the surrogate data model is refit with the emissions estimated in each Monte Carlo iteration from the full inventory analysis with data from 1990 to 2012).

Uncertainty and Time-Series Consistency

Sources of uncertainty in the Tier 3 method include management practices, uncertainties in model structure (i.e., algorithms and parameterization), and variance associated with the NRI sample. Sources of uncertainty in the IPCC (2006) Tier 1 method include the emission factors, management practices, and variance associated with the NRI sample. A Monte Carlo analysis was used to propagate uncertainties in the Tier 1 and 3 methods. For 2013 to 2016, there is additional uncertainty propagated through the Monte Carlo Analysis associated with the surrogate data method. (See Box 5-3 for information about propagating uncertainty with the surrogate data method.) The uncertainties from the Tier 1 and 3 approaches are combined to produce the final CH_4 emissions estimate using simple error propagation (IPCC 2006). Additional details on the uncertainty methods are provided in Annex 3.12. Rice cultivation CH_4 emissions in 2016 were estimated to be between 9.3 and 22.5 MMT CO_2 Eq. at a 95 percent confidence level, which indicates a range of 32 percent below to 64 percent above the actual 2016 emission estimate of 13.7 MMT CO_2 Eq. (see Table 5-15).

Table 5-15: Approach 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Rice Cultivation (MMT CO_2 Eq. and Percent)

Source	Inventory Method	Gas	2016 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
				Lower Bound	Upper Bound	Lower Bound	Upper Bound
Rice Cultivation	Tier 3	CH_4	11.9	7.7	16.2	-36%	+36%
Rice Cultivation	Tier 1	CH_4	1.8	0.8	2.8	-55%	+55%
Rice Cultivation	**Total**	**CH_4**	**13.7**	**9.3**	**22.5**	**-32%**	**+64%**

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

QA/QC and Verification

Quality control measures include checking input data, model scripts, and results to ensure data are properly handled throughout the inventory process. Inventory reporting forms and text are reviewed and revised as needed to correct transcription errors. No errors were found in the reporting forms and text.

Model results are compared to field measurements to verify if results adequately represent CH_4 emissions. The comparisons included over 15 long-term experiments, representing about 80 combinations of management treatments across all of the sites. A statistical relationship was developed to assess uncertainties in the model structure, adjusting the estimates for model bias and assessing precision in the resulting estimates (methods are described in Ogle et al. 2007). See Annex 3.12 for more information.

Recalculations Discussion

The rice CH_4 emissions data in this Inventory were not recalculated from the previous Inventory with the exception of 2013 through 2015, which were estimated using the surrogate data method (Box 5-3). This change resulted in an increase in emissions of less than 1 percent on average across the time series relative to the previous Inventory.

Planned Improvements

New land representation data and rice cultivation data were not compiled for the current Inventory. A surrogate data method has been applied to estimate emissions in the latter part of the time series, which introduces additional uncertainty in the emissions data. Therefore, a key improvement for a future Inventory will be to update the time series for CH_4 emissions from rice cultivation by compiling the latest land use data and related management statistics.

In addition, a major improvement is underway to update the time series of management data with information from the USDA-NRCS Conservation Effects Assessment Program (CEAP). This improvement will fill several gaps in the management data including more specific data on fertilizer rates, updated tillage practices, water management, organic amendments and more information on planting and harvesting dates. This improvement is expected to be completed for the 1990 through 2017 Inventory (i.e., 2019 submission). However, the timeline may be extended if there are insufficient resources to fund this improvement.

5.4 Agricultural Soil Management (CRF Source Category 3D)

Nitrous oxide is naturally produced in soils through the microbial processes of nitrification and denitrification that is driven by the availability of mineral nitrogen (N) (Firestone and Davidson 1989).[11] Mineral N is made available in soils through decomposition of soil organic matter and plant litter, as well as asymbiotic fixation of N from the atmosphere.[12] A number of agricultural activities increase mineral N availability in soils that lead to direct N_2O emissions from nitrification and denitrification at the site of a management activity (see Figure 5-3) (Mosier et al. 1998), including N fertilization; application of managed livestock manure and other organic materials such as biosolids (i.e., sewage sludge); deposition of manure on soils by domesticated animals in pastures, rangelands, and paddocks (PRP) (i.e., by grazing animals and other animals whose manure is not managed); production of N-fixing crops and forages; retention of crop residues; and drainage of organic soils (i.e., soils with a high organic matter content, otherwise known as Histosols[13]) (IPCC 2006). Additionally, agricultural soil management activities,

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[11] Nitrification and denitrification are driven by the activity of microorganisms in soils. Nitrification is the aerobic microbial oxidation of ammonium (NH_4^+) to nitrate (NO_3^-), and denitrification is the anaerobic microbial reduction of nitrate to N_2. Nitrous oxide is a gaseous intermediate product in the reaction sequence of denitrification, which leaks from microbial cells into the soil and then into the atmosphere. Nitrous oxide is also produced during nitrification, although by a less well-understood mechanism (Nevison 2000).

[12] Asymbiotic N fixation is the fixation of atmospheric N_2 by bacteria living in soils that do not have a direct relationship with plants.

[13] Drainage of organic soils in former wetlands enhances mineralization of N-rich organic matter, thereby increasing N_2O emissions from these soils.

including irrigation, drainage, tillage practices, and fallowing of land, can influence N mineralization from soil organic matter and levels of asymbiotic N fixation by impacting moisture and temperature regimes in soils. Indirect emissions of N_2O occur when N is transported from a site and is subsequently converted to N_2O; there are two pathways for indirect emissions: (1) volatilization and subsequent atmospheric deposition of applied/mineralized N, and (2) surface runoff and leaching of applied/mineralized N into groundwater and surface water.[14] Direct and indirect emissions from agricultural lands are included in this section (i.e., cropland and grassland as defined in Section 6.1 Representation of the U.S. Land Base; N_2O emissions from Forest Land and Settlements soils are found in Sections 6.2 and 6.10, respectively).

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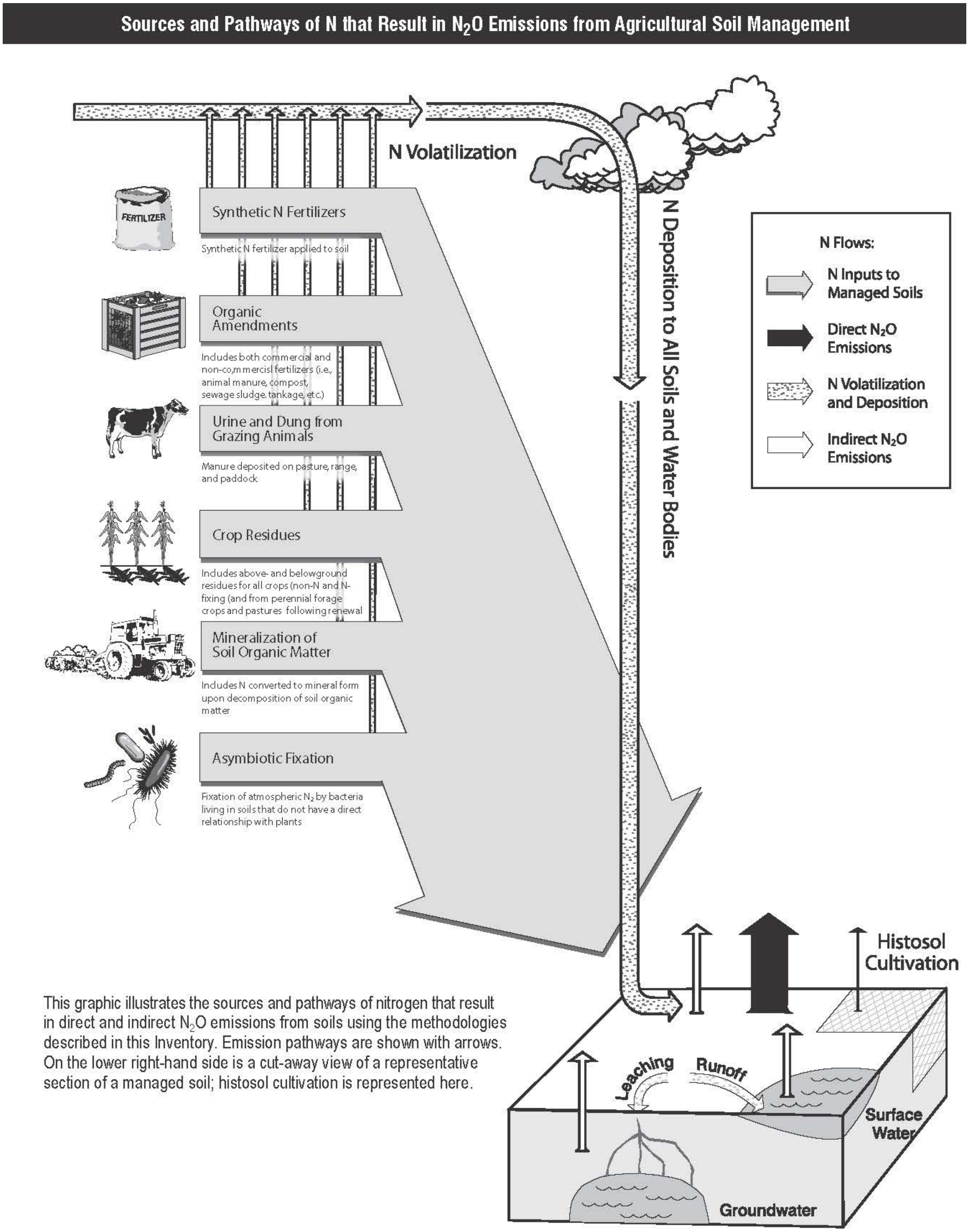
[14] These processes entail volatilization of applied or mineralized N as NH_3 and NO_x, transformation of these gases within the atmosphere (or upon deposition), and deposition of the N primarily in the form of particulate NH_4^+, nitric acid (HNO_3), and NO_x, in addition to leaching and runoff of NO_3^- that is converted to N_2O in aquatic systems.

Figure 5-3: Sources and Pathways of N that Result in N_2O Emissions from Agricultural Soil Management



This graphic illustrates the sources and pathways of nitrogen that result in direct and indirect N_2O emissions from soils using the methodologies described in this Inventory. Emission pathways are shown with arrows. On the lower right-hand side is a cut-away view of a representative section of a managed soil; histosol cultivation is represented here.

Agricultural soils produce the majority of N_2O emissions in the United States. Estimated emissions from this source in 2016 are 283.6 MMT CO_2 Eq. (952 kt) (see Table 5-16 and Table 5-17). Annual N_2O emissions from agricultural soils are 13.2 percent greater in the 2016 compared to 1990, but emissions fluctuated between 1990 and 2016 due to inter-annual variability largely associated with weather patterns, synthetic fertilizer use, and crop production. From 1990 to 2016, on average, cropland accounted for approximately 70 percent of total direct emissions, while grassland accounted for approximately 30 percent. On average, approximately 81 percent of indirect emissions are from croplands and 19 percent from grasslands. Estimated direct and indirect N_2O emissions by sub-source category are shown in Table 5-18 and Table 5-19.

Table 5-16: N_2O Emissions from Agricultural Soils (MMT CO_2 Eq.)

Activity	1990	2005	2012	2013	2014	2015	2016
Direct	**212.0**	**218.5**	**215.6**	**233.3**	**231.4**	**244.5**	**237.6**
Cropland	147.5	153.9	156.7	165.5	165.1	169.3	168.0
Grassland	64.5	64.6	59.0	67.9	66.3	75.3	69.9
Indirect	**38.5**	**35.0**	**32.3**	**43.3**	**42.6**	**50.5**	**45.9**
Cropland	30.9	28.0	25.4	35.5	34.9	41.9	37.9
Grassland	7.6	7.0	6.9	7.8	7.7	8.6	8.1
Total	**250.5**	**253.5**	**247.9**	**276.6**	**274.0**	**295.0**	**283.6**

Notes: Estimates after 2012 are based on a data splicing method (See Methodology section). Totals may not sum due to independent rounding.

Table 5-17: N_2O Emissions from Agricultural Soils (kt)

Activity	1990	2005	2012	2013	2014	2015	2016
Direct	**711**	**733**	**724**	**783**	**777**	**821**	**797**
Cropland	495	516	526	555	554	568	564
Grassland	217	217	198	228	223	253	234
Indirect	**129**	**118**	**108**	**145**	**143**	**169**	**154**
Cropland	104	94	85	119	117	140	127
Grassland	26	23	23	26	26	29	27
Total	**840**	**851**	**832**	**928**	**920**	**990**	**952**

Notes: Estimates after 2012 are based on a data splicing method (See Methodology section). Totals may not sum due to independent rounding.

Table 5-18: Direct N_2O Emissions from Agricultural Soils by Land Use Type and N Input Type (MMT CO_2 Eq.)

Activity	1990	2005	2012	2013	2014	2015	2016
Cropland	**147.5**	**153.9**	**156.7**	**165.5**	**165.1**	**169.3**	**168.0**
Mineral Soils	**144.1**	**150.6**	**153.5**	**161.9**	**161.6**	**165.8**	**164.6**
Synthetic Fertilizer	53.6	54.6	60.4	63.3	62.4	64.1	63.6
Organic Amendment[a]	10.0	10.9	11.3	10.8	10.4	10.7	10.6
Residue N[b]	22.1	22.9	23.5	25.3	25.7	26.4	26.3
Mineralization and Asymbiotic Fixation	58.4	62.2	58.2	62.6	63.1	64.6	64.1
Drained Organic Soils	**3.3**	**3.3**	**3.2**	**3.6**	**3.5**	**3.5**	**3.5**
Grassland	**64.5**	**64.6**	**59.0**	**67.9**	**66.3**	**75.3**	**69.6**
Mineral Soils	**61.3**	**61.1**	**55.7**	**64.3**	**62.7**	**71.7**	**66.0**
Synthetic Fertilizer	0.9	0.8	0.7	0.9	0.8	1.0	0.9
PRP Manure	16.1	13.8	13.3	15.2	14.8	16.0	15.2
Managed Manure[c]	0.9	1.1	1.1	1.2	1.2	1.4	1.3
Biosolids (i.e., Sewage Sludge)	0.2	0.5	0.6	0.6	0.6	0.6	0.6
Residue N[d]	14.4	15.8	14.2	16.5	16.1	18.7	17.0
Mineralization and Asymbiotic Fixation	28.5	29.2	25.8	29.9	29.3	34.0	31.0
Drained Organic Soils	3.3	3.5	3.3	3.6	3.6	3.6	3.6
Total	**212.0**	**218.5**	**215.6**	**233.3**	**231.4**	**244.5**	**237.6**

[a] Organic amendment inputs include managed manure, daily spread manure, and commercial organic fertilizers (i.e., dried blood, dried manure, tankage, compost, and other).
[b] Cropland residue N inputs include N in unharvested legumes as well as crop residue N.
[c] Managed manure inputs include managed manure and daily spread manure amendments that are applied to grassland soils.
[d] Grassland residue N inputs include N in ungrazed legumes as well as ungrazed grass residue N.
Notes: Estimates after 2012 are based on a data splicing method (See Methodology section). Totals may not sum due to independent rounding.

Table 5-19: Indirect N_2O Emissions from Agricultural Soils (MMT CO_2 Eq.)

Activity	1990		2005		2012	2013	2014	2015	2016
Cropland	**30.9**		**28.0**		**25.4**	**35.5**	**34.9**	**41.9**	**37.9**
Volatilization & Atm. Deposition	5.9		6.6		6.5	7.0	7.0	7.1	6.9
Surface Leaching & Run-Off	25.0		21.4		18.9	28.5	27.9	34.8	30.9
Grassland	**7.6**		**7.0**		**6.9**	**7.8**	**7.7**	**8.6**	**8.1**
Volatilization & Atm. Deposition	4.4		4.5		4.2	4.6	4.6	5.1	4.8
Surface Leaching & Run-Off	3.2		2.5		2.6	3.1	3.1	3.5	3.3
Total	**38.5**		**35.0**		**32.3**	**43.3**	**42.6**	**50.5**	**45.9**

Notes: Estimates after 2012 are based on a data splicing method (See Methodology section). Totals may not sum due to independent rounding.

Figure 5-4 and Figure 5-5 show regional patterns for direct N_2O emissions, Figure 5-6 and Figure 5-7 show indirect N_2O emissions from volatilization, and Figure 5-8 and Figure 5-9 show the indirect N_2O emissions from leaching and runoff in croplands and grasslands, respectively. Annual emissions in 2012[15] are shown for the Tier 3 Approach only.

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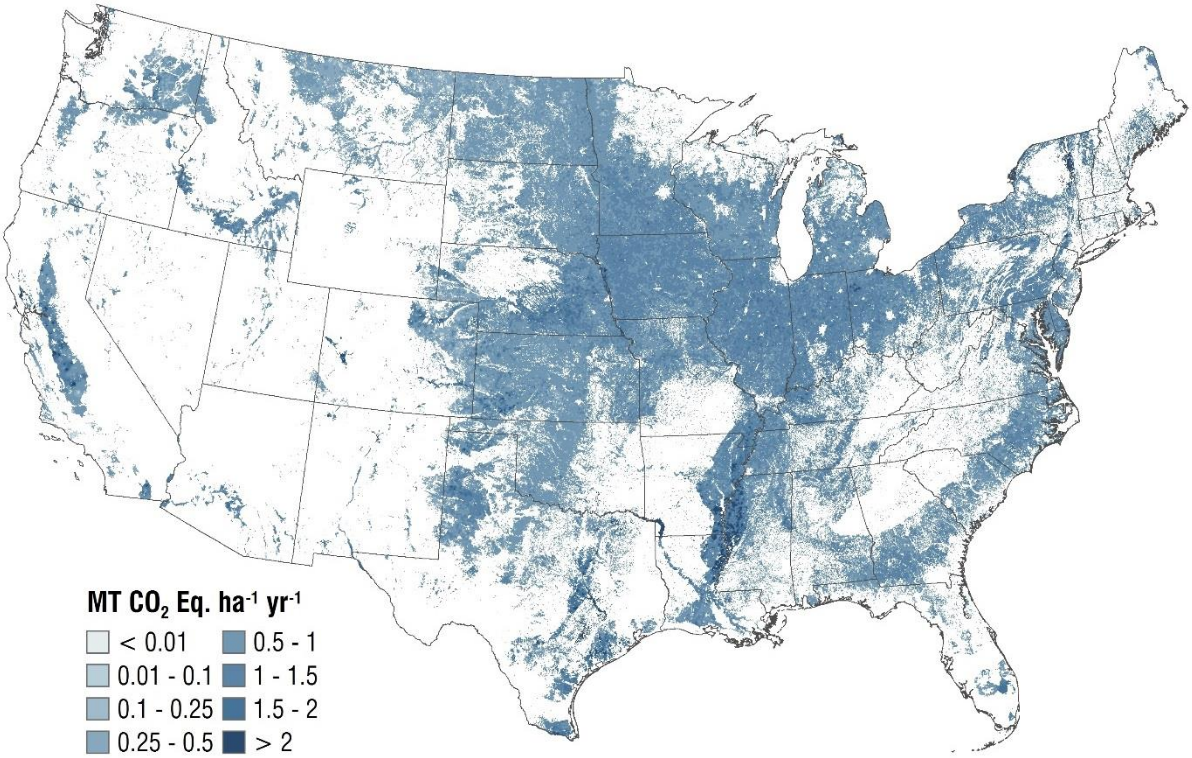
[15] Only national-scale emissions are estimated for 2013 to 2016 in the current Inventory using the splicing method, and therefore the fine-scale emission patterns in these maps are based on Inventory data from 2012.

Figure 5-4: Crops, 2012 Annual Direct N_2O Emissions Estimated Using the Tier 3 DAYCENT Model (MMT CO_2 Eq./year)

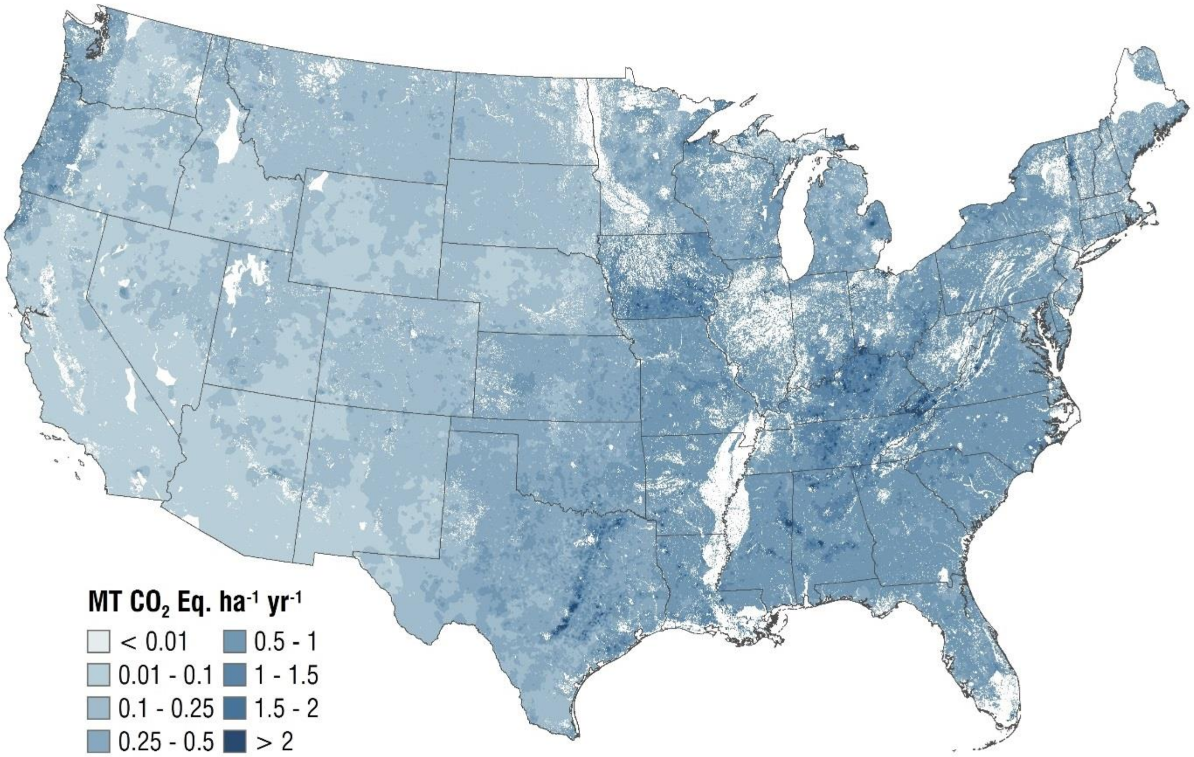


Note: Only national-scale emissions are estimated for 2013 to 2016 using a splicing method, and therefore the fine-scale emission patterns in this map are based on Inventory data from 2012.

Direct N_2O emissions from croplands occur throughout all of the cropland regions but tend to be high in the Midwestern Corn Belt Region (Illinois, Iowa, Indiana, Ohio, southern Minnesota and Wisconsin, and eastern Nebraska), where a large portion of the land is used for growing highly fertilized corn and N-fixing soybean crops (see Figure 5-4). Emissions are also high in the Lower Mississippi River Basin from Missouri to Louisiana, and highly productive irrigated areas, such as Platte River, which flows from Colorado through Nebraska, Snake River Valley in Idaho and the Central Valley in California. Direct emissions are low in many parts of the eastern United States because only a small portion of land is cultivated as well as in many western states where rainfall and access to irrigation water are limited.

Direct emissions from grasslands are highest in the southeast, particularly Kentucky and Tennessee, in addition to areas in east Texas and Iowa, where there tends to be higher rates of manure amendments on a relatively small amount of pasture, compared to other regions of the United States. However, total emissions from grasslands tend to be higher in the Great Plains and western United States (see Figure 5-5) where a high proportion of the land is dominated by grasslands and used for cattle grazing.

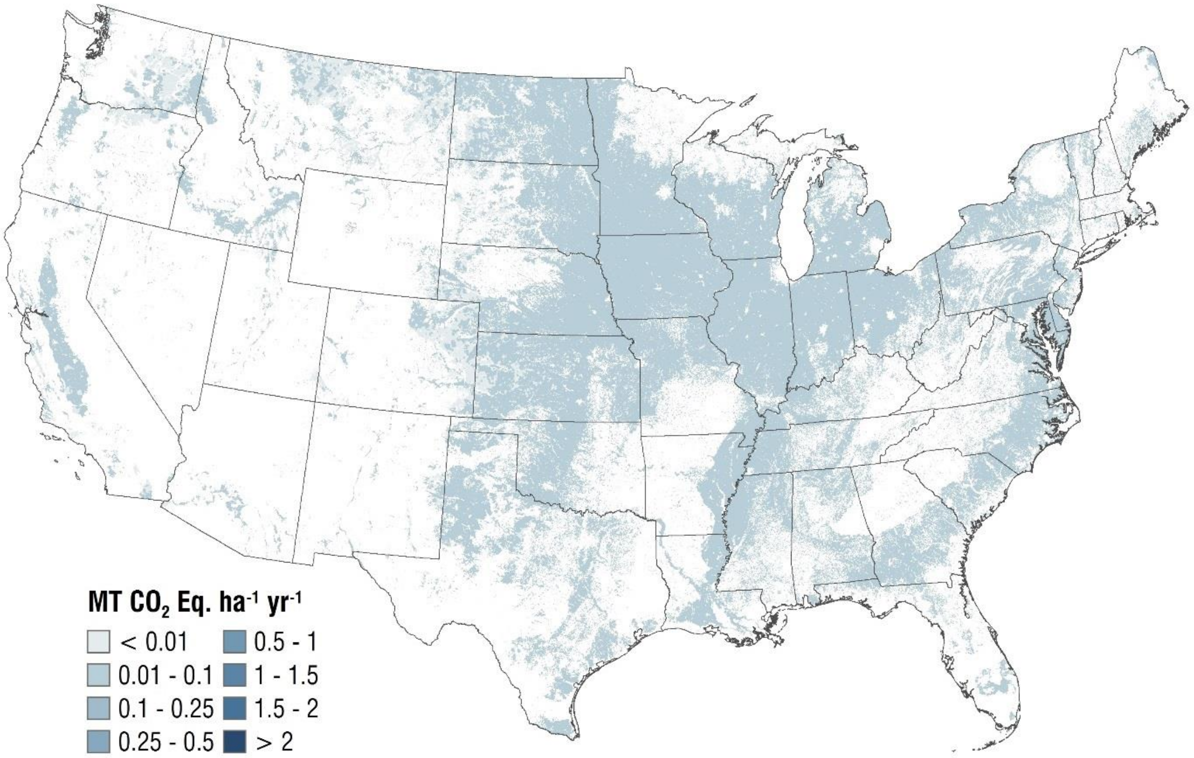
Figure 5-5: Grasslands, 2012 Annual Direct N_2O Emissions Estimated Using the Tier 3 DAYCENT Model (MMT CO_2 Eq./year)



Note: Only national-scale emissions are estimated for 2013 to 2016 using a splicing method, and therefore the fine-scale emission patterns in this map are based on Inventory data from 2012.

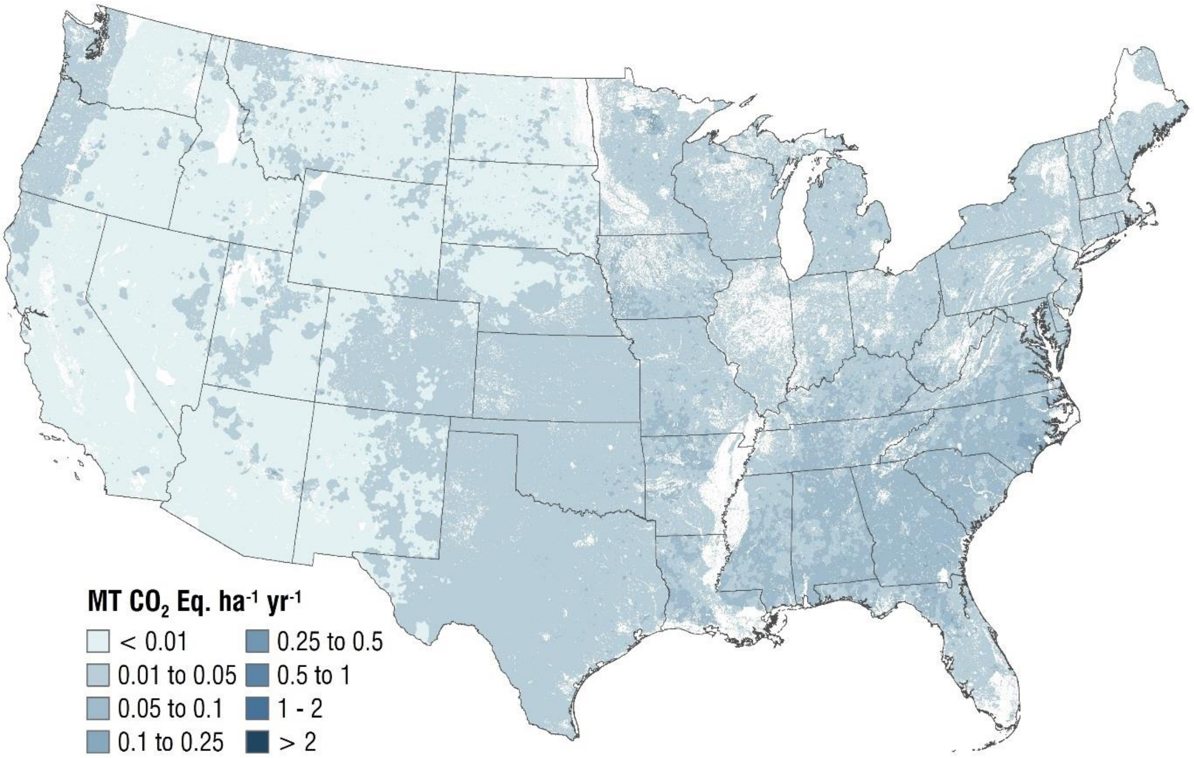
Indirect N_2O emissions from volatilization in croplands have a similar pattern as the direct N_2O emissions with high emissions in the Midwestern Corn Belt and Lower Mississippi River Basin. Indirect N_2O emissions from volatilization in grasslands are higher in the Southeastern United States than in other regions. The higher emissions in this region are mainly due to highly productive pastures that support intensive grazing, which in turn, stimulates NH_3 volatilization. Indirect N_2O emissions from surface runoff and leaching of applied/mineralized N is highest in the Eastern United States for both croplands and grasslands. This region has greater precipitation and higher levels of leaching and runoff compared to the more arid region in the Western United States.

Figure 5-6: Crops, 2012 Annual Indirect N_2O Emissions from Volatilization Using the Tier 3 DAYCENT Model (MMT CO_2 Eq./year)



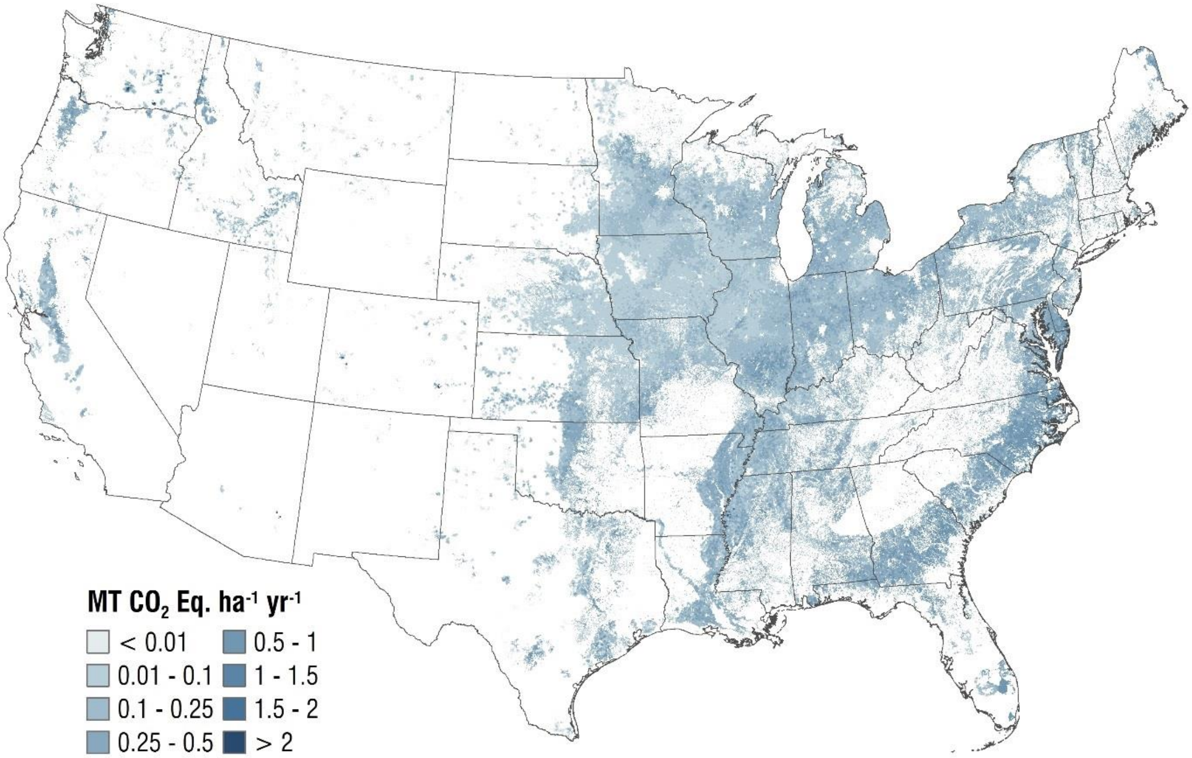
Note: Only national-scale emissions are estimated for 2013 to 2016 using a splicing method, and therefore the fine-scale emission patterns in this map are based on Inventory data from 2012.

Figure 5-7: Grasslands, 2012 Annual Indirect N_2O Emissions from Volatilization Using the Tier 3 DAYCENT Model (MMT CO_2 Eq./year)



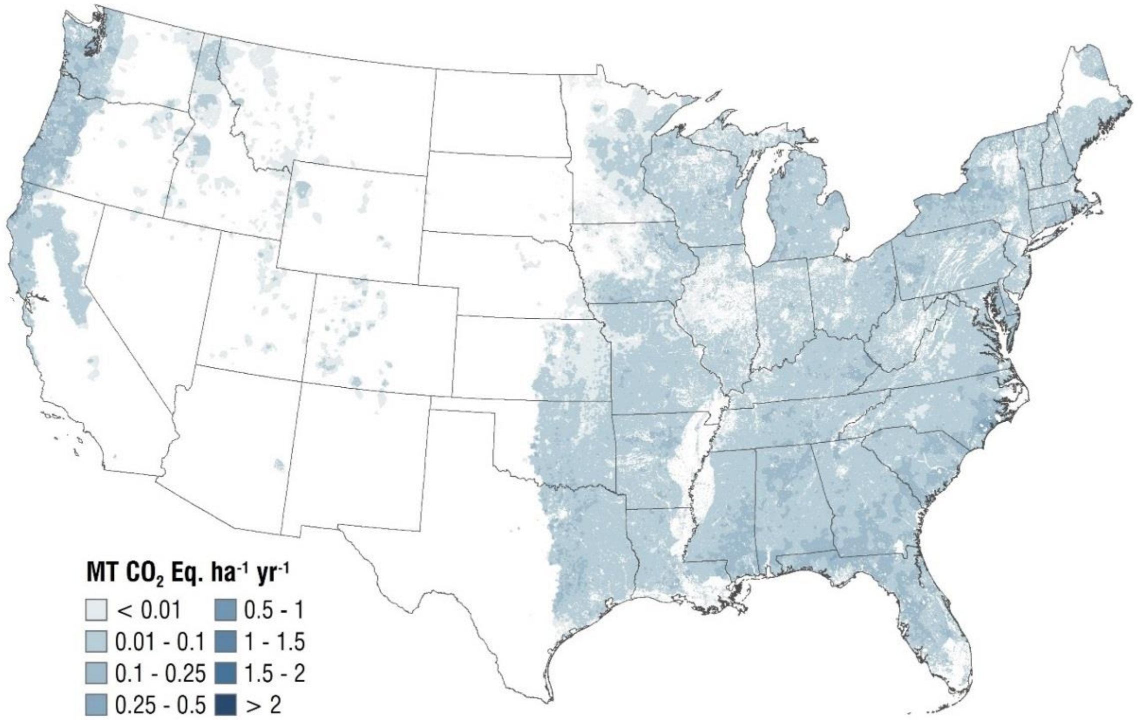
Note: Only national-scale emissions are estimated for 2013 to 2016 using a splicing method, and therefore the fine-scale emission patterns in this map are based on Inventory data from 2012.

Figure 5-8: Crops, 2012 Annual Indirect N_2O Emissions from Leaching and Runoff Using the Tier 3 DAYCENT Model (MMT CO_2 Eq./year)



Note: Only national-scale emissions are estimated for 2013 to 2016 using a splicing method, and therefore the fine-scale emission patterns in this map are based on Inventory data from 2012.

Figure 5-9: Grasslands, 2012 Annual Indirect N_2O Emissions from Leaching and Runoff Using the Tier 3 DAYCENT Model (MMT CO_2 Eq./year)



Note: Only national-scale emissions are estimated for 2013 to 2016 using a splicing method, and therefore the fine-scale emission patterns in this map are based on Inventory data from 2012.

Methodology

The *2006 IPCC Guidelines* (IPCC 2006) divide emissions from the agricultural soil management source category into five components, including (1) direct emissions from N additions to cropland and grassland mineral soils from synthetic fertilizers, biosolids (i.e., sewage sludge) applications, crop residues, organic amendments, and biological N fixation associated with planting of legumes on cropland and grassland soils; (2) direct emissions from soil organic matter mineralization due to land use and management change; (3) direct emissions from drainage of organic soils in croplands and grasslands; (4) direct emissions from soils due to manure deposited by livestock on PRP grasslands; and (5) indirect emissions from soils and water from N additions and manure deposition to soils that lead to volatilization, leaching, or runoff of N and subsequent conversion to N_2O.

In this source category, the United States reports on all croplands, as well as all "managed" grasslands, whereby management of a land use implies there are anthropogenic impacts on greenhouse gas emissions (IPCC 2006), including direct and indirect N_2O emissions from asymbiotic fixation[16] and mineralization of soil organic matter and litter. One recommendation from IPCC (2006) that has not been completely adopted is the estimation of emissions from grassland pasture renewal, which involves occasional plowing to improve forage production in pastures. Currently no data are available to address pasture renewal.

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[16] N inputs from asymbiotic N fixation are not directly addressed in *2006 IPCC Guidelines*, but are a component of the total emissions from managed lands and are included in the Tier 3 approach developed for this source.

Direct N_2O Emissions

The methodology used to estimate direct N_2O emissions from agricultural soil management in the United States is based on a combination of IPCC Tier 1 and 3 approaches, along with application of a splicing method for latter years in the Inventory time series (IPCC 2006; Del Grosso et al. 2010). A Tier 3 process-based model (DAYCENT) is used to estimate direct emissions from a variety of crops that are grown on mineral (i.e., non-organic) soils, as well as the direct emissions from non-federal grasslands with the exception of biosolids (i.e., sewage sludge) amendments (Del Grosso et al. 2010). The Tier 3 approach has been specifically designed and tested to estimate N_2O emissions in the United States, accounting for more of the environmental and management influences on soil N_2O emissions than the IPCC Tier 1 method (see Box 5-4 for further elaboration). Moreover, the Tier 3 approach allows for the Inventory to address direct N_2O emissions and soil C stock changes from mineral cropland soils in a single analysis. Carbon and N dynamics are linked in plant-soil systems through biogeochemical processes of microbial decomposition and plant production (McGill and Cole 1981). Coupling the two source categories (i.e., agricultural soil C and N_2O) in a single inventory analysis ensures that there is consistent activity data and treatment of the processes, and interactions are taken into account between C and N cycling in soils.

The Tier 3 approach is based on the cropping and land use histories recorded in the USDA National Resources Inventory (NRI) (USDA-NRCS 2015). The NRI is a statistically-based sample of all non-federal land,[17] and includes 363,286 points on agricultural land for the conterminous United States that are included in the Tier 3 method. The Tier 1 approach is used to estimate the emissions from the remaining 205,487 in the NRI survey that are designated as cropland or grassland (discussed later in this section). Each point is associated with an "expansion factor" that allows scaling of N_2O emissions from NRI points to the entire country (i.e., each expansion factor represents the amount of area with the same land-use/management history as the sample point). Each NRI point was sampled on a 5-year cycle from 1982 until 1997. For cropland, data were collected in 4 out of 5 years in the cycle (i.e., 1979 through 1982, 1984 through 1987, 1989 through 1992, and 1994 through 1997). In 1998, the NRI program began collecting annual data, and the annual data are currently available through 2012 (USDA-NRCS 2015).

Box 5-4: Tier 1 vs. Tier 3 Approach for Estimating N_2O Emissions

The IPCC (2006) Tier 1 approach is based on multiplying activity data on different N inputs (i.e., synthetic fertilizer, manure, N fixation, etc.) by the appropriate default IPCC emission factors to estimate N_2O emissions on an input-by-input basis. The Tier 1 approach requires a minimal amount of activity data, readily available in most countries (e.g., total N applied to crops); calculations are simple; and the methodology is highly transparent. In contrast, the Tier 3 approach developed for this Inventory employs a process-based model (i.e., DAYCENT) that represents the interaction of N inputs, land use and management, as well as environmental conditions at specific locations. Consequently, the Tier 3 approach produces more accurate estimates; it accounts more comprehensively for land-use and management impacts and their interaction with environmental factors (i.e., weather patterns and soil characteristics), which will enhance or dampen anthropogenic influences. However, the Tier 3 approach requires more detailed activity data (e.g., crop-specific N amendment rates), additional data inputs (i.e., daily weather, soil types, etc.), and considerable computational resources and programming expertise. The Tier 3 methodology is less transparent, and thus it is critical to evaluate the output of Tier 3 methods against measured data in order to demonstrate that the method is an improvement over lower tier methods for estimating emissions (IPCC 2006). Another important difference between the Tier 1 and Tier 3 approaches relates to assumptions regarding N cycling. Tier 1 assumes that N added to a system is subject to N_2O emissions only during that year and cannot be stored in soils and contribute to N_2O emissions in subsequent years. This is a simplifying assumption that is likely to create bias in estimated N_2O emissions for a specific year. In contrast, the process-based model used in the Tier 3 approach includes the legacy effect of N added to soils in previous years that is re-mineralized from soil organic matter and emitted as N_2O during subsequent years.

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[17] The NRI survey does include sample points on federal lands, but the program does not collect data from those sample locations.

DAYCENT is used to estimate N_2O emissions associated with production of alfalfa hay, barley, corn, cotton, dry beans, grass hay, grass-clover hay, lentils, oats, onions, peanuts, peas, potatoes, rice, sorghum, soybeans, sugar beets, sunflowers, tobacco, tomatoes, and wheat, but is not applied to estimate N_2O emissions from other crops or rotations with other crops,[18] such as sugarcane, some vegetables, tobacco, and perennial/horticultural crops. Areas that are converted between agriculture (i.e., cropland and grassland) and other land uses, such as forest land, wetland and settlements, are not simulated with DAYCENT. DAYCENT is also not used to estimate emissions from land areas with very gravelly, cobbly, or shaley soils in the topsoil (greater than 35 percent by volume in the top 30 cm of the soil profile), or to estimate emissions from drained organic soils (Histosols). The Tier 3 method has not been fully tested for estimating N_2O emissions associated with these crops and rotations, land uses, as well as organic soils or cobbly, gravelly, and shaley mineral soils. In addition, federal grassland areas are not simulated with DAYCENT due to limited activity data on land use histories. For areas that are not included in the DAYCENT simulations, the Tier 1 IPCC (2006) methodology is used to estimate (1) direct emissions from crops on mineral soils that are not simulated by DAYCENT; (2) direct emissions from PRP on federal grasslands; and (3) direct emissions from drained organic soils in croplands and grasslands.

A splicing method is used to estimate soil N_2O emissions from 2013 to 2016 at the national scale as an alternative to the Tier 1 and Tier 3 methods because new NRI activity data are not available for those years. Specifically, linear regression models with autoregressive moving-average (ARMA) errors (Brockwell and Davis 2016) are used to estimate the relationship between surrogate data and the 1990 to 2012 emissions that are derived using the Tier 3 methods. Surrogate data for these regression models include corn and soybean yields from USDA-NASS statistics,[19] and weather data from the PRISM Climate Group (PRISM 2015). For the Tier 1 method, a linear-time series model is used to estimate emissions from 2013 to 2016 without surrogate data. See Box 5-5 for more information about the splicing method. Emission estimates for 2013 to 2016 will be recalculated in future Inventory reports when new NRI data are available.

Box 5-5: Surrogate Data Method

An approach to extend the time series is needed for Agricultural Soil Management because the Inventory is only fully re-compiled every two years for many categories in the AFOLU sector as part of the biennial update reporting process, and even in years that the Inventory is re-compiled fully with the Tier 1 and 3 methods, there are typically gaps at the end of the time series. This is mainly because the National Resources Inventory (NRI), which provides critical information for estimating greenhouse gas emissions and removals, does not release data every year.

Splicing methods have been used to impute missing data at the end of the emission time series for both the Tier 1 and 3 methods. Specifically, a linear regression model with autoregressive moving-average (ARMA) errors (Brockwell and Davis 2016) is used to estimate emissions based on the modeled 1990 to 2012 emissions data, which has been compiled using the inventory methods described in this section. The model to extend the time series is given by

$$Y = X\beta + \varepsilon,$$

where Y is the response variable (e.g., soil organic carbon), $X\beta$ for the Tier 3 data contains specific surrogate data depending on the response variable, and ε is the remaining unexplained error. Models with a variety of surrogate data were tested, including commodity statistics, weather data, or other relevant information. $X\beta$ for the Tier 1 data only contains year as a predictor of emission patterns over the time series, and therefore, is a linear time series model with no surrogate data. Parameters are estimated from the emissions data for 1990 to 2012 using standard statistical techniques, and these estimates are used in the model described above to predict the missing emissions data for 2013 to 2016.

A critical issue when applying splicing methods is to account for the additional uncertainty introduced by predicting emissions with related information without compiling the full inventory. Specifically, uncertainty will increase for years with imputed estimates based on the splicing methods, compared to those years in which the full inventory is compiled. This added uncertainty is quantified within the model framework using a Monte Carlo approach. EPA

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[18] A small proportion of the major commodity crop production, such as corn and wheat, is included in the Tier 1 analysis because these crops are rotated with other crops or land uses (e.g., forest lands) that are not simulated by DAYCENT.

[19] See <https://quickstats.nass.usda.gov/>.

combined the uncertainty from the original inventory data produced with the Tier 1 and 3 methods, with the uncertainty in the parameters from the linear regression model. Specifically, the original inventory data are derived through a series of random draws from probability distribution functions that produce multiple results (e.g., 100 results are produced with the DAYCENT simulations for the Tier 3 method). In order to propagate the uncertainty from the original Monte Carlo analysis, a separate linear regression model is derived for each result from the Monte Carlo Analysis (i.e., 100 linear regression models are produced for the Tier 3 method). For each linear regression model, EPA randomly selects parameters and applies the model to estimate emissions, and in turn, has multiple estimates of N_2O emissions for 2013 to 2016 associated with each of the Monte Carlo results produced for the 1990 to 2012 time series.

Tier 3 Approach for Mineral Cropland Soils

The DAYCENT biogeochemical model (Parton et al. 1998; Del Grosso et al. 2001 and 2011) is used to estimate direct N_2O emissions from mineral cropland soils that are managed for production of a wide variety of crops (see list in previous paragraph) based on the cropping histories in the 2012 NRI (USDA-NRCS 2015). Crops simulated by DAYCENT are grown on approximately 91 percent of total cropland area in the United States. For agricultural systems in the central region of the United States, crop production for key crops (i.e., corn, soybeans, sorghum, cotton, and wheat) is simulated in DAYCENT with a NASA-CASA production algorithm (Potter et al. 1993; Potter et al. 2007) using the Moderate Resolution Imaging Spectroradiometer (MODIS) Enhanced Vegetation Index (EVI) products, MOD13Q1 and MYD13Q1, with a pixel resolution of 250m.[20]

DAYCENT is used to estimate direct N_2O emissions due to mineral N available from the following sources: (1) the application of synthetic fertilizers; (2) the application of livestock manure; (3) the retention of crop residues and subsequent mineralization of N during microbial decomposition (i.e., leaving residues in the field after harvest instead of burning or collecting residues); (4) mineralization of soil organic matter; and (5) asymbiotic fixation. Note that commercial organic fertilizers (TVA 1991 through 1994; AAPFCO 1995 through 2016) are addressed with the Tier 1 method because county-level application data would be needed to simulate applications in DAYCENT, and currently data are only available at the national scale. The third and fourth sources are generated internally by the DAYCENT model.

Synthetic fertilizer data are based on fertilizer use and rates by crop type for different regions of the United States and are obtained primarily from the USDA Economic Research Service. The data collection program was known as the Cropping Practices Surveys through 1995 (USDA-ERS 1997), and then became the Agricultural Resource Management Surveys (ARMS) (USDA-ERS 2015). Additional data are compiled through other sources particularly the National Agricultural Statistics Service (NASS 1992, 1999, 2004). Frequency and rates of livestock manure application to cropland during 1997 are estimated from data compiled by the USDA Natural Resources Conservation Service (Edmonds et al. 2003), and then adjusted using county-level estimates of manure available for application in other years. The adjustments are based on county-scale ratios of manure available for application to soils in other years relative to 1997 (see Annex 3.12 for further details). Greater availability of managed manure N relative to 1997 is assumed to increase the area amended with manure, while reduced availability of manure N relative to 1997 is assumed to reduce the amended area. Data on the county-level N available for application is estimated for managed manure systems based on the total amount of N excreted in manure minus N losses during storage and transport, and including the addition of N from bedding materials. Nitrogen losses include direct N_2O emissions, volatilization of ammonia and NO_x, runoff and leaching, and poultry manure used as a feed supplement. For unmanaged manure systems, it is assumed that no N losses or additions occur prior to the application of manure to the soil. More information on livestock manure production is available in Section 5.2 Manure Management and Annex 3.11.

The IPCC approach considers crop residue N and N mineralized from soil organic matter as activity data. However, they are not treated as activity data in DAYCENT simulations because residue production, symbiotic N fixation (e.g., legumes), mineralization of N from soil organic matter, and asymbiotic N fixation are internally generated by the model as part of the simulation. In other words, DAYCENT accounts for the influence of symbiotic N fixation,

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[20] See <https://lpdaac.usgs.gov/products/modis_products_table>.

mineralization of N from soil organic matter and crop residue retained in the field, and asymbiotic N fixation on N_2O emissions, but these are not model inputs. The N_2O emissions from crop residues are reduced by approximately 3 percent (the assumed average burned portion for crop residues in the United States) to avoid double-counting associated with non-CO_2 greenhouse gas emissions from agricultural residue burning. The estimate of residue burning is based on state inventory data (ILENR 1993; Oregon Department of Energy 1995; Noller 1996; Wisconsin Department of Natural Resources 1993; Cibrowski 1996).

Additional sources of data are used to supplement the mineral N (USDA-ERS 1997, 2011), livestock manure (Edmonds et al. 2003), and land-use information (USDA-NRCS 2015). The Conservation Technology Information Center (CTIC 2004) provides annual data on tillage activity with adjustments for long-term adoption of no-till agriculture (Towery 2001). Tillage has an influence on soil organic matter decomposition and subsequent soil N_2O emissions. The time series of tillage data from CTIC began in 1989 and ended in 2004, so further changes in tillage practices since 2004 are not currently captured in the Inventory and practices used in 2004 are assumed to apply for subsequent years. Daily weather data are used as an input in the model simulations, based on gridded weather data at a 32 km scale from the North America Regional Reanalysis Product (NARR) (Mesinger et al. 2006). Soil attributes are obtained from the Soil Survey Geographic Database (SSURGO) (Soil Survey Staff 2011).

Each NRI point is run 100 times as part of the uncertainty assessment, yielding a total of over 18 million simulations for the analysis. Soil N_2O emission estimates from DAYCENT are adjusted using a structural uncertainty estimator to account for uncertainty in model algorithms and parameter values (Del Grosso et al. 2010). Soil N_2O emissions and associated 95 percent confidence intervals are estimated for each year between 1990 and 2012, but emissions from 2013 to 2016 are estimated using a splicing method that accounts for uncertainty in the original inventory data and the splicing method (See Box 5-5). Annual data are currently available through 2012 (USDA-NRCS 2015), and the Inventory time series will be updated in the future when new NRI data are released.

Nitrous oxide emissions from managed agricultural lands are the result of interactions among anthropogenic activities (e.g., N fertilization, manure application, tillage) and other driving variables, such as weather and soil characteristics. These factors influence key processes associated with N dynamics in the soil profile, including immobilization of N by soil microbial organisms, decomposition of organic matter, plant uptake, leaching, runoff, and volatilization, as well as the processes leading to N_2O production (nitrification and denitrification). It is not possible to partition N_2O emissions into each anthropogenic activity directly from model outputs due to the complexity of the interactions (e.g., N_2O emissions from synthetic fertilizer applications cannot be distinguished from those resulting from manure applications). To approximate emissions by activity, the amount of mineral N added to the soil, or made available through decomposition of soil organic matter and plant litter, as well as asymbiotic fixation of N from the atmosphere, is determined for each N source and then divided by the total amount of mineral N in the soil according to the DAYCENT model simulation. The percentages are then multiplied by the total of direct N_2O emissions in order to approximate the portion attributed to N management practices. This approach is only an approximation because it assumes that all N made available in soil has an equal probability of being released as N_2O, regardless of its source, which is unlikely to be the case (Delgado et al. 2009). However, this approach allows for further disaggregation of emissions by source of N, which is valuable for reporting purposes and is analogous to the reporting associated with the IPCC (2006) Tier 1 method, in that it associates portions of the total soil N_2O emissions with individual sources of N.

Tier 1 Approach for Mineral Cropland Soils

The IPCC (2006) Tier 1 methodology is used to estimate direct N_2O emissions for mineral cropland soils that are not simulated by DAYCENT (e.g., DAYCENT has not been parametrized to simulate all crop types and some soil types such as *Histosols*). For the Tier 1 Approach, estimates of direct N_2O emissions from N applications are based on mineral soil N that is made available from the following practices: (1) the application of synthetic commercial fertilizers; (2) application of managed manure and non-manure commercial organic fertilizers; and (3) decomposition and mineralization of nitrogen from above- and below-ground crop residues in agricultural fields (i.e., crop biomass that is not harvested). Non-manure commercial organic amendments are only included in the Tier 1 analysis because these data are not available at the county-level, which is necessary for the DAYCENT simulations.[21] Consequently, all commercial organic fertilizer, as well as manure that is not added to crops in the DAYCENT simulations, are included in the Tier 1 analysis. The following sources are used to derive activity data:

- A process-of-elimination approach is used to estimate synthetic N fertilizer additions for crop areas not simulated by DAYCENT. The total amount of fertilizer used on farms has been estimated at the county-level by the USGS from sales records (Ruddy et al. 2006), and these data are aggregated to obtain state-level N additions to farms. For 2002 through 2012, state-level fertilizer for on-farm use is adjusted based on annual fluctuations in total U.S. fertilizer sales (AAPFCO 1995 through 2007, 2008 through 2012). After subtracting the portion of fertilizer applied to crops and grasslands simulated by DAYCENT (see Tier 3 Approach for Mineral Cropland Soils and Direct N_2O Emissions from Grassland Soils sections for information on data sources), the remainder of the total fertilizer used on farms is assumed to be applied to crops that are not simulated by DAYCENT.
- Similarly, a process-of-elimination approach is used to estimate manure N additions for crops that are not simulated by DAYCENT. The amount of manure N applied in the Tier 3 approach to crops and grasslands is subtracted from total manure N available for land application (see Tier 3 Approach for Mineral Cropland Soils and Direct N_2O Emissions from Grassland Soils sections for information on data sources), and this difference is assumed to be applied to crops that are not simulated by DAYCENT.
- Commercial organic fertilizer additions are based on organic fertilizer consumption statistics, which are converted to units of N using average organic fertilizer N content (TVA 1991 through 1994; AAPFCO 1995 through 2012). Commercial fertilizers do include some manure and biosolids (i.e., sewage sludge), but the amounts are removed from the commercial fertilizer data to avoid double counting with the manure N dataset described above and the biosolids (i.e., sewage sludge) amendment data discussed later in this section.
- Crop residue N is derived by combining amounts of above- and below-ground biomass, which are determined based on NRI crop area data (USDA-NRCS 2013), crop production yield statistics (USDA-NASS 2015), dry matter fractions (IPCC 2006), linear equations to estimate above-ground biomass given dry matter crop yields from harvest (IPCC 2006), ratios of below-to-above-ground biomass (IPCC 2006), and N contents of the residues (IPCC 2006). N inputs from residue were reduced by 3 percent to account for average residue burning portions in the United States.

The total increase in soil mineral N from applied fertilizers and crop residues is multiplied by the IPCC (2006) default emission factor to derive an estimate of direct N_2O emissions using the Tier 1 Approach.

Tier 1 soil N_2O emissions from 2013 to 2016 are estimated using a splicing method that is described in Box 5-5. As with the Tier 3 method, the time series will be recalculated in future Inventory reports when new activity data are compiled (see Planned Improvements section).

Tier 1 Approach for Drainage of Organic Soils in Croplands and Grasslands

The IPCC (2006) Tier 1 methods are used to estimate direct N_2O emissions due to drainage of organic soils in croplands and grasslands at a state scale. State-scale estimates of the total area of drained organic soils are obtained from the 2012 NRI (USDA-NRCS 2015) using soils data from the Soil Survey Geographic Database (SSURGO) (Soil Survey Staff 2011). Temperature data from Daly et al. (1994 and 1998) are used to subdivide areas into temperate and tropical climates using the climate classification from IPCC (2006). To estimate annual emissions, the total temperate area is multiplied by the IPCC default emission factor for temperate regions, and the total tropical area is multiplied by the IPCC default emission factor for tropical regions (IPCC 2006). Annual NRI data are only available between 1990 and 2012. Consequently, emissions from 2013 to 2016 are estimated using a linear time series model (see Box 5-5). Estimates for 2013 to 2016 will be recalculated in future Inventory reports when new NRI data are available.

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[21] Commercial organic fertilizers include dried blood, tankage, compost, and other, but the dried manure and biosolids (i.e., sewage sludge) is removed from the dataset in order to avoid double counting with other datasets that are used for manure N and biosolids.

Tier 1 and 3 Approaches for Direct N_2O Emissions from Grassland Soils

As with N_2O from croplands, the Tier 3 process-based DAYCENT model and Tier 1 method described in IPCC (2006) are combined to estimate emissions from non-federal grasslands and PRP manure N additions for federal grasslands, respectively. Grassland includes pasture and rangeland that produce grass forage primarily for livestock grazing. Rangelands are typically extensive areas of native grassland that are not intensively managed, while pastures are typically seeded grassland (possibly following tree removal) that may also have additional management, such as irrigation, fertilization, or interseeding legumes. DAYCENT is used to simulate N_2O emissions from NRI survey locations (USDA-NRCS 2015) on non-federal grasslands resulting from manure deposited by livestock directly onto pastures and rangelands (i.e., PRP manure), N fixation from legume seeding, managed manure amendments (i.e., manure other than PRP manure such as Daily Spread), and synthetic fertilizer application. Other N inputs are simulated within the DAYCENT framework, including N input from mineralization due to decomposition of soil organic matter and N inputs from senesced grass litter, as well as asymbiotic fixation of N from the atmosphere. The simulations used the same weather, soil, and synthetic N fertilizer data as discussed under the Tier 3 Approach in the Mineral Cropland Soils section. Mineral N fertilization rates are based on Carbon Sequestration Rural Appraisals (CSRA) conducted by the USDA-NRCS (USDA-NRCS, unpublished data). The CSRA was a solicitation of expert knowledge from USDA-NRCS staff throughout the United States to support the Inventory. Managed manure N amendments to grasslands are estimated from Edmonds et al. (2003) and adjusted for annual variation using data on the availability of managed manure N for application to soils, according to methods described in the Manure Management section (Section 5.2) and Annex 3.11. Biological N fixation is simulated within DAYCENT, and therefore is not an input to the model.

Manure N deposition from grazing animals in PRP systems (i.e., PRP manure) is another key input of N to grasslands. The amounts of PRP manure N applied on non-federal grasslands for each NRI point are based on amount of N excreted by livestock in PRP systems. The total amount of N excreted in each county is divided by the grassland area to estimate the N input rate associated with PRP manure. The resulting input rates are used in the DAYCENT simulations. DAYCENT simulations of non-federal grasslands accounted for approximately 78 percent of total PRP manure N in aggregate across the country. The remainder of the PRP manure N in each state is assumed to be excreted on federal grasslands, and the N_2O emissions are estimated using the IPCC (2006) Tier 1 method with IPCC default emission factors.

Biosolids (i.e., sewage sludge) are assumed to be applied on grasslands because of the heavy metal content and other pollutants in human waste that limit its use as an amendment to croplands. Biosolids application is estimated from data compiled by EPA (1993, 1999, 2003), McFarland (2001), and NEBRA (2007) (see Section 7.2 Wastewater Treatment for a detailed discussion of the methodology for estimating sewage sludge available for land application application). Biosolids soil amendments are only available at the national scale, and it is not possible to associate application with specific soil conditions and weather at NRI survey locations. Therefore, DAYCENT could not be used to simulate the influence of biosolids amendments on N_2O emissions from grassland soils, and consequently, emissions from biosolids are estimated using the IPCC (2006) Tier 1 method.

As previously mentioned, each NRI point is simulated 100 times as part of the uncertainty assessment, yielding a total of over 18 million simulation runs for the analysis. Soil N_2O emission estimates from DAYCENT are adjusted using a structural uncertainty estimator accounting for uncertainty in model algorithms and parameter values (Del Grosso et al. 2010). N_2O emissions for the PRP manure N deposited on federal grasslands and applied biosolids N are estimated using the Tier 1 method by multiplying the N input by the default emission factor. Emissions from manure N are estimated at the state level and aggregated to the entire country, but emissions from biosolids N are calculated exclusively at the national scale.

Soil N_2O emissions and 95 percent confidence intervals are estimated for each year between 1990 and 2012 based on the Tier 1 and 3 methods, with the exception of biosolids (discussed below), and emissions from 2013 to 2016 are estimated using a splicing method as described in Box 5-5. As with croplands, estimates for 2013 to 2016 will be recalculated in future inventories when new NRI data are available. Biosolids application data are compiled through 2016 in this Inventory, and therefore soil N_2O emissions and confidence intervals are estimated using the Tier 1 method for all years in the time series without application of the splicing method.

Total Direct N_2O Emissions from Cropland and Grassland Soils

Annual direct emissions from the Tier 1 and 3 approaches for mineral and drained organic soils occurring in both croplands and grasslands are summed to obtain the total direct N_2O emissions from agricultural soil management (see Table 5-16 and Table 5-17).

Indirect N_2O Emissions

This section describes the methods used for estimating indirect soil N_2O emissions from croplands and grasslands. Indirect N_2O emissions occur when mineral N made available through anthropogenic activity is transported from the soil either in gaseous or aqueous forms and later converted into N_2O. There are two pathways leading to indirect emissions. The first pathway results from volatilization of N as NO_x and NH_3 following application of synthetic fertilizer, organic amendments (e.g., manure, biosolids), and deposition of PRP manure. Nitrogen made available from mineralization of soil organic matter and residue, including N incorporated into crops and forage from symbiotic N fixation, and input of N from asymbiotic fixation also contributes to volatilized N emissions. Volatilized N can be returned to soils through atmospheric deposition, and a portion of the deposited N is emitted to the atmosphere as N_2O. The second pathway occurs via leaching and runoff of soil N (primarily in the form of NO_3^-) that is made available through anthropogenic activity on managed lands, mineralization of soil organic matter and residue, including N incorporated into crops and forage from symbiotic N fixation, and inputs of N into the soil from asymbiotic fixation. The NO_3^- is subject to denitrification in water bodies, which leads to N_2O emissions. Regardless of the eventual location of the indirect N_2O emissions, the emissions are assigned to the original source of the N for reporting purposes, which here includes croplands and grasslands.

Tier 1 and 3 Approaches for Indirect N_2O Emissions from Atmospheric Deposition of Volatilized N

The Tier 3 DAYCENT model and IPCC (2006) Tier 1 methods are combined to estimate the amount of N that is volatilized and eventually emitted as N_2O. DAYCENT is used to estimate N volatilization for land areas whose direct emissions are simulated with DAYCENT (i.e., most commodity and some specialty crops and most grasslands). The N inputs included are the same as described for direct N_2O emissions in the Tier 3 Approach for Mineral Cropland Soils and Direct N_2O Emissions from Grassland Soils sections. Nitrogen volatilization from all other areas is estimated using the Tier 1 method and default IPCC fractions for N subject to volatilization (i.e., N inputs on croplands not simulated by DAYCENT, PRP manure N excreted on federal grasslands, biosolids [i.e., sewage sludge] application on grasslands). For the volatilization data generated from both the DAYCENT and Tier 1 approaches, the IPCC (2006) default emission factor is used to estimate indirect N_2O emissions occurring due to re-deposition of the volatilized N (see Table 5-19).

Tier 1 and 3 Approaches for Indirect N_2O Emissions from Leaching/Runoff

As with the calculations of indirect emissions from volatilized N, the Tier 3 DAYCENT model and IPCC (2006) Tier 1 method are combined to estimate the amount of N that is subject to leaching and surface runoff into water bodies, and eventually emitted as N_2O. DAYCENT is used to simulate the amount of N transported from lands in the Tier 3 Approach. Nitrogen transport from all other areas is estimated using the Tier 1 method and the IPCC (2006) default factor for the proportion of N subject to leaching and runoff. This N transport estimate includes N applications on croplands that are not simulated by DAYCENT, biosolids amendments on grasslands, and PRP manure N excreted on federal grasslands. For both the DAYCENT Tier 3 and IPCC (2006) Tier 1 methods, nitrate leaching is assumed to be an insignificant source of indirect N_2O in cropland and grassland systems in arid regions, as discussed in IPCC (2006). In the United States, the threshold for significant nitrate leaching is based on the potential evapotranspiration (PET) and rainfall amount, similar to IPCC (2006), and is assumed to be negligible in regions where the amount of precipitation plus irrigation does not exceed 80 percent of PET. For leaching and runoff data estimated by the Tier 3 and Tier 1 approaches, the IPCC (2006) default emission factor is used to estimate indirect N_2O emissions that occur in groundwater and waterways (see Table 5-19).

Indirect soil N_2O emissions from 2013 to 2016 are estimated using the splicing method that is described in Box 5-5. As with the direct N_2O emissions, the time series will be recalculated in a future Inventory report when new activity data are compiled (see Planned Improvements section).

Uncertainty and Time-Series Consistency

Uncertainty is estimated for each of the following five components of N_2O emissions from agricultural soil management: (1) direct emissions simulated by DAYCENT; (2) the components of indirect emissions (N volatilized and leached or runoff) simulated by DAYCENT; (3) direct emissions calculated with the IPCC (2006) Tier 1 method; (4) the components of indirect emissions (N volatilized and leached or runoff) calculated with the IPCC (2006) Tier 1 method; and (5) indirect emissions estimated with the IPCC (2006) Tier 1 method. Uncertainty in direct emissions, which account for the majority of N_2O emissions from agricultural management, as well as the components of indirect emissions calculated by DAYCENT are estimated with a Monte Carlo Analysis, addressing uncertainties in model inputs and structure (i.e., algorithms and parameterization) (Del Grosso et al. 2010). For 2013 to 2016, there is additional uncertainty propagated through the Monte Carlo Analysis associated with the splicing method (See Box 5-5).

Simple error propagation methods (IPCC 2006) are used to estimate confidence intervals for direct emissions calculated with the IPCC (2006) Tier 1 method, the proportion of volatilization and leaching or runoff estimated with the IPCC (2006) Tier 1 method, and indirect N_2O emissions. Uncertainty in the splicing method is also included in the error propagation for 2013 to 2016 (see Box 5-5). Additional details on the uncertainty methods are provided in Annex 3.12. Table 5-20 shows the combined uncertainty for direct soil N_2O emissions ranged from 16 percent below to 16 percent above the 2016 emission estimate of 237.6 MMT CO_2 Eq., and the combined uncertainty for indirect soil N_2O emissions range from 65 percent below to 154 percent above the 2016 estimate of 45.9 MMT CO_2 Eq.

Table 5-20: Quantitative Uncertainty Estimates of N_2O Emissions from Agricultural Soil Management in 2016 (MMT CO_2 Eq. and Percent)

Source	Gas	2016 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Direct Soil N_2O Emissions	N_2O	237.6	199.2	276.1	-16%	16%
Indirect Soil N_2O Emissions	N_2O	45.9	16.0	116.8	-65%	154%

Notes: Due to lack of data, uncertainties in managed manure N production, PRP manure N production, other organic fertilizer amendments, and biosolids (i.e., sewage sludge) amendments to soils are currently treated as certain; these sources of uncertainty will be included in future Inventory reports.

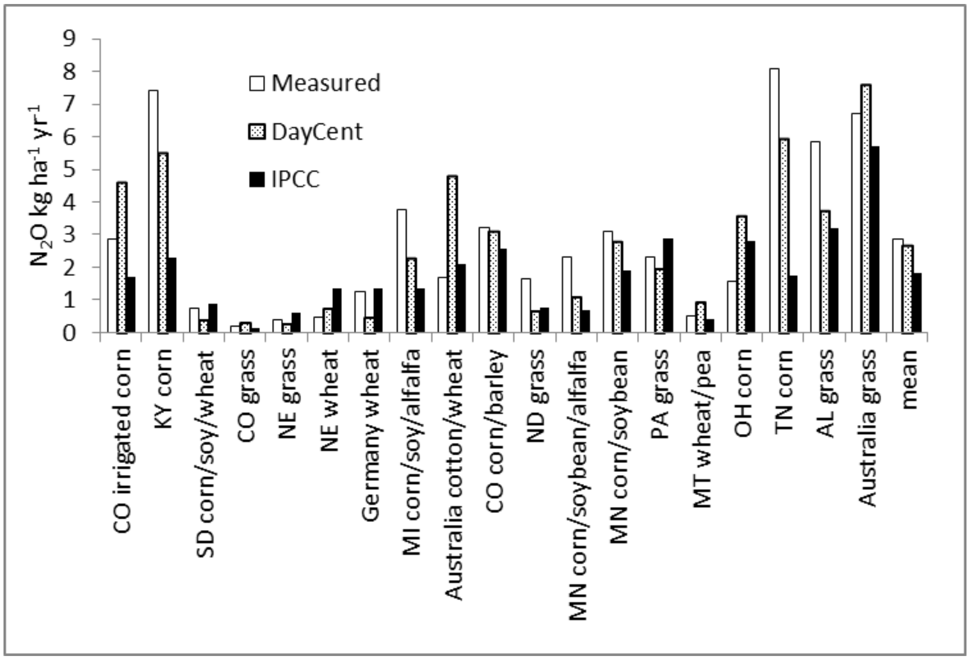
Additional uncertainty is associated with an incomplete estimation of N_2O emissions from managed croplands and grasslands in Hawaii and Alaska. The Inventory currently includes the N_2O emissions from mineral fertilizer and PRP N additions in Alaska and Hawaii, and drained organic soils in Hawaii. Land areas used for agriculture in Alaska and Hawaii are small relative to major commodity cropping states in the conterminous United States, so the emissions are likely to be small for the other sources of N (e.g., crop residue inputs), which are not currently included in the Inventory.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2016. Details on the emission trends through time are described in more detail in the Methodology section.

QA/QC and Verification

DAYCENT results for N_2O emissions and NO_3^- leaching are compared with field data representing various cropland and grassland systems, soil types, and climate patterns (Del Grosso et al. 2005; Del Grosso et al. 2008), and further evaluated by comparing the model results to emission estimates produced using the IPCC (2006) Tier 1 method for the same sites. Nitrous oxide measurement data are available for 41 sites, which mostly occur in the United States, with five in Europe and three in Australia, representing over 200 different combinations of fertilizer treatments and cultivation practices. Nitrate leaching data are available for four sites in the United States, representing 10 different combinations of fertilizer amendments/tillage practices. DAYCENT estimates of N_2O emissions are closer to measured values at most sites compared to the IPCC Tier 1 estimate (see Figure 5-10). In general, the IPCC Tier 1 methodology tends to over-estimate emissions when observed values are low and under-estimate emissions when observed values are high, while DAYCENT estimates have less bias. DAYCENT accounts for key site-level factors (i.e., weather, soil characteristics, and management) that are not addressed in the IPCC Tier 1 method, and thus the model is better able to represent the variability in N_2O emissions. DAYCENT does have a tendency to under-estimate very high N_2O emission rates; and estimates are adjusted using the statistical model derived from the comparison of model estimates to measurements (see Annex 3.12 for more information). Regardless, the comparison demonstrates that DAYCENT provides relatively high predictive capability for N_2O emissions, and is an improvement over the IPCC Tier 1 method.

Figure 5-10: Comparison of Measured Emissions at Field Sites and Modeled Emissions Using the DAYCENT Simulation Model and IPCC Tier 1 Approach (kg N_2O per ha per year)



Spreadsheets containing input data and probability distribution functions required for DAYCENT simulations of croplands and grasslands and unit conversion factors have been checked, in addition to the program scripts that are used to run the Monte Carlo uncertainty analysis. Two errors have been identified through these checks, including omission of PRP manure N from the indirect soil N_2O emissions in Alaska and Hawaii, and double-counting other organic amendments in the Tier 1 direct N_2O emission calculations. Links between spreadsheets have also been checked, updated, and corrected when necessary. Spreadsheets containing input data, emission factors, and calculations required for the Tier 1 method have been checked and updated as needed.

Recalculations Discussion

Methodological recalculations in the current Inventory are associated with the following improvements: (1) estimating emissions from 2013 to 2015 using a splicing method (other than biosolids which are estimated with a Tier 1 method for the entire time series) (Box 5-5); (2) correcting an omission of PRP manure N input from 1990 to 2012 in Alaska and Hawaii for indirect soil N_2O emission; and (3) correcting a double-counting of other organic amendments from 1990 to 2012 in the Tier 1 method for direct N_2O emissions. These changes resulted in an average decrease in emissions of 0.7 percent from 1990 to 2015 relative to the previous Inventory.

Planned Improvements

New land representation data have not been compiled for this Inventory, and a splicing method has been applied to estimate emissions in the latter part of the time series, which introduces additional uncertainty in the emissions data. Therefore, a key improvement for a future Inventory will be to recalculate the time series from 2013 to 2016 with the latest land use data from the National Resources Inventory and related management statistics, particularly data compiled through the Conservation Effects Assessment Program (discussed below).

Several planned improvements are underway. The DAYCENT biogeochemical model will be improved with a better representation of plant phenology, particularly senescence events following grain filling in crops. In addition, crop parameters associated with temperature and water stress effects on plant production will be further improved in DAYCENT with additional model calibration. Model development is underway to represent the influence of nitrification inhibitors and slow-release fertilizers (e.g., polymer-coated fertilizers) on N_2O emissions. An improved representation of drainage as well as freeze-thaw cycles are also under development. Experimental study sites will continue to be added for quantifying model structural uncertainty. Studies that have continuous (daily) measurements of N_2O (e.g., Scheer et al. 2013) will be given priority.

The time series of management data will be updated with information from the USDA-NRCS Conservation Effects Assessment Program (CEAP). This improvement will fill several gaps in the management data including more specific data on fertilizer rates, updated tillage practices, and more information on planting and harvesting dates for crops.

Improvements are underway to simulate crop residue burning in the DAYCENT model based on the amount of crop residues burned according to the data that is used in the Field Burning of Agricultural Residues source category (see Section 5.7).

Alaska and Hawaii are not included for all sources in the current Inventory for agricultural soil management, with the exception of N_2O emissions from drained organic soils in croplands and grasslands for Hawaii, synthetic fertilizer and PRP N amendments for grasslands in Alaska and Hawaii. A planned improvement over the next two years is to add the remaining sources for these states into the Inventory analysis.

There is also an improvement based on updating the Tier 1 emission factor for N_2O emissions from drained organic soils by using the revised factor in the 2013 Supplement to the *2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* (IPCC 2013).

These improvements are expected to be completed for the next Inventory (i.e., 2019 submission to the UNFCCC, 1990 through 2017 Inventory). However, the time line may be extended if there are insufficient resources to fund all or part of these planned improvements.

5.5 Liming (CRF Source Category 3G)

Crushed limestone ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$) are added to soils by land managers to increase soil pH (i.e., to reduce acidification). Carbon dioxide emissions occur as these compounds react with hydrogen ions in soils. The rate of degradation of applied limestone and dolomite depends on the soil conditions, soil type, climate regime, and whether limestone or dolomite is applied. Emissions from liming of soils have fluctuated over the past 25 years in the United States, ranging from 3.6 MMT CO_2 Eq. to 6.0 MMT CO_2 Eq. In 2016, liming of soils in the United States resulted in emissions of 3.9 MMT CO_2 Eq. (1.1 MMT C), representing a 17 percent decrease in emissions since 1990 (see Table 5-21 and Table 5-22). The trend is driven by variation in the amount of limestone and dolomite applied to soils over the time period.

Table 5-21: Emissions from Liming (MMT CO_2 Eq.)

Source	1990		2005		2012	2013	2014	2015	2016

Limestone	4.1	3.9	4.5	3.6	3.3	3.5	3.6
Dolomite	0.6	0.4	1.5	0.3	0.3	0.3	0.3
Total	**4.7**	**4.3**	**6.0**	**3.9**	**3.6**	**3.8**	**3.9**

Note: Totals may not sum due to independent rounding.

Table 5-22: Emissions from Liming (MMT C)

Source	1990	2005	2012	2013	2014	2015	2016
Limestone	1.1	1.1	1.2	1.0	0.9	1.0	1.0
Dolomite	0.2	0.1	0.4	0.1	0.1	0.1	0.1
Total	**1.3**	**1.2**	**1.6**	**1.1**	**1.0**	**1.0**	**1.1**

Note: Totals may not sum due to independent rounding.

Methodology

Carbon dioxide emissions from application of limestone and dolomite to soils were estimated using a Tier 2 methodology consistent with IPCC (2006). The annual amounts of limestone and dolomite applied (see Table 5-23) were multiplied by CO_2 emission factors from West and McBride (2005). These emission factors (0.059 metric ton C/metric ton limestone, 0.064 metric ton C/metric ton dolomite) are lower than the IPCC default emission factors because they account for the portion of carbonates that are transported from soils through hydrological processes and eventually deposited in ocean basins (West and McBride 2005). This analysis of lime dissolution is based on studies in the Mississippi River basin, where the vast majority of lime application occurs in the United States (West 2008). Moreover, much of the remaining lime application is occurring under similar precipitation regimes, and so the emission factors are considered a reasonable approximation for all lime application in the United States (West 2008).

The annual application rates of limestone and dolomite were derived from estimates and industry statistics provided in the *Minerals Yearbook* and *Mineral Industry Surveys* (Tepordei 1993 through 2006; Willett 2007a, 2007b, 2009, 2010, 2011a, 2011b, 2013a, 2014, 2015, 2016 and 2017; USGS 2008 through 2017). The U.S. Geological Survey (USGS; U.S. Bureau of Mines prior to 1997) compiled production and use information through surveys of crushed stone manufacturers. However, manufacturers provided different levels of detail in survey responses so the estimates of total crushed limestone and dolomite production and use were divided into three components: (1) production by end-use, as reported by manufacturers (i.e., "specified" production); (2) production reported by manufacturers without end-uses specified (i.e., "unspecified" production); and (3) estimated additional production by manufacturers who did not respond to the survey (i.e., "estimated" production).

Box 5-6: Comparison of the Tier 2 U.S. Inventory Approach and IPCC (2006) Default Approach

Emissions from liming of soils were estimated using a Tier 2 methodology based on emission factors specific to the United States that are lower than the IPCC (2006) emission default factors. Most lime application in the United States occurs in the Mississippi River basin, or in areas that have similar soil and rainfall regimes as the Mississippi River basin. Under these conditions, a significant portion of dissolved agricultural lime leaches through the soil into groundwater. Groundwater moves into channels and is transported to larger rives and eventually the ocean where $CaCO_3$ precipitates to the ocean floor (West and McBride 2005). The U.S.-specific emission factors (0.059 metric ton C/metric ton limestone and 0.064 metric ton C/metric ton dolomite) are about half of the IPCC (2006) emission factors (0.12 metric ton C/metric ton limestone and 0.13 metric ton C/metric ton dolomite). For comparison, the 2016 U.S. emission estimate from liming of soils is 3.9 MMT CO_2 Eq. using the U.S.-specific factors. In contrast, emissions would be estimated at 7.9 MMT CO_2 Eq. using the IPCC (2006) default emission factors.

Data on "specified" limestone and dolomite amounts were used directly in the emission calculation because the end use is provided by the manufacturers and can be used to directly determine the amount applied to soils. However, it is not possible to determine directly how much of the limestone and dolomite is applied to soils for manufacturer surveys in the "unspecified" and "estimated" categories. For these categories, the amounts of crushed limestone and dolomite applied to soils were determined by multiplying the percentage of total "specified" limestone and dolomite production that is applied to soils, by the total amounts of “unspecified” and “estimated” limestone and dolomite production. In other words, the proportion of total “unspecified” and “estimated” crushed limestone and dolomite that was applied to soils is proportional to the amount of total “specified” crushed limestone and dolomite that was applied to soils.

In addition, data were not available for 1990, 1992 and 2016 on the fractions of total crushed stone production that were limestone and dolomite, and on the fractions of limestone and dolomite production that were applied to soils. To estimate the 1990 and 1992 data, a set of average fractions were calculated using the 1991 and 1993 data. These average fractions were applied to the quantity of "total crushed stone produced or used" reported for 1990 and 1992 in the 1994 *Minerals Yearbook* (Tepordei 1996). To estimate 2016 data, 2015 fractions were applied to a 2016 estimate of total crushed stone presented in the USGS *Mineral Industry Surveys: Crushed Stone and Sand and Gravel in the First Quarter of 2017* (USGS 2017).

The primary source for limestone and dolomite activity data is the *Minerals Yearbook*, published by the Bureau of Mines through 1994 and by the USGS from 1995 to the present. In 1994, the “Crushed Stone” chapter in the *Minerals Yearbook* began rounding (to the nearest thousand metric tons) quantities for total crushed stone produced or used. It then reported revised (rounded) quantities for each of the years from 1990 to 1993. In order to minimize the inconsistencies in the activity data, these revised production numbers have been used in all of the subsequent calculations.

Table 5-23: Applied Minerals (MMT)

Mineral	1990	2005	2012	2013	2014	2015	2016
Limestone	19.0	18.1	20.8	16.4	15.3	16.2	16.5
Dolomite	2.4	1.9	6.3	1.5	1.3	1.2	1.2

Uncertainty and Time-Series Consistency

Uncertainty regarding the amount of limestone and dolomite applied to soils was estimated at ±15 percent with normal densities (Tepordei 2003; Willett 2013b). Analysis of the uncertainty associated with the emission factors included the fraction of lime dissolved by nitric acid versus the fraction that reacts with carbonic acid, and the portion of bicarbonate that leaches through the soil and is transported to the ocean. Uncertainty regarding the time associated with leaching and transport was not addressed in this analysis, but is assumed to be a relatively small contributor to the overall uncertainty (West 2005). The probability distribution functions for the fraction of lime dissolved by nitric acid and the portion of bicarbonate that leaches through the soil were represented as triangular distributions between ranges of zero and 100 percent of the estimates. The uncertainty surrounding these two components largely drives the overall uncertainty.

A Monte Carlo (Approach 2) uncertainty analysis was applied to estimate the uncertainty in CO_2 emissions from liming. The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 5-24. Carbon dioxide emissions from carbonate lime application to soils in 2016 were estimated to be between -0.4 and 7.3 MMT CO_2 Eq. at the 95 percent confidence level. This confidence interval represents a range of 111 percent below to 88 percent above the 2016 emission estimate of 3.9 MMT CO_2 Eq.

Table 5-24: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Liming (MMT CO_2 Eq. and Percent)

Source	Gas	2016 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Liming	CO_2	3.9	(0.4)	7.3	-111%	+88%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2016. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

A source-specific QA/QC plan for liming has been developed and implemented, and the quality control effort focused on the Tier 1 procedures for this Inventory. No errors were found.

Recalculations Discussion

Adjustments were made in the current Inventory to improve the results. First, limestone and dolomite application data for 2015 were updated with the recently published data from USGS (2017), rather than being approximated by a ratio method. With this revision in the activity data, the emissions decreased by 0.9 percent in 2015 relative to the previous Inventory.

5.6 Urea Fertilization (CRF Source Category 3H)

The use of urea ($CO(NH_2)_2$) as a fertilizer leads to CO_2 emissions through the release of CO_2 that was fixed during the industrial production process. In the presence of water and urease enzymes, urea is converted into ammonium (NH_4^+), hydroxyl ion (OH), and bicarbonate (HCO_3^-). The bicarbonate then evolves into CO_2 and water. Emissions from urea fertilization in the United States totaled 5.1 MMT CO_2 Eq. (1.4 MMT C) in 2016 (Table 5-25 and Table 5-26). Due to an increase in application of urea fertilizers between 1990 and 2016, CO_2 emissions have increased by 111 percent from this management activity.

Table 5-25: CO_2 Emissions from Urea Fertilization (MMT CO_2 Eq.)

Source	1990	2005	2012	2013	2014	2015	2016
Urea Fertilization	2.4	3.5	4.3	4.4	4.5	4.9	5.1

Table 5-26: CO_2 Emissions from Urea Fertilization (MMT C)

Source	1990	2005	2012	2013	2014	2015	2016
Urea Fertilization	0.7	1.0	1.2	1.2	1.2	1.3	1.4

Methodology

Carbon dioxide emissions from the application of urea to agricultural soils were estimated using the IPCC (2006) Tier 1 methodology. The method assumes that all CO_2 fixed during the industrial production process of urea are released after application. The annual amounts of urea applied to croplands (see Table 5-27) were derived from the state-level fertilizer sales data provided in *Commercial Fertilizer* reports (TVA 1991, 1992, 1993, 1994; AAPFCO 1995 through 2017).[22] These amounts were multiplied by the default IPCC (2006) emission factor (0.20 metric tons of C per metric ton of urea), which is equal to the C content of urea on an atomic weight basis. Because fertilizer sales data are reported in fertilizer years (July previous year through June current year), a calculation was performed to convert the data to calendar years (January through December). According to monthly fertilizer use data (TVA 1992b), 35 percent of total fertilizer used in any fertilizer year is applied between July and December of the previous calendar year, and 65 percent is applied between January and June of the current calendar year. For example, in the 2000 fertilizer year, 35 percent of the fertilizer was applied in July through December 1999, and 65 percent was applied in January through June 2000.

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[22] The amount of urea consumed for non-agricultural purposes in the United States is reported in the Industrial Processes and Product Use chapter, Section 4.6 Urea Consumption for Non-Agricultural Purposes.

Fertilizer sales data for the 2015 and 2016 fertilizer years (i.e., July 2014 through June 2015 and July 2015 through June 2016) were not available for this Inventory. Therefore, urea application in the 2015 and 2016 fertilizer years were estimated using a linear, least squares trend of consumption over the data from the previous five years (2010 through 2014) at the state scale. A trend of five years was chosen as opposed to a longer trend as it best captures the current inter-state and inter-annual variability in consumption. State-level estimates of CO_2 emissions from the application of urea to agricultural soils were summed to estimate total emissions for the entire United States. The fertilizer year data is then converted into calendar year data using the method described above.

Table 5-27: Applied Urea (MMT)

	1990		2005		2012	2013	2014	2015	2016
Urea Fertilizer[a]	3.3		4.8		5.8	6.1	6.2	6.7	7.0

[a] These numbers represent amounts applied to all agricultural land, including *Cropland Remaining Cropland, Land Converted to Cropland, Grassland Remaining Grassland, Land Converted to Grassland, Settlements Remaining Settlements, Land Converted to Settlements, Forest Land Remaining Forest Land* and *Land Converted to Forest Land,* as it is not currently possible to apportion the data by land-use category.

Uncertainty and Time-Series Consistency

Uncertainty estimates are presented in Table 5-28 for urea fertilization. An Approach 2 Monte Carlo analysis was completed. The largest source of uncertainty was the default emission factor, which assumes that 100 percent of the C in $CO(NH_2)_2$ applied to soils is ultimately emitted into the environment as CO_2. This factor does not incorporate the possibility that some of the C may be retained in the soil, and therefore the uncertainty range was set from 0 percent emissions to the maximum emission value of 100 percent using a triangular distribution. In addition, urea consumption data also have uncertainty that is propagated through the emission calculation using a Monte Carlo simulation approach as described by the IPCC (2006). Carbon dioxide emissions from urea fertilization of agricultural soils in 2016 were estimated to be between 2.9 and 5.3 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of 43 percent below to 3 percent above the 2016 emission estimate of 5.1 MMT CO_2 Eq.

Table 5-28: Quantitative Uncertainty Estimates for CO_2 Emissions from Urea Fertilization (MMT CO_2 Eq. and Percent)

Source	Gas	2016 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a]			
			(MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Urea Fertilization	CO_2	5.1	2.9	5.3	-43%	3%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

There are additional uncertainties that are not quantified in this analysis. Urea for non-fertilizer use, such as aircraft deicing, may be included in consumption totals, but the amount is likely very small. For example, research on aircraft deicing practices based on a 1992 survey found a known annual usage of approximately 2,000 tons of urea for deicing; this would constitute 0.06 percent of the 1992 consumption of urea (EPA 2000). Similarly, surveys conducted from 2002 to 2005 indicate that total urea use for deicing at U.S. airports is estimated to be 3,740 metric tons per year, or less than 0.07 percent of the fertilizer total for 2007 (Itle 2009). In addition, there is uncertainty surrounding the underlying assumptions behind the calculation that converts fertilizer years to calendar years. These uncertainties are negligible over multiple years because an over- or under-estimated value in one calendar year is addressed with corresponding increase or decrease in the value for the subsequent year.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2016. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

A source-specific QA/QC plan for Urea Fertilization has been developed and implemented, and no errors were found.

Recalculations Discussion

Recalculations resulted from updated urea application estimates in a new AAPFCO report (2017). Specifically, the 2013 activity data (i.e., amount of urea applied) for the states of California, Maryland, and Mississippi were updated. New activity data for 2014 were applied to all states; 2015 and 2016 estimates were derived using the new data for 2013 and 2014. This resulted in an emissions decrease for the United States of 1.3 percent in 2013, 5.1 percent in 2014, and 2.9 percent in 2015.

5.7 Field Burning of Agricultural Residues (CRF Source Category 3F)

Crop production creates large quantities of agricultural crop residues, which farmers manage in a variety of ways. For example, crop residues can be left in the field and possibly incorporated into the soil with tillage; collected and used as fuel, animal bedding material, supplemental animal feed, or construction material; composted and applied to soils; transported to landfills; or burned in the field. Field burning of crop residues is not considered a net source of CO_2 emissions because the C released to the atmosphere as CO_2 during burning is reabsorbed during the next growing season by the crop. However, crop residue burning is a net source of CH_4, N_2O, CO, and NO_x, which are released during combustion.

In the United States, field burning of agricultural residues commonly occurs in southeastern states, the Great Plains, and the Pacific Northwest (McCarty 2011). The primary crops that are managed with residue burning include corn, cotton, lentils, rice, soybeans, sugarcane, and wheat (McCarty 2009). Rice, sugarcane, and wheat residues account for approximately 70 percent of all crop residue burning and emissions (McCarty 2011). In 2016, CH_4 and N_2O emissions from field burning of agricultural residues were 0.3 MMT CO_2 Eq. (11 kt) and 0.1 MMT CO_2 Eq. (0.3 kt), respectively (see Table 5-29 and Table 5-30). Annual emissions of CH_4 and N_2O have increased from 1990 to 2016 by 20 percent and 21 percent, respectively. The increase in emissions over time is due to larger amounts of residue production with higher yielding crop varieties and fuel loads.

Table 5-29: CH_4 and N_2O Emissions from Field Burning of Agricultural Residues (MMT CO_2 Eq.)

Gas/Crop Type	1990	2005	2012	2013	2014	2015	2016
CH_4	**0.2**	**0.2**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**
Wheat	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Rice	0.1	+	0.1	0.1	0.1	+	0.1
Sugarcane	+	+	+	+	+	+	+
Corn	+	+	+	+	+	+	+
Cotton	+	+	+	+	+	+	+
Soybeans	+	+	+	+	+	+	+
Lentil	+	+	+	+	+	+	+
N_2O	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Wheat	+	+	+	+	+	+	+
Rice	+	+	+	+	+	+	+
Sugarcane	+	+	+	+	+	+	+
Corn	+	+	+	+	+	+	+
Cotton	+	+	+	+	+	+	+
Soybeans	+	+	+	+	+	+	+
Lentil	+	+	+	+	+	+	+
Total	**0.3**	**0.3**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**

+ Does not exceed 0.05 MMT CO_2 Eq.
Note: Totals may not sum due to independent rounding.

Table 5-30: CH_4, N_2O, CO, and NO_x Emissions from Field Burning of Agricultural Residues (kt)

Gas/Crop Type	1990	2005	2012	2013	2014	2015	2016
CH_4	**9**	**8**	**11**	**11**	**11**	**11**	**11**
Wheat	5	4	5	5	5	5	5
Rice	2	2	2	2	2	2	2
Sugarcane	+	1	1	1	2	2	1
Corn	1	1	1	1	2	2	2
Soybeans	1	1	1	1	1	1	1
Lentil	+	+	+	+	+	+	+
Cotton	+	+	+	+	+	+	+
N_2O	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Wheat	+	+	+	+	+	+	+
Rice	+	+	+	+	+	+	+
Sugarcane	+	+	+	+	+	+	+
Corn	+	+	+	+	+	+	+
Cotton	+	+	+	+	+	+	+
Soybeans	+	+	+	+	+	+	+
Lentil	+	+	+	+	+	+	+
CO	**191**	**178**	**232**	**239**	**240**	**239**	**230**
NO_x	**6**	**6**	**7**	**7**	**8**	**8**	**7**

+ Does not exceed 0.5 kt.

Methodology

A U.S.-specific Tier 2 method was used to estimate greenhouse gas emissions from field burning of agricultural residues from 1990 to 2015[23] (for more details comparing the U.S.-specific approach to the IPCC (2006) default approach, see Box 5-7). In order to estimate the amounts of C and N released during burning, the following equation was used:

$$\text{C or N released} = \Sigma \text{ for all crop types and states} \left(\frac{\text{AB}}{\text{CAH} \times \text{CP} \times \text{RCR} \times \text{DMF} \times \text{BE} \times \text{CE} \times (\text{FC or FN})} \right)$$

where,

Area Burned (AB)	=	Total area of crop burned, by state
Crop Area Harvested (CAH)	=	Total area of crop harvested, by state
Crop Production (CP)	=	Annual production of crop in kt, by state
Residue: Crop Ratio (RCR)	=	Amount of residue produced per unit of crop production
Dry Matter Fraction (DMF)	=	Amount of dry matter per unit of biomass for a crop
Fraction of C or N (FC or FN)	=	Amount of C or N per unit of dry matter for a crop
Burning Efficiency (BE)	=	The proportion of prefire fuel biomass consumed[24]
Combustion Efficiency (CE)	=	The proportion of C or N released with respect to the total amount of C or N available in the burned material, respectively

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[23] The emission estimates for 2016 are estimated using an extrapolation method described later in this section.

[24] In IPCC/UNEP/OECD/IEA (1997), the equation for C or N released contains the variable 'fraction oxidized in burning'. This variable is equivalent to (burning efficiency × combustion efficiency).

Crop Production and Crop Area Harvested were available by state and year from USDA (2016) for all crops (except rice in Florida and Oklahoma, as detailed below). The amount of C or N released was used in the following equation to determine the CH_4, CO, N_2O, and NO_x emissions from the Field Burning of Agricultural Residues:

$$\text{CH}_4 \text{ and CO, or N}_2\text{O and NO}_x \text{ Emissions from Field Burning of Agricultural Residues} =$$

$$\text{C or N Released} \times \text{ER} \times \text{CF}$$

where,

Emissions Ratio (ER) = g CH_4-C or CO-C/g C released, or g N_2O-N or NO_x-N/g N released
Conversion Factor (CF) = conversion, by molecular weight ratio, of CH_4-C to C (16/12), or CO-C to C (28/12), or N_2O-N to N (44/28), or NO_x-N to N (30/14)

Box 5-7: Comparison of Tier 2 U.S. Inventory Approach and IPCC (2006) Default Approach

Emissions from Field Burning of Agricultural Residues were calculated using a Tier 2 methodology that is based on the method developed by the IPCC/UNEP/OECD/IEA (1997) and incorporates crop- and country-specific emission factors and variables. The rationale for using the IPCC/UNEP/OECD/IEA (1997) approach rather than the method provided in the *2006 IPCC Guidelines* is as follows: (1) the equations from both guidelines rely on the same underlying variables (though the formats differ); (2) the IPCC (2006) equation was developed to be broadly applicable to all types of biomass burning, and, thus, is not specific to agricultural residues; and (3) the IPCC (2006) default factors are provided only for four crops (corn, rice, sugarcane, and wheat) while this Inventory includes emissions from seven crops (corn, cotton, lentils, rice, soybeans, sugarcane, and wheat).

A comparison of the methods and factors used in: (1) the current Inventory and (2) the default IPCC (2006) approach was undertaken for the time series from 1990 through 2015 to determine the difference in overall estimates between the two approaches. To estimate greenhouse gas emissions from field burning of agricultural residues using the IPCC (2006) methodology, the following equation—cf. IPCC (2006) Equation 2.27—was used:

$$\text{Emissions (kt)} = \text{AB} \times (\text{M}_\text{B} \times \text{C}_\text{f}) \times \text{G}_\text{ef} \times 10^{-6}$$

where,

Area Burned (AB) = Total area of crop burned (ha)
Mass Burned ($M_B \times C_f$) = IPCC (2006) default fuel biomass consumption (metric tons dry matter burnt ha^{-1}) and US-Specific Values using NASS Statistics (USDA 2016)
Emission Factor (G_{ef}) = IPCC (2006) emission factor (g kg^{-1} dry matter burnt)

The IPCC (2006) Tier 1 method approach that utilizes default mass of fuel values resulted in 1 percent higher emissions of CH_4 and 14 percent higher emissions of N_2O compared to this Inventory. If U.S.-specific data are used to derive the Mass of Fuel (Mb) from USDA-NASS statistics (USDA 2016), i.e., Tier 2 method, then the IPCC (2006) method resulted in 28 percent higher emissions of CH_4 and 44 percent higher emissions of N_2O compared to the Tier 1 method. This larger difference is attributable to lower combustion efficiency values in IPCC/UNEP/OECD/IEA (1997). In particular, sugarcane has a much lower combustion efficiency value in the earlier guidelines. A lower value is justified because sugarcane is burned prior to harvesting and has a higher moisture content that reduces the combustion efficiency, unlike most other crops (IPCC/UNEP/OECD/IEA 1997). IPCC (2006) does not address the unique burning regime of sugarcane. Overall, the IPCC/UNEP/OECD/IEA (1997) method is considered more appropriate for U.S. conditions because it is more flexible for incorporating country-specific data compared to IPCC (2006) approach.

Crop yield data (except rice in Florida) were based on USDA's *QuickStats* (USDA 2016), and crop area data were based on the 2012 NRI (USDA-NRCS 2015). In order to estimate total crop production, the crop yield data from USDA Quick Stats crop yields was multiplied by the NRI crop areas. Rice yield data for Florida was estimated separately because yield data were not collected by USDA. Total rice production for Florida was determined using NRI crop areas and total yields were based on average primary and ratoon rice yields from Schueneman and Deren (2002). Relative proportions of ratoon crops were derived from information in several publications (Schueneman 1999, 2000, 2001; Deren 2002; Kirstein 2003, 2004; Cantens 2004, 2005; Gonzalez 2007 through 2014). The production data for the crop types whose residues are burned are presented in Table 5-31. Crop weight by bushel was obtained from Murphy (1993).

The fraction of crop area burned was calculated using data on area burned by crop type and state[25] from McCarty (2010) for corn, cotton, lentils, rice, soybeans, sugarcane, and wheat.[26] McCarty (2010) used remote sensing data from MODIS to estimate area burned by crop. State-level area burned data were divided by state-level crop area harvested data to estimate the percent of crop area burned by crop type for each state. The average percentage of crop area burned at the national scale is shown in Table 5-32. Data on fraction of crop area burned were only available from McCarty (2010) for the years 2003 through 2007. For other years in the time series, the percent area burned was set equal to the average over the five-year period from 2003 to 2007. Table 5-32 shows the resulting percentage of crop residue burned at the national scale by crop type. State-level estimates are also available upon request.

All residue:crop product mass ratios except sugarcane and cotton were obtained from Strehler and Stützle (1987). The ratio for sugarcane is from Kinoshita (1988) and the ratio for cotton is from Huang et al. (2007). The residue: crop ratio for lentils was assumed to be equal to the average of the values for peas and beans. Residue dry matter fractions for all crops except soybeans, lentils, and cotton were obtained from Turn et al. (1997). Soybean and lentil dry matter fractions were obtained from Strehler and Stützle (1987); the value for lentil residue was assumed to equal the value for bean residue. The cotton dry matter fraction was taken from Huang et al. (2007). The residue C contents and N contents for all crops except soybeans and cotton are from Turn et al. (1997). The residue C content for soybeans is the IPCC default (IPCC/UNEP/OECD/IEA 1997), and the N content of soybeans is from Barnard and Kristoferson (1985). The C and N contents of lentils were assumed to equal those of soybeans. The C and N contents of cotton are from Lachnicht et al. (2004). The burning efficiency was assumed to be 93 percent, and the combustion efficiency was assumed to be 88 percent, for all crop types, except sugarcane (EPA 1994). For sugarcane, the burning efficiency was assumed to be 81 percent (Kinoshita 1988) and the combustion efficiency was assumed to be 68 percent (Turn et al. 1997). See Table 5-33 for a summary of the crop-specific conversion factors. Emission ratios and mole ratio conversion factors for all gases were based on the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997) (see Table 5-34).

Table 5-31: Agricultural Crop Production (kt of Product)

Crop	1990	2005	2012	2013	2014	2015	2016
Corn[a]	249,806	323,724	311,751	398,817	429,405	422,436	NE
Cotton	4,633	6,560	5,967	5,647	5,934	5,575	NE
Lentils	+	119	121	147	134	117	NE
Rice	9,428	12,253	10,080	10,381	10,347	10,202	NE
Soybeans	56,626	88,036	85,523	93,928	102,065	102,772	NE
Sugarcane	18,765	18,211	16,555	16,129	17,136	18,336	NE
Wheat	79,951	69,190	71,234	69,287	64,650	66,672	NE

+ Does not exceed 0.5 kt.

NE (Not Estimated). 2016 crop production values were not compiled for the current Inventory.

[a] Corn for grain (i.e., excludes corn for silage).

Table 5-32: U.S. Average Percent Crop Area Burned by Crop (Percent)

State	1990	2005	2012	2013	2014	2015	2016
Corn	+	+	+	+	+	+	NE
Cotton	1%	1%	1%	1%	1%	1%	NE
Lentils	+	1%	+	+	+	+	NE
Rice	8%	5%	7%	7%	7%	7%	NE
Soybeans	+	+	+	+	+	+	NE

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[25] Alaska and Hawaii were excluded.

[26] McCarty (2009) also examined emissions from burning of Kentucky bluegrass and a general “other crops/fallow” category, but USDA crop area and production data were insufficient to estimate emissions from these crops using the methodology employed in the Inventory. McCarty (2009) estimates that approximately 18 percent of crop residue emissions result from burning of the Kentucky bluegrass and “other crops” categories.

Sugarcane	13%		25%		53%	52%	53%	54%	NE
Wheat	2%		2%		3%	3%	3%	2%	NE

+ Does not exceed 0.5 percent.

NE (Not Estimated). 2016 crop area burned was not compiled for the current Inventory.

Table 5-33: Key Assumptions for Estimating Emissions from Field Burning of Agricultural Residues

Crop	Residue: Crop Ratio	Dry Matter Fraction	C Fraction	N Fraction	Burning Efficiency (Fraction)	Combustion Efficiency (Fraction)
Corn	1.0	0.91	0.448	0.006	0.93	0.88
Cotton	1.6	0.90	0.445	0.012	0.93	0.88
Lentils	2.0	0.85	0.450	0.023	0.93	0.88
Rice	1.4	0.91	0.381	0.007	0.93	0.88
Soybeans	2.1	0.87	0.450	0.023	0.93	0.88
Sugarcane	0.2	0.62	0.424	0.004	0.81	0.68
Wheat	1.3	0.93	0.443	0.006	0.93	0.88

Table 5-34: Greenhouse Gas Emission Ratios and Conversion Factors

Gas	Emission Ratio	Conversion Factor
CH_4:C	0.005[a]	16/12
CO:C	0.060[a]	28/12
N_2O:N	0.007[b]	44/28
NO_x:N	0.121[b]	30/14

[a] Mass of C compound released (units of C) relative to mass of total C released from burning (units of C).

[b] Mass of N compound released (units of N) relative to mass of total N released from burning (units of N).

For this Inventory, new activity data were not compiled for Field Burning of Agricultural Residues because the Inventory is only fully re-compiled every two years for many categories in the AFOLU sector as part of the biennial update reporting process. Therefore, a linear extrapolation of the trend in the time series was applied to estimate the emissions for 2016. Specifically, a linear regression model with autoregressive moving-average (ARMA) errors was used to estimate the trend in emissions over time from 1990 through 2015, and in turn, the trend was used to approximate the 2016 emissions (Brockwell and Davis 2016). The Tier 2 method described previously will be applied to recalculate the 2016 emissions in the next Inventory (i.e., 1990 through 2017 report).

Uncertainty and Time-Series Consistency

Emissions are estimated using a linear regression model with autoregressive moving-average (ARMA) errors for 2016. The linear regression ARMA model produced estimates of the upper and lower bounds of the emission estimate (Table 5-35), and the results are summarized in Table 5-35. Methane emissions from field burning of agricultural residues in 2016 were estimated to be between 0.23 and 0.31 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 14 percent below and 14 percent above the 2016 emission estimate of 0.3 MMT CO_2 Eq. Nitrous oxide emissions were estimated to be between 0.08 and 0.11 MMT CO_2 Eq., or approximately 14 percent below and 14 percent above the 2016 emission estimate of 0.1 MMT CO_2 Eq.

Table 5-35: Approach 2 Quantitative Uncertainty Estimates for CH_4 and N_2O Emissions from Field Burning of Agricultural Residues (MMT CO_2 Eq. and Percent)

Source	Gas	2016 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate			
			(MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound

Field Burning of Agricultural Residues	CH_4	0.3	0.23	0.31	-14%	14%
Field Burning of Agricultural Residues	N_2O	0.1	0.08	0.11	-14%	14%

[a] Range of emission estimates predicted by ARMA linear regression time-series model for a 95 percent confidence interval.

Due to data limitations, there are additional uncertainties in agricultural residue burning, particularly the omission of burning associated with Kentucky bluegrass and “other crop” residues.

QA/QC and Verification

A source-specific QA/QC plan for field burning of agricultural residues was implemented with Tier 1 analyses, and no errors were found in the current Inventory.

Recalculations Discussion

No recalculations were conducted for the current Inventory.

Planned Improvements

A new method is in development that will directly link agricultural residue burning with the Tier 3 methods that are used in several other source categories, including Agricultural Soil Management, *Cropland Remaining Cropland*, and *Land Converted to Cropland* chapters of the Inventory. The method is based on the DAYCENT model, and burning events will be simulated directly within the process-based model framework using information derived from remote sensing fire products. This improvement will lead to greater consistency in the methods for these sources, and better ensure mass balance of C and N in the Inventory analysis.

6. Land Use, Land-Use Change, and Forestry

This chapter provides an assessment of the greenhouse gas fluxes resulting from land use and land-use change in the United States.[1] The Intergovernmental Panel on Climate Change's *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006) recommends reporting fluxes according to changes within and conversions between certain land-use types termed: Forest Land, Cropland, Grassland, Wetlands, and Settlements (as well as Other Land).

The greenhouse gas flux from *Forest Land Remaining Forest Land* is reported for all forest ecosystem carbon (C) stocks (i.e., aboveground biomass, belowground biomass, dead wood, litter, and C stock changes from mineral and organic soils), harvested wood pools, and non-carbon dioxide (non-CO_2) emissions from forest fires, the application of synthetic nitrogen fertilizers to forest soils, and the draining of organic soils. Fluxes from *Land Converted to Forest Land* are included for aboveground biomass, belowground biomass, dead wood, litter, and C stock changes from mineral soils.

Fluxes are reported for four agricultural land use/land-use change categories: *Cropland Remaining Cropland, Land Converted to Cropland, Grassland Remaining Grassland*, and *Land Converted to Grassland*. The reported greenhouse gas fluxes from these agricultural lands include changes in soil organic C stocks in mineral and organic soils due to land use and management, and for the subcategories of *Forest Land Converted to Cropland* and *Forest Land Converted to Grassland*, the changes in aboveground biomass, belowground biomass, dead wood, and litter C stocks are also reported. The greenhouse gas flux from *Grassland Remaining Grassland* also includes estimates of non-CO_2 emissions from grassland fires.

Fluxes from *Wetlands Remaining Wetlands* include changes in C stocks and methane (CH_4) and nitrous oxide (N_2O) emissions from managed peatlands, as well as soil C stock changes in coastal wetlands, CH_4 emissions from vegetated coastal wetlands, and N_2O emissions from aquaculture in coastal wetlands. Estimates for *Land Converted to Wetlands* include soil C stock changes and CH_4 emissions from land converted to vegetated coastal wetlands.

Fluxes from *Settlements Remaining Settlements* include changes in C stocks and N_2O emissions from soils, and CO_2 fluxes from urban trees and landfilled yard trimmings and food scraps. The reported greenhouse gas flux from *Land Converted to Settlements* includes changes in C stocks in mineral and organic soils due to land use and management for all land use conversions to settlements, and the C stock changes in aboveground biomass, belowground biomass, dead wood, and litter are also included for the subcategory *Forest Land Converted to Settlements*.

The land use, land-use change, and forestry (LULUCF) sector in 2016 resulted in a net increase in C stocks (i.e., net CO_2 removals) of 754.9 MMT CO_2 Eq. (205.9 MMT C).[2] This represents an offset of approximately 11.6 percent of

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[1] The term "flux" is used to describe the net emissions of greenhouse gases accounting for both the emissions of CO_2 to and the removals of CO_2 from the atmosphere. Removal of CO_2 from the atmosphere is also referred to as "carbon sequestration."

[2] LULUCF Carbon Stock Change is the net C stock change from the following categories: *Forest Land Remaining Forest Land, Land Converted to Forest Land, Cropland Remaining Cropland, Land Converted to Cropland, Grassland Remaining Grassland, Land Converted to Grassland, Wetlands Remaining Wetlands, Land Converted to Wetlands, Settlements Remaining Settlements,* and *Land Converted to Settlements.*

total (i.e., gross) greenhouse gas emissions in 2016. Emissions of CH_4 and N_2O from LULUCF activities in 2016 are 38.1 MMT CO_2 Eq. and represent 0.6 percent of total greenhouse gas emissions.[3]

Total C sequestration in the LULUCF sector decreased by approximately 9.1 percent between 1990 and 2016. This decrease was primarily due to a decrease in the rate of net C accumulation in forests and *Cropland Remaining Cropland*, as well as an increase in emissions from *Land Converted to Settlements*.[4] Net C accumulation in *Settlements Remaining Settlements* increased from 1990 to 2016, while net C accumulation in *Forest Land Remaining Forest Land*, *Land Converted to Forest Land*, *Cropland Remaining Cropland*, and *Grassland Remaining Grassland* slowed over this period. Net C accumulation remained steady from 1990 to 2016 in *Wetlands Remaining Wetlands* and *Land Converted to Wetlands*. Emissions from *Land Converted to Cropland* decreased during this period, while emissions from *Land Converted to Grassland* increased. The C stock change from LULUCF is summarized in Table 6-1.

Table 6-1: Net CO_2 Flux from Land Use, Land-Use Change, and Forestry (MMT CO_2 Eq.)

Land-Use Category	1990	2005	2012	2013	2014	2015	2016
Forest Land Remaining Forest Land	**(697.7)**	**(664.6)**	**(666.9)**	**(670.9)**	**(669.3)**	**(666.2)**	**(670.5)**
Changes in Forest Carbon Stocks[a]	(697.7)	(664.6)	(666.9)	(670.9)	(669.3)	(666.2)	(670.5)
Land Converted to Forest Land	**(92.0)**	**(81.6)**	**(74.9)**	**(74.9)**	**(75.0)**	**(75.0)**	**(75.0)**
Changes in Forest Carbon Stocks[b]	(92.0)	(81.6)	(74.9)	(74.9)	(75.0)	(75.0)	(75.0)
Cropland Remaining Cropland	**(40.9)**	**(26.5)**	**(21.4)**	**(11.4)**	**(12.0)**	**(6.3)**	**(9.9)**
Changes in Mineral and Organic Soil Carbon Stocks	(40.9)	(26.5)	(21.4)	(11.4)	(12.0)	(6.3)	(9.9)
Land Converted to Cropland	**43.3**	**25.9**	**22.7**	**23.3**	**23.2**	**23.2**	**23.8**
Changes in all Ecosystem Carbon Stocks[c]	43.3	25.9	22.7	23.3	23.2	23.2	23.8
Grassland Remaining Grassland	**(4.2)**	**5.5**	**(20.8)**	**(3.7)**	**(7.5)**	**9.6**	**(1.6)**
Changes in Mineral and Organic Soil Carbon Stocks	(4.2)	5.5	(20.8)	(3.7)	(7.5)	9.6	(1.6)
Land Converted to Grassland	**17.9**	**19.2**	**20.4**	**21.9**	**21.5**	**23.3**	**22.0**
Changes in all Ecosystem Carbon Stocks[c]	17.9	19.2	20.4	21.9	21.5	23.3	22.0
Wetlands Remaining Wetlands	**(7.6)**	**(8.9)**	**(7.7)**	**(7.8)**	**(7.8)**	**(7.8)**	**(7.9)**
Changes in Organic Soil Carbon Stocks in Peatlands	1.1	1.1	0.8	0.8	0.8	0.8	0.7
Changes in Mineral and Organic Soil Carbon Stocks in Coastal Wetlands	(8.6)	(10.0)	(8.6)	(8.6)	(8.6)	(8.6)	(8.6)
Land Converted to Wetlands	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**
Changes in Mineral and Organic Soil Carbon Stocks[d]	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Settlements Remaining Settlements	**(86.2)**	**(91.4)**	**(99.2)**	**(99.8)**	**(101.2)**	**(102.2)**	**(103.7)**
Changes in Organic Soil Carbon Stocks	0.1	0.5	1.3	1.3	1.3	1.3	1.3
Changes in Urban Tree Carbon Stocks	(60.4)	(80.5)	(88.4)	(89.5)	(90.6)	(91.7)	(92.9)
Changes in Yard Trimmings and Food Scrap Carbon Stocks in Landfills	(26.0)	(11.4)	(12.2)	(11.6)	(11.9)	(11.8)	(12.1)
Land Converted to Settlements	**37.2**	**68.4**	**68.3**	**68.3**	**68.2**	**68.1**	**68.0**
Changes in all Ecosystem Carbon Stocks[c]	37.2	68.4	68.3	68.3	68.2	68.1	68.0
LULUCF Carbon Stock Change	**(830.2)**	**(754.2)**	**(779.5)**	**(755.0)**	**(760.0)**	**(733.4)**	**(754.9)**

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[3] LULUCF emissions include the CH_4 and N_2O emissions reported for *Peatlands Remaining Peatlands*, Forest Fires, Drained Organic Soils, Grassland Fires, and *Coastal Wetlands Remaining Coastal Wetlands*; CH_4 emissions from *Land Converted to Coastal Wetlands*; and N_2O emissions from Forest Soils and Settlement Soils.

[4] Carbon sequestration estimates are net figures. The C stock in a given pool fluctuates due to both gains and losses. When losses exceed gains, the C stock decreases, and the pool acts as a source. When gains exceed losses, the C stock increases, and the pool acts as a sink; also referred to as net C sequestration or removal.

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

[a] Includes the net changes to carbon stocks stored in all forest ecosystem pools (including drained and undrained organic soils) and harvested wood products.

[b] Includes the net changes to carbon stocks stored in all forest ecosystem pools (excludes drained organic soils which are included in the flux from *Forest Land Remaining Forest Land* because it is not possible to separate the activity data at this time).

[c] Includes changes in mineral and organic soil carbon stocks for all land use conversions to cropland, grassland, and settlements, respectively. Also includes aboveground/belowground biomass, dead wood, and litter carbon stock changes for conversion of forest land to cropland, grassland, and settlements, respectively.

[d] Includes carbon stock changes for land converted to vegetated coastal wetlands.

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Emissions from LULUCF activities are shown in Table 6-2. Forest fires were the largest source of CH_4 emissions from LULUCF in 2016, totaling 18.5 MMT CO_2 Eq. (740 kt of CH_4). *Coastal Wetlands Remaining Coastal Wetlands* resulted in CH_4 emissions of 3.6 MMT CO_2 Eq. (143 kt of CH_4). Grassland fires resulted in CH_4 emissions of 0.3 MMT CO_2 Eq. (11 kt of CH_4). *Peatlands Remaining Peatlands*, *Land Converted to Wetlands,* and *Drained Organic Soils* resulted in CH_4 emissions of less than 0.05 MMT CO_2 Eq. each.

Forest fires were also the largest source of N_2O emissions from LULUCF in 2016, totaling 12.2 MMT CO_2 Eq. (41 kt of N_2O). Nitrous oxide emissions from fertilizer application to settlement soils in 2016 totaled to 2.5 MMT CO_2 Eq. (8 kt of N_2O). This represents an increase of 74.6 percent since 1990. Additionally, the application of synthetic fertilizers to forest soils in 2016 resulted in N_2O emissions of 0.5 MMT CO_2 Eq. (2 kt of N_2O). Nitrous oxide emissions from fertilizer application to forest soils have increased by 455.1 percent since 1990, but still account for a relatively small portion of overall emissions. Grassland fires resulted in N_2O emissions of 0.3 MMT CO_2 Eq. (1 kt of N_2O). *Coastal Wetlands Remaining Coastal Wetlands* and *Drained Organic Soils* resulted in N_2O emissions of 0.1 MMT CO_2 Eq. each (less than 0.5 kt of N_2O), and *Peatlands Remaining Peatlands* resulted in N_2O emissions of less than 0.05 MMT CO_2 Eq.

Emissions and removals from LULUCF are summarized in Figure 6-1 and Table 6-3 by land-use and category, and Table 6-4 and Table 6-5 by gas in MMT CO_2 Eq. and kt, respectively.

Table 6-2: Emissions from Land Use, Land-Use Change, and Forestry by Gas (MMT CO_2 Eq.)

Gas/Land-Use Sub-Category	1990	2005	2012	2013	2014	2015	2016
CH_4	**6.7**	**13.3**	**15.0**	**10.9**	**11.2**	**22.4**	**22.4**
Forest Land Remaining Forest Land: Forest Fires	3.2	9.4	10.8	7.2	7.2	18.5	18.5
Wetlands Remaining Wetlands: Coastal Wetlands Remaining Coastal Wetlands	3.4	3.5	3.5	3.6	3.6	3.6	3.6
Grassland Remaining Grassland: Grassland Fires	0.1	0.3	0.6	0.2	0.4	0.3	0.3
Forest Land Remaining Forest Land: Drained Organic Soils	+	+	+	+	+	+	+
Land Converted to Wetlands: Land Converted to Coastal Wetlands	+	+	+	+	+	+	+
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	+	+	+	+	+	+	+
N_2O	**3.9**	**9.7**	**11.1**	**8.3**	**8.4**	**15.8**	**15.7**
Forest Land Remaining Forest Land: Forest Fires	2.1	6.2	7.1	4.8	4.7	12.2	12.2
Settlements Remaining Settlements: Settlement Soils[a]	1.4	2.5	2.7	2.6	2.6	2.5	2.5
Forest Land Remaining Forest Land: Forest Soils[b]	0.1	0.5	0.5	0.5	0.5	0.5	0.5
Grassland Remaining Grassland: Grassland Fires	0.1	0.3	0.6	0.2	0.4	0.3	0.3
Wetlands Remaining Wetlands: Coastal Wetlands Remaining Coastal Wetlands	0.1	0.2	0.1	0.1	0.1	0.1	0.1
Forest Land Remaining Forest Land: Drained Organic Soils	0.1	0.1	0.1	0.1	0.1	0.1	0.1

Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	+	+	+	+	+	+	+
LULUCF Emissions	**10.6**	**23.0**	**26.1**	**19.2**	**19.6**	**38.2**	**38.1**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Estimates include emissions from N fertilizer additions on both *Settlements Remaining Settlements* and *Land Converted to Settlements*.

[b] Estimates include emissions from N fertilizer additions on both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land.*

Note: Totals may not sum due to independent rounding.

Figure 6-1: 2016 LULUCF Chapter Greenhouse Gas Sources and Sinks (MMT CO_2 Eq.)

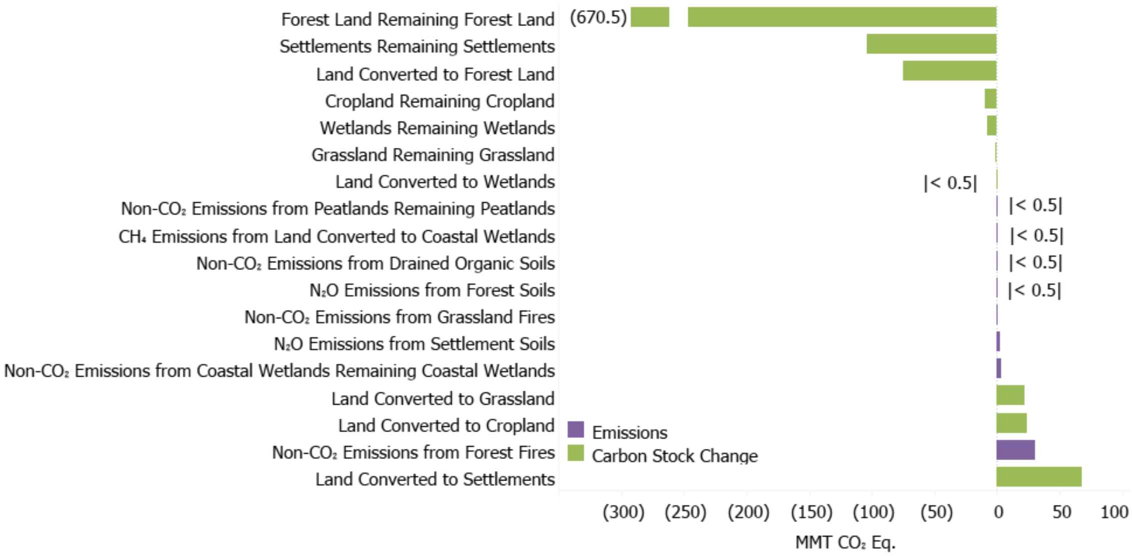

Table 6-3: Emissions and Removals (Net Flux) from Land Use, Land-Use Change, and Forestry (MMT CO_2 Eq.)

Land-Use Category	1990	2005	2012	2013	2014	2015	2016
Forest Land Remaining Forest Land	**(692.2)**	**(648.4)**	**(648.4)**	**(658.4)**	**(656.7)**	**(634.9)**	**(639.2)**
Changes in Forest Carbon Stocks[a]	(697.7)	(664.6)	(666.9)	(670.9)	(669.3)	(666.2)	(670.5)
Non-CO_2 Emissions from Forest Fires	5.3	15.6	17.9	11.9	11.9	30.7	30.7
N_2O Emissions from Forest Soils[b]	0.1	0.5	0.5	0.5	0.5	0.5	0.5
Non-CO_2 Emissions from Drained Organic Soils	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Land Converted to Forest Land	**(92.0)**	**(81.6)**	**(74.9)**	**(74.9)**	**(75.0)**	**(75.0)**	**(75.0)**
Changes in Forest Carbon Stocks[c]	(92.0)	(81.6)	(74.9)	(74.9)	(75.0)	(75.0)	(75.0)
Cropland Remaining Cropland	**(40.9)**	**(26.5)**	**(21.4)**	**(11.4)**	**(12.0)**	**(6.3)**	**(9.9)**
Changes in Mineral and Organic Soil Carbon Stocks	(40.9)	(26.5)	(21.4)	(11.4)	(12.0)	(6.3)	(9.9)
Land Converted to Cropland	**43.3**	**25.9**	**22.7**	**23.3**	**23.2**	**23.2**	**23.8**
Changes in all Ecosystem Carbon Stocks[d]	43.3	25.9	22.7	23.3	23.2	23.2	23.8
Grassland Remaining Grassland	**(4.1)**	**6.2**	**(19.6)**	**(3.3)**	**(6.7)**	**10.2**	**(1.0)**
Changes in Mineral and Organic Soil Carbon Stocks	(4.2)	5.5	(20.8)	(3.7)	(7.5)	9.6	(1.6)
Non-CO_2 Emissions from Grassland Fires	0.2	0.7	1.2	0.4	0.8	0.7	0.6
Land Converted to Grassland	**17.9**	**19.2**	**20.4**	**21.9**	**21.5**	**23.3**	**22.0**
Changes in all Ecosystem Carbon Stocks[d]	17.9	19.2	20.4	21.9	21.5	23.3	22.0
Wetlands Remaining Wetlands	**(4.0)**	**(5.3)**	**(4.1)**	**(4.1)**	**(4.1)**	**(4.1)**	**(4.1)**
Changes in Organic Soil Carbon Stocks in Peatlands	1.1	1.1	0.8	0.8	0.8	0.8	0.7
Changes in Mineral and Organic Soil Carbon Stocks in Coastal Wetlands	(8.6)	(10.0)	(8.6)	(8.6)	(8.6)	(8.6)	(8.6)
CH_4 Emissions from Coastal Wetlands	3.4	3.5	3.5	3.6	3.6	3.6	3.6

Remaining Coastal Wetlands							
N_2O Emissions from Coastal Wetlands Remaining Coastal Wetlands	0.1	0.2	0.1	0.1	0.1	0.1	0.1
Non-CO_2 Emissions from Peatlands Remaining Peatlands	+	+	+	+	+	+	+
Land Converted to Wetlands	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**
Changes in Mineral and Organic Soil Carbon Stocks[e]	(+)	(+)	(+)	(+)	(+)	(+)	(+)
CH_4 Emissions from Land Converted to Coastal Wetlands	+	+	+	+	+	+	+
Settlements Remaining Settlements	**(84.8)**	**(88.9)**	**(96.5)**	**(97.1)**	**(98.6)**	**(99.6)**	**(101.2)**
Changes in Organic Soil Carbon Stocks	0.1	0.5	1.3	1.3	1.3	1.3	1.3
Changes in Urban Tree Carbon Stocks	(60.4)	(80.5)	(88.4)	(89.5)	(90.6)	(91.7)	(92.9)
Changes in Yard Trimming and Food Scrap Carbon Stocks in Landfills	(26.0)	(11.4)	(12.2)	(11.6)	(11.9)	(11.8)	(12.1)
N_2O Emissions from Settlement Soils[f]	1.4	2.5	2.7	2.6	2.6	2.5	2.5
Land Converted to Settlements	**37.2**	**68.4**	**68.3**	**68.3**	**68.2**	**68.1**	**68.0**
Changes in all Ecosystem Carbon Stocks[d]	37.2	68.4	68.3	68.3	68.2	68.1	68.0
LULUCF Emissions[g]	**10.6**	**23.0**	**26.1**	**19.2**	**19.6**	**38.2**	**38.1**
LULUCF Carbon Stock Change[h]	**(830.2)**	**(754.2)**	**(779.5)**	**(755.0)**	**(760.0)**	**(733.4)**	**(754.9)**
LULUCF Sector Net Total[i]	**(819.6)**	**(731.1)**	**(753.5)**	**(735.8)**	**(740.4)**	**(695.2)**	**(716.8)**

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

[a] Includes the net changes to carbon stocks stored in all forest ecosystem pools (including drained and undrained organic soils) and harvested wood products.

[b] Estimates include emissions from N fertilizer additions on both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.

[c] Includes the net changes to carbon stocks stored in all forest ecosystem pools (excludes drained organic soils which are included in the flux from *Forest Land Remaining Forest Land* because it is not possible to separate the activity data at this time).

[d] Includes changes in mineral and organic soil carbon stocks for all land use conversions to cropland, grassland, and settlements, respectively. Also includes aboveground/belowground biomass, dead wood, and litter carbon stock changes for conversion of forest land to cropland, grassland, and settlements, respectively.

[e] Includes carbon stock changes for land converted to vegetated coastal wetlands.

[f] Estimates include emissions from N fertilizer additions on both *Settlements Remaining Settlements* and *Land Converted to Settlements* because it is not possible to separate the activity data at this time.

[g] LULUCF emissions include the CH_4 and N_2O emissions reported for *Peatlands Remaining Peatlands*, Forest Fires, Drained Organic Soils, Grassland Fires, and *Coastal Wetlands Remaining Coastal Wetlands*; CH_4 emissions from *Land Converted to Coastal Wetlands*; and N_2O emissions from Forest Soils and Settlement Soils.

[h] LULUCF Carbon Stock Change includes any C stock gains and losses from all land use and land use conversion categories.

[i] The LULUCF Sector Net Total is the net sum of all CH_4 and N_2O emissions to the atmosphere plus net carbon stock changes.

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Table 6-4: Emissions and Removals from Land Use, Land-Use Change, and Forestry (MMT CO_2 Eq.)

Gas/Land-Use Category	1990	2005	2012	2013	2014	2015	2016
Carbon Stock Change[a]	**(830.2)**	**(754.2)**	**(779.5)**	**(755.0)**	**(760.0)**	**(733.4)**	**(754.9)**
Forest Land Remaining Forest Land	(697.7)	(664.6)	(666.9)	(670.9)	(669.3)	(666.2)	(670.5)
Land Converted to Forest Land	(92.0)	(81.6)	(74.9)	(74.9)	(75.0)	(75.0)	(75.0)
Cropland Remaining Cropland	(40.9)	(26.5)	(21.4)	(11.4)	(12.0)	(6.3)	(9.9)
Land Converted to Cropland	43.3	25.9	22.7	23.3	23.2	23.2	23.8
Grassland Remaining Grassland	(4.2)	5.5	(20.8)	(3.7)	(7.5)	9.6	(1.6)
Land Converted to Grassland	17.9	19.2	20.4	21.9	21.5	23.3	22.0
Wetlands Remaining Wetlands	(7.6)	(8.9)	(7.7)	(7.8)	(7.8)	(7.8)	(7.9)
Land Converted to Wetlands	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Settlements Remaining Settlements	(86.2)	(91.4)	(99.2)	(99.8)	(101.2)	(102.2)	(103.7)
Land Converted to Settlements	37.2	68.4	68.3	68.3	68.2	68.1	68.0
CH_4	**6.7**	**13.3**	**15.0**	**10.9**	**11.2**	**22.4**	**22.4**
Forest Land Remaining Forest Land: Forest Fires	3.2	9.4	10.8	7.2	7.2	18.5	18.5

Wetlands Remaining Wetlands: Coastal Wetlands Remaining Coastal Wetlands	3.4	3.5	3.5	3.6	3.6	3.6	3.6
Grassland Remaining Grassland: Grassland Fires	0.1	0.3	0.6	0.2	0.4	0.3	0.3
Forest Land Remaining Forest Land: Drained Organic Soils	+	+	+	+	+	+	+
Land Converted to Wetlands: Land Converted to Coastal Wetlands	+	+	+	+	+	+	+
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	+	+	+	+	+	+	+
N_2O	**3.9**	**9.7**	**11.1**	**8.3**	**8.4**	**15.8**	**15.7**
Forest Land Remaining Forest Land: Forest Fires	2.1	6.2	7.1	4.8	4.7	12.2	12.2
Settlements Remaining Settlements: Settlement Soils[b]	1.4	2.5	2.7	2.6	2.6	2.5	2.5
Forest Land Remaining Forest Land: Forest Soils[c]	0.1	0.5	0.5	0.5	0.5	0.5	0.5
Grassland Remaining Grassland: Grassland Fires	0.1	0.3	0.6	0.2	0.4	0.3	0.3
Wetlands Remaining Wetlands: Coastal Wetlands Remaining Coastal Wetlands	0.1	0.2	0.1	0.1	0.1	0.1	0.1
Forest Land Remaining Forest Land: Drained Organic Soils	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	+	+	+	+	+	+	+
LULUCF Emissions[d]	**10.6**	**23.0**	**26.1**	**19.2**	**19.6**	**38.2**	**38.1**
LULUCF Carbon Stock Change[a]	**(830.2)**	**(754.2)**	**(779.5)**	**(755.0)**	**(760.0)**	**(733.4)**	**(754.9)**
LULUCF Sector Net Total[e]	**(819.6)**	**(731.1)**	**(753.5)**	**(735.8)**	**(740.4)**	**(695.2)**	**(716.8)**

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

[a] LULUCF Carbon Stock Change is the net C stock change from the following categories: *Forest Land Remaining Forest Land, Land Converted to Forest Land, Cropland Remaining Cropland, Land Converted to Cropland, Grassland Remaining Grassland, Land Converted to Grassland, Wetlands Remaining Wetlands, Land Converted to Wetlands, Settlements Remaining Settlements,* and *Land Converted to Settlements.*

[b] Estimates include emissions from N fertilizer additions on both *Settlements Remaining Settlements* and *Land Converted to Settlements*.

[c] Estimates include emissions from N fertilizer additions on both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.

[d] LULUCF emissions include the CH_4 and N_2O emissions reported for *Peatlands Remaining Peatlands*, Forest Fires, Drained Organic Soils, Grassland Fires, and *Coastal Wetlands Remaining Coastal Wetlands*; CH_4 emissions from *Land Converted to Coastal Wetlands*; and N_2O emissions from Forest Soils and Settlement Soils.

[e] The LULUCF Sector Net Total is the net sum of all CH_4 and N_2O emissions to the atmosphere plus net carbon stock changes.

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Table 6-5: Emissions and Removals from Land Use, Land-Use Change, and Forestry (kt)

Gas/Land-Use Category	1990	2005	2012	2013	2014	2015	2016
Carbon Stock Change[a]	**(830,249)**	**(754,155)**	**(779,547)**	**(755,006)**	**(760,007)**	**(733,352)**	**(754,857)**
Forest Land Remaining Forest Land	(697,690)	(664,566)	(666,869)	(670,857)	(669,250)	(666,188)	(670,456)
Land Converted to Forest Land	(92,018)	(81,576)	(74,883)	(74,948)	(74,978)	(75,003)	(75,024)
Cropland Remaining Cropland	(40,940)	(26,544)	(21,385)	(11,367)	(12,018)	(6,321)	(9,941)
Land Converted to Cropland	43,326	25,878	22,705	23,292	23,192	23,151	23,757
Grassland Remaining Grassland	(4,214)	5,492	(20,814)	(3,745)	(7,549)	9,596	(1,621)
Land Converted to Grassland	17,880	19,155	20,440	21,857	21,465	23,325	22,038
Wetlands Remaining Wetlands	(7,563)	(8,948)	(7,740)	(7,787)	(7,786)	(7,804)	(7,862)
Land Converted to Wetlands	(19)	(15)	(24)	(24)	(24)	(24)	(24)
Settlements Remaining Settlements	(86,241)	(91,413)	(99,230)	(99,773)	(101,222)	(102,174)	(103,697)
Land Converted to Settlements	37,230	68,384	68,254	68,346	68,163	68,089	67,973
CH_4	**269**	**531**	**599**	**437**	**448**	**896**	**895**

Forest Land Remaining Forest Land: Forest Fires	127	377	433	286	289	740	740
Wetlands Remaining Wetlands: Coastal Wetlands Remaining Coastal Wetlands	138	140	142	142	142	143	143
Grassland Remaining Grassland: Grassland Fires	3	13	23	8	16	13	11
Forest Land Remaining Forest Land: Drained Organic Soils	1	1	1	1	1	1	1
Land Converted to Wetlands: Land Converted to Coastal Wetlands	1	+	+	+	+	+	+
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	+	+	+	+	+	+	+
N_2O	**13**	**33**	**37**	**28**	**28**	**53**	**53**
Forest Land Remaining Forest Land: Forest Fires	7	21	24	16	16	41	41
Settlements Remaining Settlements: Settlement Soils[b]	5	8	9	9	9	9	8
Forest Land Remaining Forest Land: Forest Soils[c]	+	2	2	2	2	2	2
Grassland Remaining Grassland: Grassland Fires	+	1	2	1	1	1	1
Wetlands Remaining Wetlands: Coastal Wetlands Remaining Coastal Wetlands	+	1	+	+	+	+	+
Forest Land Remaining Forest Land: Drained Organic Soils	+	+	+	+	+	+	+
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	+	+	+	+	+	+	+

+ Absolute value does not exceed 0.5 kt

[a] LULUCF Carbon Stock Change is the net C stock change from the following categories: *Forest Land Remaining Forest Land, Land Converted to Forest Land, Cropland Remaining Cropland, Land Converted to Cropland, Grassland Remaining Grassland, Land Converted to Grassland, Wetlands Remaining Wetlands, Land Converted to Wetlands, Settlements Remaining Settlements,* and *Land Converted to Settlements*.

[b] Estimates include emissions from N fertilizer additions on both *Settlements Remaining Settlements* and *Land Converted to Settlements.*

[c] Estimates include emissions from N fertilizer additions on both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration

Box 6-1: Methodological Approach for Estimating and Reporting U.S. Emissions and Removals

In following the United Nations Framework Convention on Climate Change (UNFCCC) requirement under Article 4.1 to develop and submit national greenhouse gas emission inventories, the gross emissions total presented in this report for the United States excludes emissions and removals from LULUCF. The LULUCF Sector Net Total presented in this report for the United States includes emissions and removals from LULUCF. All emissions and removals estimates are calculated using internationally-accepted methods provided by the IPCC in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories (2006 IPCC Guidelines)* and the *2013 Supplement to the 2006 Guidelines for National Greenhouse Gas Inventories: Wetlands*. Additionally, the calculated emissions and removals in a given year for the United States are presented in a common manner in line with the UNFCCC reporting guidelines for the reporting of inventories under this international agreement.[5] The use of consistent methods to calculate emissions and removals by all nations providing their inventories to the UNFCCC ensures that these reports are comparable. The presentation of emissions and removals provided in this Inventory do not preclude

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[5] See <http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf>.

alternative examinations, but rather, this Inventory presents emissions and removals in a common format consistent with how countries are to report Inventories under the UNFCCC. The report itself, and this chapter, follows this standardized format, and provides an explanation of the application of methods used to calculate emissions and removals.

Box 6-2: Biennial Inventory Compilation

For the current Inventory (i.e., 1990 through 2016 report), a biennial inventory compilation process has been implemented for the LULUCF and Agriculture chapters. As part of this biennial compilation process, during alternating years, modified approaches will be applied to extend the emissions/removals time series of some LULUCF and Agriculture source and sink categories rather than implementing a full inventory compilation (i.e., updating activity data and running models). In the current Inventory, for each category where these modified approaches for extending the time series have been utilized, the alternative methods have been transparently documented in their respective Methodology sections of the chapter. This biennial compilation schedule has been adopted for the LULUCF and Agriculture chapters in order to conserve and efficiently utilize resources that are needed to implement key improvements. Over the next four to six years, this process will result in more rapid improvements to the LULUCF and Agriculture chapters. The next Inventory report (i.e., 1990 through 2017 report) will include a full compilation of the LULUCF and Agriculture chapters along with a number of key improvements.

6.1 Representation of the U.S. Land Base

A national land-use categorization system that is consistent and complete, both temporally and spatially, is needed in order to assess land use and land-use change status and the associated greenhouse gas fluxes over the Inventory time series. This system should be consistent with IPCC (2006), such that all countries reporting on national greenhouse gas fluxes to the UNFCCC should: (1) describe the methods and definitions used to determine areas of managed and unmanaged lands in the country (Table 6-6), (2) describe and apply a consistent set of definitions for land-use categories over the entire national land base and time series (i.e., such that increases in the land areas within particular land-use categories are balanced by decreases in the land areas of other categories unless the national land base is changing) (Table 6-7), and (3) account for greenhouse gas fluxes on all managed lands. The IPCC (2006, Vol. IV, Chapter 1) considers all anthropogenic greenhouse gas emissions and removals associated with land use and management to occur on managed land, and all emissions and removals on managed land should be reported based on this guidance (see IPCC 2010 for further discussion). Consequently, managed land serves as a proxy for anthropogenic emissions and removals. This proxy is intended to provide a practical framework for conducting an inventory, even though some of the greenhouse gas emissions and removals on managed land are influenced by natural processes that may or may not be interacting with the anthropogenic drivers. Guidelines for factoring out natural emissions and removals may be developed in the future, but currently the managed land proxy is considered the most practical approach for conducting an inventory in this sector (IPCC 2010). This section of the Inventory has been developed in order to comply with this guidance.

Three databases are used to track land management in the United States and are used as the basis to classify U.S. land area into the thirty-six IPCC land-use and land-use change categories (Table 6-7) (IPCC 2006). The primary databases are the U.S. Department of Agriculture (USDA) National Resources Inventory (NRI)[6] and the USDA Forest Service (USFS) Forest Inventory and Analysis (FIA)[7] Database. The Multi-Resolution Land Characteristics Consortium (MRLC) National Land Cover Dataset (NLCD)[8] is also used to identify land uses in regions that were not included in the NRI or FIA. New activity data were not compiled for this Inventory, however, so the 2015

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[6] NRI data are available at <http://www.nrcs.usda.gov/wps/portal/nrcs/site/national/home>.

[7] FIA data are available at <http://www.fia.fs.fed.us/tools-data/default.asp>.

[8] NLCD data are available at <http://www.mrlc.gov/> and MRLC is a consortium of several U.S. government agencies.

estimates are used as a proxy for 2016. The time series will be updated with new activity data in the next Inventory (i.e., 1990 through 2017 Inventory).

The total land area included in the U.S. Inventory is 936 million hectares across the 50 states.[9] Approximately 890 million hectares of this land base is considered managed and 46 million hectares is unmanaged, which has not changed by much over the time series of the Inventory (Table 6-7). In 2015, the United States had a total of 293 million hectares of managed Forest Land (2.4 percent increase since 1990), 163 million hectares of Cropland (6.6 percent decrease since 1990), 325 million hectares of managed Grassland (1.1 percent decrease since 1990), 42 million hectares of managed Wetlands (5.6 percent decrease since 1990), 43 million hectares of Settlements (29 percent increase since 1990), and 23 million hectares of managed Other Land (4 percent increase from 1990) (Table 6-7). Wetlands are not differentiated between managed and unmanaged, and are reported solely as managed.[10] In addition, C stock changes are not currently estimated for the entire land base, which leads to discrepancies between the managed land area data presented here and in the subsequent sections of the Inventory (e.g., *Forest Land Remaining Forest Land, Grassland Remaining Grassland* within interior Alaska).[11] Planned improvements are under development to account for C stock changes and greenhouse gas emissions on all managed land (e.g., Grasslands and Forest Lands in Alaska) and ensure consistency between the total area of managed land in the land-representation description and the remainder of the Inventory.

Dominant land uses vary by region, largely due to climate patterns, soil types, geology, proximity to coastal regions, and historical settlement patterns (Figure 6-2). Forest Land tends to be more common in the eastern states, mountainous regions of the western United States and Alaska. Cropland is concentrated in the mid-continent region of the United States, and Grassland is more common in the western United States and Alaska. Wetlands are fairly ubiquitous throughout the United States, though they are more common in the upper Midwest and eastern portions of the country, as well as coastal regions. Settlements are more concentrated along the coastal margins and in the eastern states.

Table 6-6: Managed and Unmanaged Land Area by Land-Use Categories for All 50 States (Thousands of Hectares)

Land-Use Categories	1990	2005	2012	2013	2014	2015	2016[a]
Managed Lands	**889,924**	**889,914**	**889,897**	**889,896**	**889,896**	**889,896**	**889,896**
Forest Land	286,612	289,064	292,439	292,879	293,180	293,480	293,480
Croplands	174,510	165,599	163,040	163,040	163,040	163,040	163,040
Grasslands	328,520	328,863	325,955	325,601	325,300	324,998	324,998
Settlements	33,370	40,298	43,118	43,118	43,118	43,118	43,118
Wetlands	45,004	43,523	42,558	42,471	42,472	42,474	42,474
Other Land	21,908	22,567	22,787	22,787	22,787	22,787	22,787
Unmanaged Lands	**46,272**	**46,282**	**46,299**	**46,300**	**46,300**	**46,300**	**46,300**
Forest Land	9,515	8,474	8,593	8,601	8,601	8,601	8,601
Croplands	0	0	0	0	0	0	0
Grasslands	25,953	27,043	26,942	26,936	26,936	26,936	26,936
Settlements	0	0	0	0	0	0	0
Wetlands	0	0	0	0	0	0	0
Other Land	10,804	10,765	10,764	10,764	10,764	10,764	10,764
Total Land Areas	**936,196**	**936,196**	**936,196**	**936,196**	**936,196**	**936,196**	**936,196**
Forest Land	296,127	297,538	301,032	301,480	301,780	302,081	302,081
Croplands	174,510	165,599	163,040	163,040	163,040	163,040	163,040
Grasslands	354,473	355,906	352,897	352,537	352,235	351,933	351,933
Settlements	33,370	40,298	43,118	43,118	43,118	43,118	43,118

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[9] The current land representation does not include areas from U.S. Territories, but there are planned improvements to include these regions in future Inventories.

[10] According to the IPCC (2006), wetlands are considered managed if they are created through human activity, such as dam construction, or the water level is artificially altered by human activity. Distinguishing between managed and unmanaged wetlands in the United States is difficult due to limited data availability. Wetlands are not characterized within the NRI with information regarding water table management. As a result, all Wetlands are reported as managed. See the Planned Improvements section of the Inventory for future refinements to the Wetland area estimates.

[11] These "managed area" discrepancies also occur in the Common Reporting Format (CRF) tables submitted to the UNFCCC.

Wetlands	45,004	43,523	42,558	42,471	42,472	42,474	42,474
Other Land	32,713	33,332	33,551	33,551	33,551	33,551	33,551

[a] The land use data for the 2015 estimates are used as a proxy for 2016 because new activity data were not compiled for 2016 in the current Inventory. New activity data will be compiled for the next Inventory (i.e., 1990 through 2017 report) to update the time series.

Table 6-7: Land Use and Land-Use Change for the U.S. Managed Land Base for All 50 States (Thousands of Hectares)

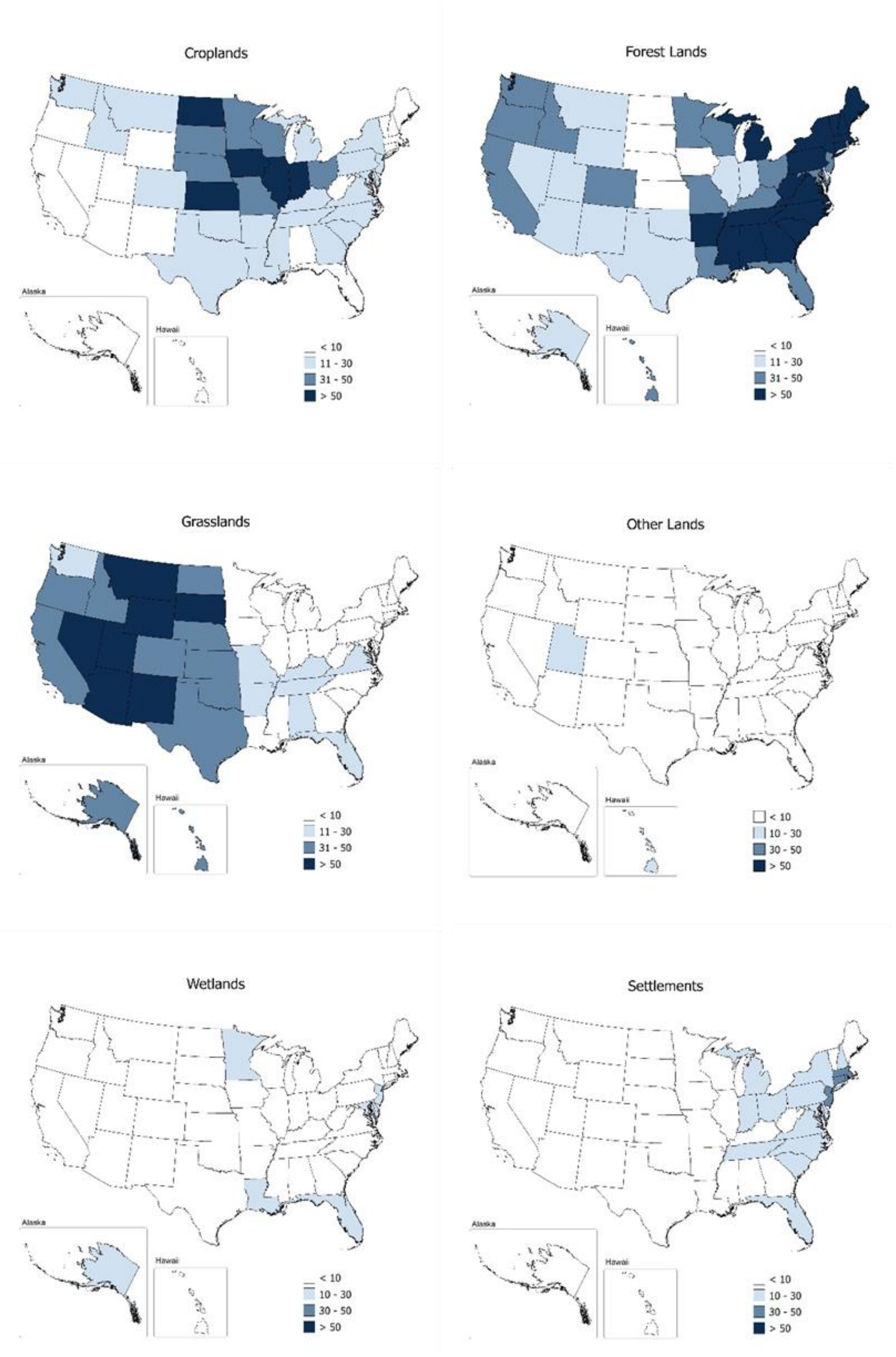
Land-Use & Land-Use Change Categories[a]	1990	2005	2012	2013	2014	2015	2016[b]
Total Forest Land	**286,612**	**289,064**	**292,439**	**292,879**	**293,180**	**293,480**	**293,480**
FF	285,369	288,011	291,458	291,897	292,193	292,493	292,493
CF	213	193	165	165	165	165	165
GF	909	692	676	677	678	678	678
WF	24	27	28	28	32	31	31
SF	13	15	17	17	17	17	17
OF	84	126	95	95	95	95	95
Total Cropland	**174,510**	**165,599**	**163,040**	**163,040**	**163,040**	**163,040**	**163,040**
CC	162,051	150,583	149,722	149,722	149,722	149,722	149,722
FC	286	94	60	60	60	60	60
GC	11,754	14,418	12,827	12,827	12,827	12,827	12,827
WC	150	176	128	128	128	128	128
SC	76	85	91	91	91	91	91
OC	192	243	213	213	213	213	213
Total Grassland	**328,520**	**328,863**	**325,955**	**325,601**	**325,300**	**324,998**	**324,998**
GG	318,373	306,412	304,078	303,724	303,422	303,120	303,120
FG	1,154	4,114	3,961	3,961	3,961	3,961	3,961
CG	8,309	16,825	16,555	16,555	16,555	16,555	16,555
WG	231	429	199	199	199	199	199
SG	53	106	114	114	114	114	114
OG	400	976	1,048	1,048	1,048	1,048	1,048
Total Wetlands	**45,004**	**43,523**	**42,558**	**42,471**	**42,472**	**42,474**	**42,474**
WW	44,249	42,138	41,358	41,270	41,271	41,273	41,273
FW	43	62	55	55	56	56	56
CW	214	378	346	346	346	346	346
GW	452	835	700	700	700	700	700
SW	5	0	1	1	1	1	1
OW	41	110	98	98	98	98	98
Total Settlements	**33,370**	**40,298**	**43,118**	**43,118**	**43,118**	**43,118**	**43,118**
SS	30,469	31,978	35,848	35,848	35,848	35,848	35,848
FS	342	445	418	418	418	418	418
CS	1,247	3,550	2,982	2,982	2,982	2,982	2,982
GS	1,250	4,102	3,653	3,653	3,653	3,653	3,653
WS	6	25	26	26	26	26	26
OS	58	199	190	190	190	190	190
Total Other Land	**21,908**	**22,567**	**22,787**	**22,787**	**22,787**	**22,787**	**22,787**
OO	21,000	20,728	20,809	20,809	20,809	20,809	20,809
FO	41	68	75	75	75	75	75
CO	300	613	679	679	679	679	679
GO	481	982	1,109	1,109	1,109	1,109	1,109
WO	82	168	102	102	102	102	102
SO	5	9	13	13	13	13	13
Grand Total	**889,924**	**889,914**	**889,897**	**889,896**	**889,896**	**889,896**	**889,896**

[a] The abbreviations are "F" for Forest Land, "C" for Cropland, "G" for Grassland, "W" for Wetlands, "S" for Settlements, and "O" for Other Lands. Lands remaining in the same land-use category are identified with the land-use abbreviation given twice (e.g., "FF" is *Forest Land Remaining Forest Land*), and land-use change categories are identified with the previous land use abbreviation followed by the new land-use abbreviation (e.g., "CF" is *Cropland Converted to Forest Land*).

[b] The land use data for the 2015 estimates are used as a proxy for 2016 because new activity data were not compiled for 2016 in the current Inventory. New activity data will be compiled for the next Inventory (i.e., 1990 through 2017 Inventory report) to update the time series.

Notes: All land areas reported in this table are considered managed. A planned improvement is underway to deal with an exception for Wetlands, which based on the definitions for the current U.S. Land Representation Assessment includes both managed and unmanaged lands. U.S. Territories have not been classified into land uses and are not included in the U.S. Land Representation Assessment. See the Planned Improvements section for discussion on plans to include territories in future Inventories. In addition, C stock changes are not currently estimated for the entire land base, which leads to discrepancies between the managed land area data presented here and in the subsequent sections of the Inventory.

Figure 6-2: Percent of Total Land Area for Each State in the General Land-Use Categories for 2015



Note: Updated land representation data have not been compiled in the current Inventory, therefore the state-scale spatial patterns in this map are based on the previous Inventory (i.e., 1990 through 2015 report).

Methodology

IPCC Approaches for Representing Land Areas

IPCC (2006) describes three approaches for representing land areas. Approach 1 provides data on the total area for each individual land-use category, but does not provide detailed information on changes of area between categories and is not spatially explicit other than at the national or regional level. With Approach 1, total net conversions between categories can be detected, but not the individual changes (i.e., additions and/or losses) between the land-use categories that led to those net changes. Approach 2 introduces tracking of individual land-use changes between the categories (e.g., Forest Land to Cropland, Cropland to Forest Land, and Grassland to Cropland), using survey samples or other forms of data, but does not provide location data on all parcels of land. Approach 3 extends Approach 2 by providing location data on all parcels of land, such as maps, along with the land-use history. The three approaches are not presented as hierarchical tiers and are not mutually exclusive.

According to IPCC (2006), the approach or mix of approaches selected by an inventory agency should reflect calculation needs and national circumstances. For this analysis, the NRI, FIA, and the NLCD have been combined to provide a complete representation of land use for managed lands. These data sources are described in more detail later in this section. NRI and FIA are Approach 2 data sources that do not provide spatially-explicit representations of land use and land-use conversions, even though land use and land-use conversions are tracked explicitly at the survey locations. NRI and FIA data are aggregated and used to develop a land-use conversion matrix for a political or ecologically-defined region. NLCD is a spatially-explicit time series of land-cover data that is used to inform the classification of land use, and is therefore Approach 3 data. Lands are treated as remaining in the same category (e.g., *Cropland Remaining Cropland*) if a land-use change has not occurred in the last 20 years. Otherwise, the land is classified in a land-use change category based on the current use and most recent use before conversion to the current use (e.g., *Cropland Converted to Forest Land*).

Definitions of Land Use in the United States

Managed and Unmanaged Land

The United States definition of managed land is similar to the general definition of managed land provided by the IPCC (2006), but with some additional elaboration to reflect national circumstances. Based on the following definitions, most lands in the United States are classified as managed:

- *Managed Land*: Land is considered managed if direct human intervention has influenced its condition. Direct intervention occurs mostly in areas accessible to human activity and includes altering or maintaining the condition of the land to produce commercial or non-commercial products or services; to serve as transportation corridors or locations for buildings, landfills, or other developed areas for commercial or non-commercial purposes; to extract resources or facilitate acquisition of resources; or to provide social functions for personal, community, or societal objectives where these areas are readily accessible to society.[12]
- *Unmanaged Land*: All other land is considered unmanaged. Unmanaged land is largely comprised of areas inaccessible to society due to the remoteness of the locations. Though these lands may be influenced

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[12] Wetlands are an exception to this general definition, because these lands, as specified by IPCC (2006), are only considered managed if they are created through human activity, such as dam construction, or the water level is artificially altered by human activity. Distinguishing between managed and unmanaged wetlands in the United States is difficult due to limited data availability. Wetlands are not characterized within the NRI with information regarding water table management. Therefore, unless wetlands are managed for cropland or grassland, it is not possible to know if they are artificially created or if the water table is managed based on the use of NRI data. As a result, all Wetlands are reported as managed, but emissions are only reported for coastal regions and peatlands due to insufficient activity data to estimate emissions and limited resources to improve the inventory. See the Planned Improvements section of the Inventory for future refinements to the Wetland area estimates.

indirectly by human actions such as atmospheric deposition of chemical species produced in industry or CO_2 fertilization, they are not influenced by a direct human intervention.[13]

In addition, land that is previously managed remains in the managed land base for 20 years before re-classifying the land as unmanaged in order to account for legacy effects of management on C stocks. Unmanaged land is also re-classified as managed over time if anthropogenic activity is introduced into the area based on the definition of managed land.

Land-Use Categories

As with the definition of managed lands, IPCC (2006) provides general non-prescriptive definitions for the six main land-use categories: Forest Land, Cropland, Grassland, Wetlands, Settlements and Other Land. In order to reflect national circumstances, country-specific definitions have been developed, based predominantly on criteria used in the land-use surveys for the United States. Specifically, the definition of Forest Land is based on the FIA definition of forest,[14] while definitions of Cropland, Grassland, and Settlements are based on the NRI.[15] The definitions for Other Land and Wetlands are based on the IPCC (2006) definitions for these categories.

- *Forest Land*: A land-use category that includes areas at least 120 feet (36.6 meters) wide and at least one acre (0.4 hectare) in size with at least 10 percent cover (or equivalent stocking) by live trees including land that formerly had such tree cover and that will be naturally or artificially regenerated. Trees are woody plants having a more or less erect perennial stem(s) capable of achieving at least 3 inches (7.6 cm) in diameter at breast height, or 5 inches (12.7 cm) diameter at root collar, and a height of 16.4 feet (5 m) at maturity in situ. Forest Land includes all areas recently having such conditions and currently regenerating or capable of attaining such condition in the near future. Forest Land also includes transition zones, such as areas between forest and non-forest lands that have at least 10 percent cover (or equivalent stocking) with live trees and forest areas adjacent to urban and built-up lands. Unimproved roads and trails, streams, and clearings in forest areas are classified as forest if they are less than 120 feet (36.6 m) wide or an acre (0.4 ha) in size. However, land is not classified as Forest Land if completely surrounded by urban or developed lands, even if the criteria are consistent with the tree area and cover requirements for Forest Land. These areas are classified as Settlements. In addition, Forest Land does not include land that is predominantly under an agricultural land use (Oswalt et al. 2014).
- *Cropland*: A land-use category that includes areas used for the production of adapted crops for harvest; this category includes both cultivated and non-cultivated lands. Cultivated crops include row crops or close-grown crops and also hay or pasture in rotation with cultivated crops. Non-cultivated cropland includes continuous hay, perennial crops (e.g., orchards) and horticultural cropland. Cropland also includes land with agroforestry, such as alley cropping and windbreaks,[16] if the dominant use is crop production, assuming the stand or woodlot does not meet the criteria for Forest Land. Lands in temporary fallow or enrolled in conservation reserve programs (i.e., set-asides[17]) are also classified as Cropland, as long as these areas do not meet the Forest Land criteria. Roads through Cropland, including interstate highways, state highways, other paved roads, gravel roads, dirt roads, and railroads are excluded from Cropland area estimates and are, instead, classified as Settlements.
- *Grassland*: A land-use category on which the plant cover is composed principally of grasses, grass-like plants (i.e., sedges and rushes), forbs, or shrubs suitable for grazing and browsing, and includes both pastures and native rangelands. This includes areas where practices such as clearing, burning, chaining, and/or chemicals are applied to maintain the grass vegetation. Land is also categorized as Grassland with

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[13] There are some areas, such as Forest Land and Grassland in Alaska that are classified as unmanaged land due to the remoteness of their location.

[14] See <http://www.fia.fs.fed.us/library/field-guides-methods-proc/docs/2015/Core-FIA-FG-7.pdf>, page 22.

[15] See <http://www.nrcs.usda.gov/wps/portal/nrcs/site/national/home>.

[16] Currently, there is no data source to account for biomass C stock change associated with woody plant growth and losses in alley cropping systems and windbreaks in cropping systems, although these areas are included in the Cropland land base.

[17] A set-aside is cropland that has been taken out of active cropping and converted to some type of vegetative cover, including, for example, native grasses or trees.

three or fewer years of continuous hay production.[18] Savannas, deserts, and tundra are considered Grassland.[19] Drained wetlands are considered Grassland if the dominant vegetation meets the plant cover criteria for Grassland. Woody plant communities of low forbs and shrubs, such as mesquite, chaparral, mountain shrub, and pinyon-juniper, are also classified as Grassland if they do not meet the criteria for Forest Land. Grassland includes land managed with agroforestry practices, such as silvopasture and windbreaks, if the land is principally grasses, grass-like plants, forbs, and shrubs suitable for grazing and browsing, and assuming the stand or woodlot does not meet the criteria for Forest Land. Roads through Grassland, including interstate highways, state highways, other paved roads, gravel roads, dirt roads, and railroads are excluded from Grassland and are, instead, classified as Settlements.

- *Wetlands*: A land-use category that includes land covered or saturated by water for all or part of the year, in addition to the areas of lakes, reservoirs, and rivers. Managed Wetlands are those where the water level is artificially changed, or were created by human activity. Certain areas that fall under the managed Wetlands definition are included in other land uses based on the IPCC guidance, including Cropland (drained wetlands for crop production and also systems that are flooded for most or just part of the year, such as rice cultivation and cranberry production), Grassland (drained wetlands dominated by grass cover), Forest Land (including drained or un-drained forested wetlands), and Settlements (drained wetlands in developed areas).
- *Settlements*: A land-use category representing developed areas consisting of units of 0.25 acres (0.1 ha) or more that includes residential, industrial, commercial, and institutional land; construction sites; public administrative sites; railroad yards; cemeteries; airports; golf courses; sanitary landfills; sewage treatment plants; water control structures and spillways; parks within urban and built-up areas; and highways, railroads, and other transportation facilities. Also included are tracts of less than 10 acres (4.05 ha) that may meet the definitions for Forest Land, Cropland, Grassland, or Other Land but are completely surrounded by urban or built-up land, and so are included in the Settlements category. Rural transportation corridors located within other land uses (e.g., Forest Land, Cropland, and Grassland) are also included in Settlements.
- *Other Land*: A land-use category that includes bare soil, rock, ice, and all land areas that do not fall into any of the other five land-use categories. Following the guidance provided by the IPCC (2006), C stock changes and non-CO_2 emissions are not estimated for Other Lands because these areas are largely devoid of biomass, litter and soil C pools. However, C stock changes and non-CO_2 emissions are estimated for *Land Converted to Other Land* during the first 20 years following conversion to account for legacy effects.

Land-Use Data Sources: Description and Application to U.S. Land Area Classification

U.S. Land-Use Data Sources

The three main sources for land-use data in the United States are the NRI, FIA, and the NLCD (Table 6-8). These data sources are combined to account for land use in all 50 states. FIA and NRI data are used when available for an area because the surveys contain additional information on management, site conditions, crop types, biometric measurements, and other data that is needed to estimate C stock changes, N_2O, and CH_4 emissions on those lands. If NRI and FIA data are not available for an area, however, then the NLCD product is used to represent the land use.

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[18] Areas with four or more years of continuous hay production are Cropland because the land is typically more intensively managed with cultivation, greater amounts of inputs, and other practices.

[19] *2006 IPCC Guidelines* do not include provisions to separate desert and tundra as land-use categories.

Table 6-8: Data Sources Used to Determine Land Use and Land Area for the Conterminous United States, Hawaii, and Alaska

	NRI	FIA	NLCD
Forest Land			
Conterminous United States			
Non-Federal		•	
Federal		•	
Hawaii			
Non-Federal	•		
Federal			•
Alaska			
Non-Federal		•	•
Federal		•	•
Croplands, Grasslands, Other Lands, Settlements, and Wetlands			
Conterminous United States			
Non-Federal	•		
Federal			•
Hawaii			
Non-Federal	•		
Federal			•
Alaska			
Non-Federal		•	•
Federal		•	•

National Resources Inventory

For the Inventory, the NRI is the official source of data for land use and land use change on non-federal lands in the conterminous United States and Hawaii (except Forest Land), and is also used to determine the total land base for the conterminous United States and Hawaii. The NRI is a statistically-based survey conducted by the USDA Natural Resources Conservation Service and is designed to assess soil, water, and related environmental resources on non-federal lands. The NRI has a stratified multi-stage sampling design, where primary sample units are stratified on the basis of county and township boundaries defined by the United States Public Land Survey (Nusser and Goebel 1997). Within a primary sample unit (typically a 160 acre [64.75 ha] square quarter-section), three sample points are selected according to a restricted randomization procedure. Each point in the survey is assigned an area weight (expansion factor) based on other known areas and land-use information (Nusser and Goebel 1997). The NRI survey utilizes data derived from remote sensing imagery and site visits in order to provide detailed information on land use and management, particularly for Croplands and Grasslands (i.e., agricultural lands), and is used as the basis to account for C stock changes in agricultural lands (except federal Grasslands). The NRI survey was conducted every 5 years between 1982 and 1997, but shifted to annualized data collection in 1998. The land use between five-year periods from 1982 and 1997 are assumed to be the same for a five-year time period if the land use is the same at the beginning and end of the five-year period (Note: most of the data has the same land use at the beginning and end of the five-year periods). If the land use had changed during a five-year period, then the change is assigned at random to one of the five years. For crop histories, years with missing data are estimated based on the sequence of crops grown during years preceding and succeeding a missing year in the NRI history. This gap-filling approach allows for development of a full time series of land-use data for non-federal lands in the conterminous United States and Hawaii. This Inventory incorporates data through 2012 from the NRI. The land use patterns are assumed to remain the same from 2012 through 2016 for this Inventory, but the time series will be updated when new data are released.

Forest Inventory and Analysis

The FIA program, conducted by the USFS, is another statistically-based survey for the conterminous United States in addition to the southeast and south central coastal Alaska, and the official source of data on Forest Land area and management data for the Inventory. FIA engages in a hierarchical system of sampling, with sampling categorized as Phases 1 through 3, in which sample points for phases are subsets of the previous phase. Phase 1 refers to collection of remotely-sensed data (either aerial photographs or satellite imagery) primarily to classify land into forest or non-forest and to identify landscape patterns like fragmentation and urbanization. Phase 2 is the collection of field data on a network of ground plots that enable classification and summarization of area, tree, and other attributes associated with forest-land uses. Phase 3 plots are a subset of Phase 2 plots where data on indicators of forest health are measured. Data from all three phases are also used to estimate C stock changes for Forest Land. Historically, FIA inventory surveys have been conducted periodically, with all plots in a state being measured at a frequency of every five to 14 years. A new national plot design and annual sampling design was introduced by the FIA program in 1998 and is now used in all states. Annualized sampling means that a portion of plots throughout each state is sampled each year, with the goal of measuring all plots once every five to seven years in the eastern United States and once every ten years in the western United States. See Annex 3.13 to see the specific survey data available by state. The most recent year of available data varies state by state (range of most recent data is from 2012 through 2015; see Table A-236).

National Land Cover Dataset

While the NRI survey sample covers the conterminous United States and Hawaii, land use data are only collected on non-federal lands. In addition, FIA only records data for forest land across the land base in the conterminous United States and a portion of Alaska.[20] Consequently, gaps exist in the land representation when the datasets are combined, such as federal grassland operated by Bureau of Land Management (BLM), USDA, and National Park Service, as well as Alaska.[21] The NLCD is used as a supplementary database to account for land use on federal lands in the conterminous United States and Hawaii, in addition to federal and non-federal lands in Alaska.

NLCD products provide land-cover for 1992, 2001, 2006, and 2011 in the conterminous United States (Homer et al. 2007), and also for Alaska in 2001 and 2011 and Hawaii in 2001. For the conterminous United States, the NLCD data have been further processed to derive Land Cover Change Products for 2001, 2006, and 2011 (Fry et al. 2011; Homer et al. 2007; Homer et al. 2015). A Land Cover Change Product is also available for Alaska from 2001 to 2011. A NLCD change product is not available for Hawaii because data are only available for one year, i.e., 2001. The NLCD products are based primarily on Landsat Thematic Mapper imagery at a 30-meter resolution, and contain 21 categories of land-cover information, which have been aggregated into the 36 IPCC land-use categories for the conterminous United States and Alaska, and into the six IPCC land-use categories for Hawaii.

The aggregated maps of IPCC land-use categories were used in combination with the NRI database to represent land use and land-use change for federal lands, as well as federal and non-federal lands in Alaska. Specifically, NRI survey locations designated as federal lands were assigned a land use/land use change category based on the NLCD maps that had been aggregated into the IPCC categories. This analysis addressed shifts in land ownership across years between federal or non-federal classes as represented in the NRI survey (i.e., the ownership is classified for each survey location in the NRI). The sources of these additional data are discussed in subsequent sections of the report.

Managed Land Designation

Lands are designated as managed in the United States based on the definition provided earlier in this section. In order to apply the definition in an analysis of managed land, the following criteria are used:

- All Croplands and Settlements are designated as managed so only Grassland, Forest Land or Other Lands may be designated as unmanaged land;
- All Forest Lands with active fire protection are considered managed;
- All Grassland is considered managed at a county scale if there are livestock in the county;[22]
- Other areas are considered managed if accessible based on the proximity to roads and other transportation corridors, and/or infrastructure;

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[20] FIA does collect some data on non-forest land use, but these are held in regional databases versus the national database. The status of these data is being investigated.

[21] The NRI survey program does not include U.S. Territories with the exception of non-federal lands in Puerto Rico. The FIA program recently began implementing surveys of forest land in U.S. Territories and those data will be used in the years ahead. Furthermore, NLCD does not include coverage for all U.S. Territories.

[22] Assuming all Grasslands are grazed in a county with even very small livestock populations is a conservative assumption about human impacts on Grasslands. Currently, detailed information on grazing at sub-county scales is not available for the United States to make a finer delineation of managed land.

- Protected lands maintained for recreational and conservation purposes are considered managed (i.e., managed by public and private organizations);
- Lands with active and/or past resource extraction are considered managed; and
- Lands that were previously managed but subsequently classified as unmanaged, remain in the managed land base for 20 years following the conversion to account for legacy effects of management on C stocks.

The analysis of managed lands is conducted using a geographic information system. Lands that are used for crop production or settlements are determined from the NLCD (Fry et al. 2011; Homer et al. 2007; Homer et al. 2015). Forest Lands with active fire management are determined from maps of federal and state management plans from the National Atlas (U.S. Department of Interior 2005) and Alaska Interagency Fire Management Council (1998). It is noteworthy that all forest lands in the conterminous United States have active fire protection, and are therefore designated as managed regardless of accessibility or other criteria. The designation of grasslands as managed is based on livestock population data at the county scale from the USDA National Agricultural Statistics Service (U.S. Department of Agriculture 2015). Accessibility is evaluated based on a 10-km buffer surrounding road and train transportation networks using the ESRI Data and Maps product (ESRI 2008), and a 10-km buffer surrounding settlements using NLCD. Lands maintained for recreational purposes are determined from analysis of the Protected Areas Database (U.S. Geological Survey 2012). The Protected Areas Database includes lands protected from conversion of natural habitats to anthropogenic uses and describes the protection status of these lands. Lands are considered managed that are protected from development if the regulations allow for extractive or recreational uses or suppression of natural disturbance. Lands that are protected from development and not accessible to human intervention, including no suppression of disturbances or extraction of resources, are not included in the managed land base. Multiple data sources are used to determine lands with active resource extraction: Alaska Oil and Gas Information System (Alaska Oil and Gas Conservation Commission 2009), Alaska Resource Data File (U.S. Geological Survey 2012), Active Mines and Mineral Processing Plants (U.S. Geological Survey 2005), and *Coal Production and Preparation Report* (U.S. Energy Information Administration 2011). A buffer of 3,300 and 4,000 meters is established around petroleum extraction and mine locations, respectively, to account for the footprint of operation and impacts of activities on the surrounding landscape. The buffer size is based on visual analysis of approximately 130 petroleum extraction sites and 223 mines. The resulting managed land area is overlaid on the NLCD to estimate the area of managed land by land use for both federal and non-federal lands. The remaining land represents the unmanaged land base. The resulting spatial product is used to identify NRI survey locations that are considered managed and unmanaged for the conterminous United States and Hawaii,[23] in addition to determining which areas in the NLCD for Alaska are included in the managed land base.

Approach for Combining Data Sources

The managed land base in the United States has been classified into the 36 IPCC land-use/land-use conversion categories using definitions developed to meet national circumstances, while adhering to IPCC (2006).[24] In practice, the land was initially classified into a variety of land-use subcategories within the NRI, FIA, and NLCD datasets, and then aggregated into the 36 broad land use and land-use change categories identified in IPCC (2006). All three datasets provide information on forest land areas in the conterminous United States, but the area data from FIA serve as the official dataset for Forest Land.

Therefore, another step in the analysis is to address the inconsistencies in the representation of the Forest Land among the three databases. NRI and FIA have different criteria for classifying Forest Land in addition to different sampling designs, leading to discrepancies in the resulting estimates of Forest Land area on non-federal land in the conterminous United States. Similarly, there are discrepancies between the NLCD and FIA data for defining and classifying Forest Land on federal lands. Any change in Forest Land Area in the NRI and NLCD also requires a corresponding change in other land use areas because of the dependence between the Forest Land area and the amount of land designated as other land uses, such as the amount of Grassland, Cropland, and Wetlands (i.e., areas for the individual land uses must sum to the total managed land area of the country).

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[23] The exception is cropland and settlement areas in the NRI, which are classified as managed, regardless of the managed land base derived from the spatial analysis described in this section.

[24] Definitions are provided in the previous section.

FIA is the main database for forest statistics, and consequently, the NRI and NLCD are adjusted to achieve consistency with FIA estimates of Forest Land in the conterminous United States. Adjustments are made in the *Forest Land Remaining Forest Land*, *Land Converted to Forest Land*, and Forest Land converted to other uses (i.e., Grassland, Cropland and Wetlands). All adjustments are made at the state scale to address the differences in Forest Land definitions and the resulting discrepancies in areas among the land use and land-use change categories. There are three steps in this process. The first step involves adjustments for *Land Converted to Forest Land* (Grassland, Cropland, and Wetlands), followed by adjustments in Forest Land converted to another land use (i.e., Grassland, Cropland, and Wetlands), and finally adjustments to *Forest Land Remaining Forest Land*.

In the first step, *Land Converted to Forest Land* in the NRI and NLCD are adjusted to match the state-level estimates in the FIA data for non-federal and federal *Land Converted to Forest Land*, respectively. FIA data do not provide specific land-use categories that are converted to Forest Land, but rather a sum of all *Land Converted to Forest Land*. The NRI and NLCD provide information on specific land use conversions, such as *Grassland Converted to Forest Land*. Therefore, adjustments at the state level to NRI and NLCD are made proportional to the amount of specific land use conversions into Forest Land for the state, prior to any adjustments. For example, if 50 percent of land use change to Forest Land is associated with *Grassland Converted to Forest Land* in a state according to NRI or NLCD, then half of the discrepancy with FIA data in the area of *Land Converted to Forest Land* is addressed by increasing or decreasing the area in *Grassland Converted to Forest Land*. Moreover, any increase or decrease in *Grassland Converted to Forest Land* in NRI or NLCD is addressed by a corresponding change in the area of *Grassland Remaining Grassland*, so that the total amount of managed area is not changed within an individual state.

In the second step, state-level areas are adjusted in the NRI and NLCD to address discrepancies with FIA data for Forest Land converted to other uses. Similar to *Land Converted to Forest Land*, FIA does not provide information on the specific land-use changes, and so areas associated with Forest Land conversion to other land uses in NRI and NLCD are adjusted proportional to the amount of area in each conversion class in these datasets.

In the final step, the area of *Forest Land Remaining Forest Land* in a given state according to the NRI and NLCD is adjusted to match the FIA estimates for non-federal and federal land, respectively. It is assumed that the majority of the discrepancy in *Forest Land Remaining Forest Land* is associated with an under- or over-prediction of *Grassland Remaining Grassland* and *Wetland Remaining Wetland* in the NRI and NLCD. This step also assumes that there are no changes in the land use conversion categories. Therefore, corresponding increases or decreases are made in the area estimates of *Grasslands Remaining Grasslands* and *Wetlands Remaining Wetlands* from the NRI and NLCD. This adjustment balances the change in *Forest Land Remaining Forest Land* area, which ensures no change in the overall amount of managed land within an individual state. The adjustments are based on the proportion of land within each of these land-use categories at the state level according to NRI and NLCD (i.e., a higher proportion of Grassland led to a larger adjustment in Grassland area).

The modified NRI data are then aggregated to provide the land-use and land-use change data for non-federal lands in the conterminous United States, and the modified NLCD data are aggregated to provide the land use and land-use change data for federal lands. Data for all land uses in Hawaii are based on NRI for non-federal lands and on NLCD for federal lands. Land use data in Alaska are based on the NLCD data after adjusting this dataset to be consistent with forest land areas in the FIA (Table 6-8). The result is land use and land-use change data for the conterminous United States, Hawaii, and Alaska.

A summary of the details on the approach used to combine data sources for each land use are described below.

- *Forest Land*: Land representation for both non-federal and federal forest lands in the conterminous United States and coastal Alaska are based on the FIA. FIA is used as the basis for both Forest Land area data as well as to estimate C stocks and fluxes on Forest Land in the conterminous United States. FIA does have survey plots in coastal Alaska that are used to determine the C stock changes, and the associated area data for this region are harmonized with the NLCD using the methods described above. Forest land in interior Alaska is currently being surveyed by the FIA program, but there is insufficient data at this time so forest land in this region is based on the 2001 and 2011 NLCD. NRI is used in the current report to provide Forest Land areas on non-federal lands in Hawaii, and NLCD is used for federal lands. FIA data is being collected in Hawaii and U.S. Territories, however there is insufficient data to make population estimates for this Inventory.

- *Cropland*: Cropland is classified using the NRI, which covers all non-federal lands within 49 states (excluding Alaska), including state and local government-owned land as well as tribal lands. NRI is used as the basis for both Cropland area data as well as to estimate soil C stocks and fluxes on Cropland. NLCD is used to determine Cropland area and soil C stock changes on federal lands in the conterminous United States and Hawaii. NLCD is also used to determine croplands in Alaska, but C stock changes are not estimated for this region in the current Inventory.
- *Grassland*: Grassland on non-federal lands is classified using the NRI within 49 states (excluding Alaska), including state and local government-owned land as well as tribal lands. NRI is used as the basis for both Grassland area data as well as to estimate soil C stocks and fluxes on Grassland. Grassland area and soil C stock changes are determined using the classification provided in the NLCD for federal land within the conterminous United States. NLCD is also used to estimate the areas of federal and non-federal grasslands in Alaska, and the federal lands in Hawaii, but the current Inventory does not include C stock changes in these areas.
- *Wetlands*: NRI captures wetlands on non-federal lands within 49 states (excluding Alaska), while the land representation data for federal wetlands and wetlands in Alaska are based on the NLCD.[25]
- *Settlements*: NRI captures non-federal settlement area in 49 states (excluding Alaska). If areas of Forest Land or Grassland under 10 acres (4.05 ha) are contained within settlements or urban areas, they are classified as Settlements (urban) in the NRI database. If these parcels exceed the 10 acre (4.05 ha) threshold and are Grassland, they will be classified as such by NRI. Regardless of size, a forested area is classified as non-forest by FIA if it is located within an urban area. Land representation for settlements on federal lands and Alaska is based on the NLCD.
- *Other Land*: Any land that is not classified into one of the previous five land-use categories, is categorized as Other Land using the NRI for non-federal areas in the conterminous United States and Hawaii and using the NLCD for the federal lands in all regions of the United States and for non-federal lands in Alaska.

Some lands can be classified into one or more categories due to multiple uses that meet the criteria of more than one definition. However, a ranking has been developed for assignment priority in these cases. The ranking process is from highest to lowest priority based on the following order:

Settlements > Cropland > Forest Land > Grassland > Wetlands > Other Land

Settlements are given the highest assignment priority because they are extremely heterogeneous with a mosaic of patches that include buildings, infrastructure, and travel corridors, but also open grass areas, forest patches, riparian areas, and gardens. The latter examples could be classified as Grassland, Forest Land, Wetlands, and Cropland, respectively, but when located in close proximity to settlement areas, they tend to be managed in a unique manner compared to non-settlement areas. Consequently, these areas are assigned to the Settlements land-use category. Cropland is given the second assignment priority, because cropping practices tend to dominate management activities on areas used to produce food, forage, or fiber. The consequence of this ranking is that crops in rotation with pasture are classified as Cropland, and land with woody plant cover that is used to produce crops (e.g., orchards) is classified as Cropland, even though these areas may meet the definitions of Grassland or Forest Land, respectively. Similarly, Wetlands are considered Croplands if they are used for crop production, such as rice or cranberries. Forest Land occurs next in the priority assignment because traditional forestry practices tend to be the focus of the management activity in areas with woody plant cover that are not croplands (e.g., orchards) or settlements (e.g., housing subdivisions with significant tree cover). Grassland occurs next in the ranking, while Wetlands and then Other Land complete the list.

The assignment priority does not reflect the level of importance for reporting greenhouse gas emissions and removals on managed land, but is intended to classify all areas into a discrete land use category. Currently, the IPCC does not make provisions in the guidelines for assigning land to multiple uses. For example, a wetland is classified as Forest Land if the area has sufficient tree cover to meet the stocking and stand size requirements. Similarly, wetlands are classified as Cropland if they are used for crop production, such as rice or cranberries, or as Grassland

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[25] This analysis does not distinguish between managed and unmanaged wetlands, which is a planned improvement for the Inventory.

if they are composed principally of grasses, grass-like plants (i.e., sedges and rushes), forbs, or shrubs suitable for grazing and browsing. Regardless of the classification, emissions from these areas are included in the Inventory if the land is considered managed, and therefore impacted by anthropogenic activity in accordance with the guidance provided by the IPCC (2006).

QA/QC and Verification

The land base derived from the NRI, FIA, and NLCD was compared to the Topologically Integrated Geographic Encoding and Referencing (TIGER) survey (U.S. Census Bureau 2010). The U.S. Census Bureau gathers data on the U.S. population and economy, and has a database of land areas for the country. The area estimates of land-use categories, based on NRI, FIA, and NLCD, are derived from remote sensing data instead of the land survey approach used by the U.S. Census Survey. The U.S. Census Survey does not provide a time series of land-use change data or land management information, which is needed for reporting greenhouse gas emissions from land use and land use change. Regardless, the U.S. Census Survey does provide sufficient information to provide a check on the Inventory data. The U.S. Census Survey has about 46 million more hectares of land in the U.S. land base compared to the total area estimate of 936 million hectares derived from the combined NRI, FIA, and NLCD data. Much of this difference is associated with open waters in coastal regions and the Great Lakes, which is included in the TIGER Survey of the U.S. Census, but not included in the land representation using the NRI, FIA and NLCD. There is only a 0.4 percent difference when open water in coastal regions is removed from the TIGER data.

Recalculations Discussion

The land representation data in the current Inventory were not recalculated from the previous Inventory.

Planned Improvements

New land representation data were not compiled for the current Inventory. In addition, land use and land use change area estimates for 2016 were assumed to be the same as the data for 2015 in the previous (i.e., 1990 through 2015) Inventory. Therefore, a key improvement in a future Inventory will be to update the time series for land representation with the latest NRI, FIA, and NLCD data sets.

Another key planned improvement for the Inventory is to fully incorporate area data by land-use type for U.S. Territories. Fortunately, most of the managed land in the United States is included in the current land-use statistics, but a complete accounting is a key goal for the near future. Preliminary land-use area data for U.S. Territories by land-use category are provided in Box 6-3.

Box 6-3: Preliminary Estimates of Land Use in U.S. Territories

Several programs have developed land cover maps for U.S. Territories using remote sensing imagery, including the Gap Analysis Program, Caribbean Land Cover project, National Land Cover Dataset, USFS Pacific Islands Imagery Project, and the National Oceanic and Atmospheric Administration (NOAA) Coastal Change Analysis Program (C-CAP). Land-cover data can be used to inform a land-use classification if there is a time series to evaluate the dominate practices. For example, land that is principally used for timber production with tree cover over most of the time series is classified as forest land even if there are a few years of grass dominance following timber harvest. These products were reviewed and evaluated for use in the national Inventory as a step towards implementing a planned improvement to include U.S. Territories in the land representation for the Inventory. Recommendations are to use the NOAA C-CAP Regional Land Cover Database for the smaller island Territories (U.S. Virgin Islands, Guam, Northern Marianas Islands, and American Samoa) because this program is ongoing and therefore will be continually updated. The C-CAP product does not cover the entire territory of Puerto Rico so the NLCD was used for this area. The final selection of a land-cover product for these territories is still under discussion. Results are presented below (in hectares). The total land area of all U.S. Territories is 1.05 million hectares, representing 0.1 percent of the total land base for the United States.

Table 6-9: Total Land Area (Hectares) by Land-Use Category for U.S. Territories

	Puerto Rico	U.S. Virgin Islands	Guam	Northern Marianas Islands	American Samoa	Total
Cropland	19,712	138	236	289	389	20,764
Forest Land	404,004	13,107	24,650	25,761	15,440	482,962
Grasslands	299,714	12,148	15,449	13,636	1,830	342,777
Other Land	5,502	1,006	1,141	5,186	298	13,133
Settlements	130,330	7,650	11,146	3,637	1,734	154,496
Wetlands	24,525	4,748	1,633	260	87	31,252
Total	**883,788**	**38,796**	**54,255**	**48,769**	**19,777**	**1,045,385**

Implementation is underway to apply methods in the *2013 Supplement to the 2006 Guidelines for National Greenhouse Gas Inventories: Wetlands* as part of the U.S. Greenhouse Gas Inventory. Specifically, greenhouse gas emissions from coastal wetlands have been developed for the Inventory using the NOAA C-CAP land cover product. The NOAA C-CAP product is not used directly in the land representation analysis, however, so a planned improvement for the next (i.e., 1990 through 2017) Inventory report is to reconcile the coastal wetlands data from the C-CAP product with the wetlands area data provided in the NRI. Further implementation of the new guidance will have implications for the classification of managed and unmanaged wetlands in the Inventory report, and more detailed wetlands datasets will likely also be evaluated and integrated into the analysis.

NOAA C-CAP data for Hawaii were recently released for 2011, and will be used to analyze land use change for this state in the near future. There are also other databases that may need to be reconciled with the NRI and NLCD datasets, particularly for Settlements. Urban area estimates, used to produce C stock and flux estimates from urban trees, are currently based on population data (1990, 2000, and 2010 U.S. Census data). Using the population statistics, “urban clusters” are defined as areas with more than 500 people per square mile. The USFS is currently moving ahead with an Urban Forest Inventory program so that urban forest area estimates will be consistent with FIA forest area estimates outside of urban areas, which would be expected to reduce omissions and overlap of forest area estimates along urban boundary areas.

6.2 Forest Land Remaining Forest Land (CRF Category 4A1)

Changes in Forest Carbon Stocks (CRF Category 4A1)

Delineation of Carbon Pools

For estimating carbon (C) stocks or stock change (flux), C in forest ecosystems can be divided into the following five storage pools (IPCC 2006):

- Aboveground biomass, which includes all living biomass above the soil including stem, stump, branches, bark, seeds, and foliage. This category includes live understory.
- Belowground biomass, which includes all living biomass of coarse living roots greater than 2 millimeters (mm) diameter.
- Dead wood, which includes all non-living woody biomass either standing, lying on the ground (but not including litter), or in the soil.

- Litter, which includes the litter, fumic, and humic layers, and all non-living biomass with a diameter less than 7.5 centimeters (cm) at transect intersection, lying on the ground.
- Soil organic C (SOC), including all organic material in soil to a depth of 1 meter but excluding the coarse roots of the belowground pools.

In addition, there are two harvested wood pools included when estimating C flux:

- Harvested wood products (HWP) in use.
- HWP in solid waste disposal sites (SWDS).

Forest Carbon Cycle

Carbon is continuously cycled among the previously defined C storage pools and the atmosphere as a result of biogeochemical processes in forests (e.g., photosynthesis, respiration, decomposition, and disturbances such as fires or pest outbreaks) and anthropogenic activities (e.g., harvesting, thinning, and replanting). As trees photosynthesize and grow, C is removed from the atmosphere and stored in living tree biomass. As trees die and otherwise deposit litter and debris on the forest floor, C is released to the atmosphere and is also transferred to the litter, dead wood and soil pools by organisms that facilitate decomposition.

The net change in forest C is not equivalent to the net flux between forests and the atmosphere because timber harvests do not cause an immediate flux of all harvested biomass C to the atmosphere. Instead, harvesting transfers a portion of the C stored in wood to a "product pool." Once in a product pool, the C is emitted over time as CO_2 in the case of decomposition and as CO_2, CH_4, N_2O, CO, and NO_x when the wood product combusts. The rate of emission varies considerably among different product pools. For example, if timber is harvested to produce energy, combustion releases C immediately, and these emissions are reported for information purposes in the Energy sector while the harvest (i.e., the associated reduction in forest C stocks) and subsequent combustion are implicitly estimated in the Land Use, Land-Use Change, and Forestry (LULUCF) sector (i.e., the harvested timber does not enter the HWP pools). Conversely, if timber is harvested and used as lumber in a house, it may be many decades or even centuries before the lumber decays and C is released to the atmosphere. If wood products are disposed of in SWDS, the C contained in the wood may be released many years or decades later, or may be stored almost permanently in the SWDS. These latter fluxes, with the exception of CH_4 from wood in SWDS which is included in the Waste sector, are also estimated in the LULUCF sector.

Net Change in Carbon Stocks within Forest Land of the United States

This section describes the general method for quantifying the net changes in C stocks in the five C storage pools and two harvested wood pools. The underlying methodology for determining C stock and stock change relies on data from the Forest Inventory and Analysis (FIA) program within the USDA Forest Service. The annual forest inventory system is implemented across all U.S. forest lands within the conterminous 48 states, but at this time does not include interior Alaska, Hawaii, and U.S. Territories although inventories have been initiated in those states and some territories. The methods for estimation and monitoring are continuously improved and these improvements are reflected in the C estimates (Domke et al. 2016; Domke et al. 2017). First, the total C stocks are estimated for each C storage pool, next the net changes in C stocks for each pool are estimated, and then the changes in stocks are summed for all pools to estimate total net flux. The focus on C implies that all C-based greenhouse gases are included, and the focus on stock change suggests that specific ecosystem fluxes do not need to be separately itemized in this report. Changes in C stocks from disturbances, such as forest fires or harvesting, are included in the net changes. For instance, an inventory conducted after fire counts only the trees that are left. Therefore, changes in C stocks from natural disturbances, such as wildfires, pest outbreaks, and storms, are included in the forest inventory approach; however, they are highly variable from year to year. The IPCC (2006) recommends estimating changes in C stocks from forest lands according to several land-use types and conversions, specifically *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*, with the former being lands that have been forest lands for 20 years or longer and the latter being lands that have been classified as forest lands for less than 20 years. The methods and data used to delineate forest C stock changes by these two categories continue to improve and in order to facilitate this delineation, a combination of modeling approaches for carbon estimation were used this year in the United States.

Forest Area in the United States

Approximately 33 percent of the U.S. land area is estimated to be forested in 2016 based on the U.S. definition of forest land as provided in the Section 6.1 Representation of the U.S. Land Base. Only FIA plots that were used in the 1990 through 2015 Inventory were used in the current Inventory to ensure consistency with the other land use categories and maintain the area estimates reported in the Land Representation, which are consistent with the 1990 through 2015 Inventory area estimates because new area activity data were not compiled for the current Inventory, and 2016 area estimates were assumed to remain the same as the 2015 estimates (see Section 6.1 Representation of the U.S. Land Base). The forest inventories from each of the conterminous 48 states (USDA Forest Service 2016a, 2016b) comprise an estimated 266 million hectares of forest land that are considered managed and are included in the current Inventory. An additional 6.2 million hectares of forest land in southeast and south central coastal Alaska are inventoried and are also included here. Some differences exist in forest land area estimates from the latest update to the Resources Planning Act (RPA) Assessment (Oswalt et al. 2014) and the forest land area estimates included in this report, which are based on the annual inventory data used in the 1990 through 2015 Inventory for all states (USDA Forest Service 2016b). Sufficient annual inventory data are not yet available for Hawaii and interior Alaska, but estimates of these areas are included in Oswalt et al. (2014). Updated survey data for central and western forest land in both Oklahoma and Texas have only recently become available, and these forests contribute to overall C stocks reported below. While Hawaii and U.S. Territories have relatively small areas of forest land and thus may not substantially influence the overall C budget for forest land, these regions will be added to the forest C estimates as sufficient data become available. Agroforestry systems that meet the definition of forest land are also not currently included in the current Inventory since they are not explicitly inventoried by either the FIA program or the Natural Resources Inventory (NRI)[26] of the USDA Natural Resources Conservation Service (Perry et al. 2005).

An estimated 77 percent (211 million hectares) of U.S. forests in southeast and southcentral coastal Alaska and the conterminous United States are classified as timberland, meaning they meet minimum levels of productivity and have not been removed from production. Approximately ten percent of southeast and southcentral coastal Alaska forest land and 80 percent of forest land in the conterminous United States are classified as timberland. Of the remaining non-timberland, 30 million hectares are reserved forest lands (withdrawn by law from management for production of wood products) and 69 million hectares are lower productivity forest lands (Oswalt et al. 2014). Historically, the timberlands in the conterminous 48 states have been more frequently or intensively surveyed than the forest land removed from production because it does not meet the minimum level of productivity.

Since the late 1980s, forest land area in southeast and southcentral coastal Alaska and the conterminous United States has increased by about 14 million hectares (Oswalt et al. 2014) with the southern region of the United States containing the most forest land (Figure 6-3). A substantial portion of this accrued forest land is from the conversion of abandoned croplands to forest (e.g., Woodall et al. 2015b). Current trends in the estimated forest land area in the conterminous United States and the portion of southeast and south central coastal Alaska represented here show an average annual rate of increase of 0.1 percent. In addition to the increase in forest area, the major influences to the net C flux from forest land across the 1990 to 2016 time series are management activities and the ongoing impacts of previous land-use conversions. These activities affect the net flux of C by altering the amount of C stored in forest ecosystems and also the area converted to forest land. For example, intensified management of forests that leads to an increased rate of growth of aboveground biomass (and possible changes to the other C storage pools) may increase the eventual biomass density of the forest, thereby increasing the uptake and storage of C in the aboveground biomass pool.[27] Though harvesting forests removes much of the C in aboveground biomass (and possibly changes C density in other pools), on average, the estimated volume of annual net growth in the conterminous U.S. states is about double the volume of annual removals on timberlands (Oswalt et al. 2014). The net effects of forest management and changes in *Forest Land Remaining Forest Land* are captured in the estimates of C stocks and fluxes presented in this section.

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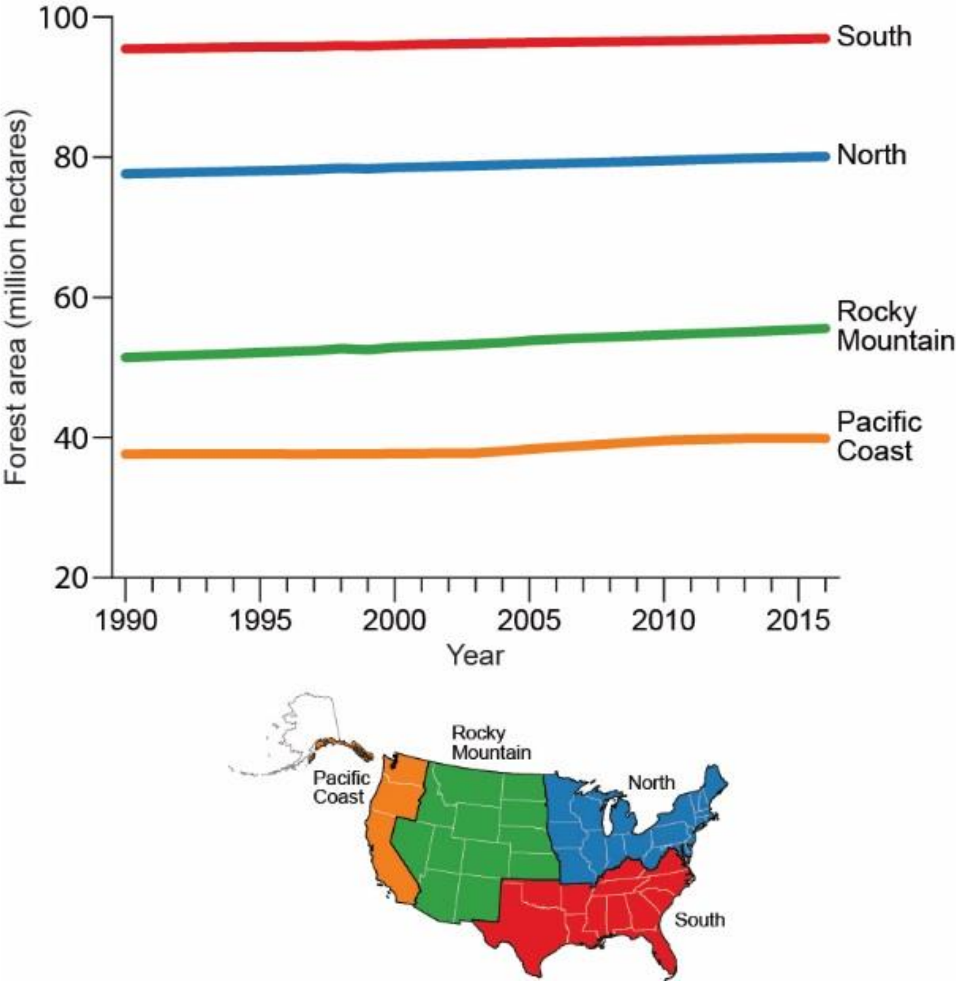
[26] The Natural Resources Inventory of the USDA Natural Resources Conservation Service is described in Section 6.1—Representation of the U.S. Land Base.

[27] The term "biomass density" refers to the mass of live vegetation per unit area. It is usually measured on a dry-weight basis. Dry biomass is assumed to be 50 percent C by weight.

Figure 6-3: Changes in Forest Area by Region for *Forest Land Remaining Forest Land* in the conterminous United States and coastal Alaska (1990-2016, Million Hectares)



Forest Carbon Stocks and Stock Change

In the United States, forest management practices, the regeneration of forest areas cleared more than 20 years prior to the reporting year, and timber harvesting have resulted in net uptake (i.e., net sequestration) of C each year from 1990 through 2016. The rate of forest clearing in the 17th century following European settlement had slowed by the late 19th century. Through the later part of the 20th century many areas of previously forested land in the United States were allowed to revert to forests or were actively reforested. The impacts of these land-use changes still influence C fluxes from these forest lands. More recently, the 1970s and 1980s saw a resurgence of federally-sponsored forest management programs (e.g., the Forestry Incentive Program) and soil conservation programs (e.g., the Conservation Reserve Program), which have focused on tree planting, improving timber management activities, combating soil erosion, and converting marginal cropland to forests. In addition to forest regeneration and management, forest harvests have also affected net C fluxes. Because most of the timber harvested from U.S. forest land is used in wood products, and many discarded wood products are disposed of in SWDS rather than by incineration, significant quantities of C in harvested wood are transferred to these long-term storage pools rather than being released rapidly to the atmosphere (Skog 2008). With sustainable harvesting practices and regeneration of these forested lands, along with continued input of harvested products into the HWP pool, C stocks in the *Forest Land Remaining Forest Land* category are likely to continue to increase in the near term, though possibly at a lower rate. Changes in C stocks in the forest ecosystem and harvested wood pools associated with *Forest Land Remaining Forest Land* were estimated to result in net sequestration of 671.2 MMT CO_2 Eq. (183.1 MMT C) in 2016 (Table 6-10 and Table 6-11). The estimated net sequestration of C in the Forest Ecosystem was 571.6 MMT CO_2 Eq. (155.9

MMT C) in 2016 (Table 6-10 and Table 6-11). The majority of this sequestration, 315.3 MMT CO_2 Eq. (86.0 MMT C), was from aboveground biomass in 2016. Overall, estimates of average C density in forest ecosystems (including all pools) remained stable at approximately 0.0002 MMT C ha^{-1} from 1990 to 2016. This was calculated by dividing the Forest Land area estimates by Forest Ecosystem C Stock estimates for every year (see Table 6-12) and then calculating the mean across the entire time series, i.e., 1990 through 2016. The stable forest ecosystem C density when combined with increasing forest area results in net C accumulation over time. These increases may be influenced in some regions by reductions in C density or forest land area due to natural disturbances (e.g., wildfire, weather, insects/disease). Aboveground live biomass is responsible for the majority of net sequestration among all forest ecosystem pools (Figure 6-4).

The estimated net sequestration of C in HWP was 99.6 MMT CO_2 Eq. (27.2 MMT C) in 2016 (Table 6-10 and Table 6-11). The majority of this sequestration, 66.1 MMT CO_2 Eq. (18.0 MMT C), was from wood and paper in SWDS. Products in use were an estimated 33.5 MMT CO_2 Eq. (9.1 MMT C) in 2016.

Table 6-10: Net CO_2 Flux from Forest Pools in *Forest Land Remaining Forest Land* and Harvested Wood Pools (MMT CO_2 Eq.)

Carbon Pool	1990	2005	2012	2013	2014	2015	2016[b]
Forest Ecosystem	**(574.7)**	**(557.3)**	**(598.5)**	**(596.1)**	**(593.7)**	**(571.1)**	**(571.6)**
Aboveground Biomass	(327.9)	(314.4)	(331.5)	(329.6)	(327.7)	(310.0)	(315.3)
Belowground Biomass	(70.0)	(66.6)	(69.7)	(69.2)	(68.7)	(64.6)	(65.7)
Dead Wood	(33.5)	(40.3)	(49.1)	(49.2)	(49.2)	(43.7)	(39.2)
Litter	(17.0)	(14.3)	(16.3)	(16.3)	(16.3)	(15.2)	(16.1)
Soil (Mineral)	(126.1)	(121.7)	(132.0)	(131.9)	(131.9)	(137.6)	(135.4)
Soil (Organic)[a]	(0.1)	+	0.1	0.1	0.1	0.1	0.094
Harvested Wood	**(123.8)**	**(108.0)**	**(69.2)**	**(75.6)**	**(76.4)**	**(95.9)**	**(99.6)**
Products in Use	(54.8)	(44.6)	(7.0)	(13.0)	(13.7)	(31.4)	(33.5)
SWDS	(69.0)	(63.5)	(62.2)	(62.6)	(62.7)	(64.4)	(66.1)
Total Net Flux	**(698.4)**	**(665.3)**	**(667.6)**	**(671.6)**	**(670.0)**	**(666.9)**	**(671.2)**

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

[a] These estimates do not include C stock changes from drained organic soils. See Table 6-21 and Table 6-22 for CO_2 emissions from drainage of organic soils from both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.

[b] The approach for estimating forest ecosystem carbon stock changes on *Forest Land Remaining Forest Land* was consistent with the methods used in the 1990 through 2015 Inventory and is described in Annex 3.13. Only FIA plots that were used in the 1990 through 2015 Inventory were used in the current Inventory to ensure consistency with the other land use categories and maintain the area estimates reported in the Land Representation.

Notes: Forest ecosystem C stocks do not include forest stocks in U.S. Territories, Hawaii, a portion of managed forests in Alaska, or trees on non-forest land (e.g., agroforestry systems and urban areas—see section 6.10 *Settlements Remaining Settlements* for estimates of C stock change from urban trees). Parentheses indicate net C sequestration (i.e., a net removal of C from the atmosphere). Total net flux is an estimate of the actual net flux between the total forest C pool and the atmosphere. Harvested wood estimates are based on results from annual surveys and models. Totals may not sum due to independent rounding.

Table 6-11: Net C Flux from Forest Pools in *Forest Land Remaining Forest Land* and Harvested Wood Pools (MMT C)

Carbon Pool	1990	2005	2012	2013	2014	2015	2016[b]
Forest Ecosystem	**(156.7)**	**(152.0)**	**(163.2)**	**(162.6)**	**(161.9)**	**(155.7)**	**(155.9)**
Aboveground Biomass	(89.4)	(85.7)	(90.4)	(89.9)	(89.4)	(84.6)	(86.0)
Belowground Biomass	(19.1)	(18.2)	(19.0)	(18.9)	(18.7)	(17.6)	(17.9)
Dead Wood	(9.1)	(11.0)	(13.4)	(13.4)	(13.4)	(11.9)	(10.7)
Litter	(4.6)	(3.9)	(4.4)	(4.4)	(4.4)	(4.1)	(4.4)
Soil (Mineral)	(34.4)	(33.2)	(36.0)	(36.0)	(36.0)	(37.5)	(36.9)
Soil (Organic)[a]	+	+	+	+	+	+	0.026
Harvested Wood	**(33.8)**	**(29.5)**	**(18.9)**	**(20.6)**	**(20.8)**	**(26.1)**	**(27.2)**

Products in Use	(14.9)	(12.2)	(1.9)	(3.5)	(3.7)	(8.6)	(9.1)
SWDS	(18.8)	(17.3)	(17.0)	(17.1)	(17.1)	(17.6)	(18.0)
Total Net Flux	**(190.5)**	**(181.5)**	**(182.1)**	**(183.2)**	**(182.7)**	**(181.9)**	**(183.1)**

+ Absolute value does not exceed 0.05 MMT C

[a] These estimates do not include carbon stock changes from drained organic soils. See Table 6-21 and Table 6-22 for C stock changes from drainage of organic soils from *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.

[b] The approach for estimating carbon stock changes on *Forest Land Remaining Forest Land* was consistent with the methods used in the 1990 through 2015 Inventory and is described in Annex 3.13. Only FIA plots that were used in the 1990 through 2015 Inventory were used in the current Inventory to ensure consistency with the other land use categories and maintain the area estimates reported in the Land Representation.

Notes: Forest C stocks do not include forest stocks in U.S. Territories, Hawaii, a portion of managed lands in Alaska, or trees on non-forest land (e.g., agroforestry systems and urban areas—see Section 6.10 *Settlements Remaining Settlements* for estimates of C stock change from urban trees). Parentheses indicate net C sequestration (i.e., a net removal of C from the atmosphere). Total net flux is an estimate of the actual net flux between the total forest C pool and the atmosphere. Harvested wood estimates are based on results from annual surveys and models. Totals may not sum due to independent rounding.

Stock estimates for forest ecosystem and harvested wood C storage pools are presented in Table 6-12. Together, the estimated aboveground biomass and soil C pools account for a large proportion of total forest ecosystem C stocks. Note that the forest land area estimates in Table 6-12 do not precisely match those in Section 6.1 Representation of the U.S. Land Base for *Forest Land Remaining Forest Land*. This is because the forest land area estimates in Table 6-12 only include managed forest land in the conterminous 48 states and southeast and south central coastal Alaska (which is the current area encompassed by FIA survey data, approximately 6.2 million ha) while the area estimates in Section 6.1 include all managed forest land in Alaska (approximately 25.9 million ha with approximately 19.7 million ha in interior Alaska, which is not currently included in this Inventory) and Hawaii.

Table 6-12: Forest Area (1,000 ha) and C Stocks in *Forest Land Remaining Forest Land* and Harvested Wood Pools (MMT C)

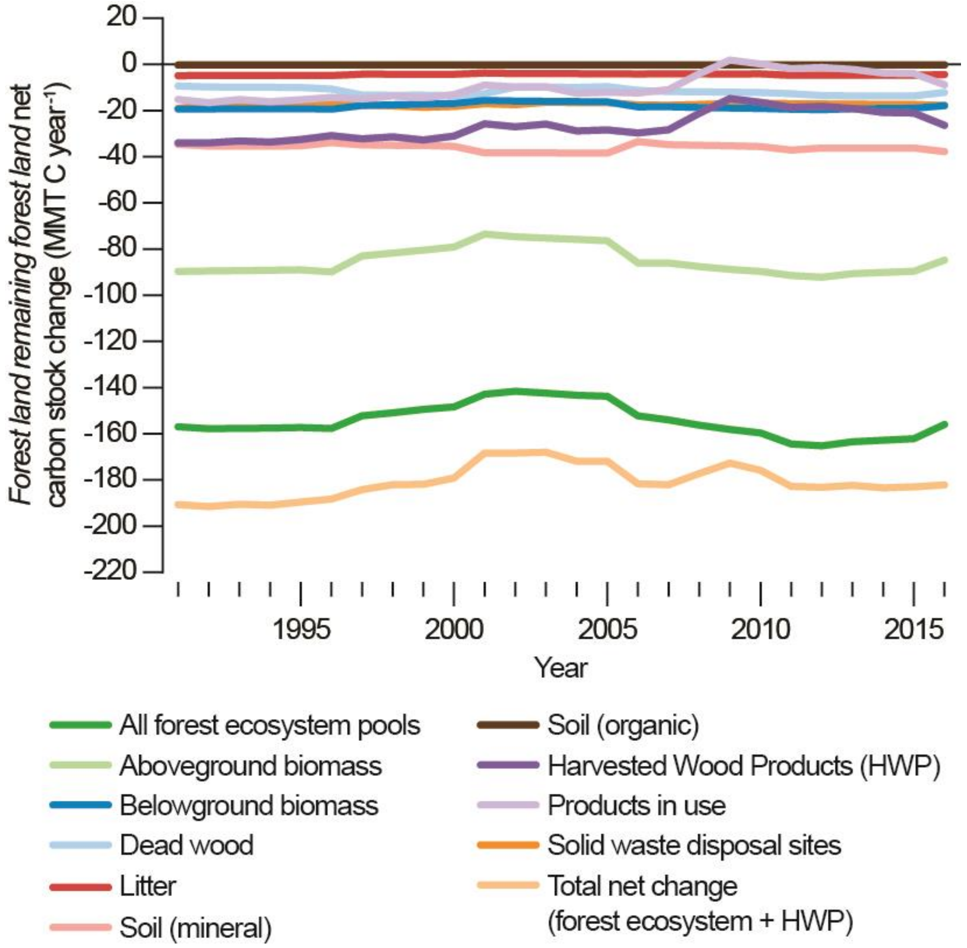
	1990	2005	2012	2013	2014	2015	2016	2017[b]
Forest Area (1000 ha)	***262,119***	***267,479***	***271,064***	***271,512***	***271,812***	***272,113***	***272,260***	***272,260***
Carbon Pools (MMT C)								
Forest Ecosystem	**46,967**	**49,223**	**50,331**	**50,494**	**50,657**	**50,819**	**50,975**	**51,131**
Aboveground Biomass	11,889	13,122	13,742	13,833	13,922	14,012	14,096	14,182
Belowground Biomass	2,439	2,700	2,831	2,850	2,869	2,888	2,905	2,923
Dead Wood	2,262	2,424	2,507	2,521	2,534	2,548	2,560	2,570
Litter	2,568	2,630	2,659	2,663	2,668	2,672	2,676	2,680
Soil (Mineral)	27,456	27,994	28,240	28,276	28,312	28,348	28,385	28,422
Soil (Organic)[a]	352	352	352	352	352	352	352	352
Harvested Wood	**1,895**	**2,353**	**2,498**	**2,517**	**2,538**	**2,559**	**2,585**	**2,612**
Products in Use	1,249	1,447	1,474	1,476	1,479	1,483	1,492	1,501
SWDS	646	906	1,025	1,042	1,059	1,076	1,093	1,111
Total C Stock	**48,862**	**51,576**	**52,830**	**53,012**	**53,195**	**53,378**	**53,560**	**53,743**

[a] These estimates do not include C stock changes from drained organic soils. See Table 6-21 and Table 6-22 for C stock changes from drainage of organic soils from *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.

[b] The approach for estimating carbon stock changes on *Forest Land Remaining Forest Land* was consistent with the methods used in the 1990 through 2015 Inventory and is described in Annex 3.13. Only FIA plots that were used in the 1990 through 2015 Inventory were used in the current Inventory to ensure consistency with the other land use categories and maintain the area estimates reported in the Land Representation. As a result, Forest Land area estimates were assumed to remain constant from 2016 to 2017 while carbon stocks increased in 2017 consistent with previous years in the time series.

Notes: Forest area and C stock estimates include all *Forest Land Remaining Forest Land* in the conterminous 48 states and southeast and south central coastal Alaska (6.2 million ha), which is the current area encompassed by FIA survey data. Forest C stocks do not include forest stocks in U.S. Territories, Hawaii, a large portion of interior Alaska (19.7 million ha), or trees on non-forest land (e.g., agroforestry systems and urban areas—see section 6.10 *Settlements Remaining Settlements* for estimates of C stock change from urban trees). The forest area estimates in this table do not match those in Section 6.1 Representation of the U.S. Land Base, which includes all managed forest land in Alaska and Hawaii. Harvested wood product stocks include exports, even if the logs are processed in other countries, and exclude imports. Harvested wood estimates are based on results from annual surveys and models. Totals may not sum due to independent rounding. Population estimates compiled using FIA data are assumed to represent stocks as of January 1 of the Inventory year. Flux is the net annual change in stock. Thus, an estimate of flux for 2016 requires estimates of C stocks for 2016 and 2017.

Figure 6-4: Estimated Net Annual Changes in C Stocks for All C Pools in *Forest Land Remaining Forest Land* in the Conterminous U.S. and Coastal Alaska (1990-2016, MMT C per Year)



Box 6-4: CO_2 Emissions from Forest Fires

As stated previously, the forest inventory approach implicitly includes all C losses due to disturbances such as forest fires, because only C remaining in the forest is estimated. Net C stock change is estimated by subtracting consecutive C stock estimates. A forest fire disturbance removes C from the forest. The inventory data on which net C stock estimates are based already reflect this C loss. Therefore, estimates of net annual changes in C stocks for U.S. forest land already includes CO_2 emissions from forest fires occurring in the conterminous states as well as the portion of managed forest lands in Alaska that are captured in the current Inventory. Because it is of interest to quantify the magnitude of CO_2 emissions from fire disturbance, these separate estimates are highlighted here. Note that these CO_2 estimates are based on the same methodology as applied for the non-CO_2 greenhouse gas emissions from forest fires that are also quantified in a separate section below as required by IPCC Guidance and UNFCCC Reporting Requirements.

The IPCC (2006) methodology and a combination of U.S.-specific data on annual area burned and potential fuel availability together with default combustion factors were employed to estimate CO_2 emissions from forest fires.

The latest information on area burned is used to compile fire emissions for the U.S. At the time this Inventory was compiled, fire data for 2016 were not available so estimates from 2015 were used. It is important to note that the wildfire emissions in 2015 were markedly higher than in recent years. The 2016 estimates will be updated in subsequent reports as fire data becomes available. Estimated CO_2 emissions for wildfires in the conterminous 48 states and in Alaska as well as prescribed fires in 2016 were estimated to be 248.2 MMT CO_2 per year (Table 6-13). This estimate is an embedded component of the net annual forest C stock change estimates provided previously (i.e., Table 6-11), but this separate approach to estimate emissions is necessary in order to associate a portion of emissions, including estimates of CH_4 and N_2O, with fire. See the discussion in Annex 3.13 for more details on this methodology. Note that the estimates for Alaska provided in Table 6-13 include all managed forest land in the state and are not limited to the subset with permanent inventory plots on managed lands as specified elsewhere in this chapter (i.e., Table 6-11).

Table 6-13: Estimates of CO_2 (MMT per Year) Emissions from Forest Fires in the Conterminous 48 States and Alaska[a]

Year	CO_2 emitted from Wildfires in the Conterminous 48 States (MMT yr^{-1})	CO_2 emitted from Wildfires in Alaska (MMTyr^{-1})	CO_2 emitted from Prescribed Fires (MMTyr^{-1})	Total CO_2 emitted (MMTyr^{-1})
1990	22.5	19.6	0.2	42.3
2005	44.1	80.6	1.3	125.9
2012	138.6	2.7	2.9	144.2
2013	67.9	22.3	5.5	95.6
2014	84.1	4.9	6.1	95.0
2015	164.1	80.7	3.5	248.2
2016[b]	164.1	80.7	3.5	248.2

[a] These emissions have already been included in the estimates of net annual changes in C stocks, which include the amount sequestered minus any emissions, including the assumption that combusted wood may continue to decay through time.

[b] The data for 2016 were unavailable when these estimates were summarized; therefore 2015, the most recent available estimate, is applied to 2016.

Methodology and Data Sources

The methodology described herein is consistent with IPCC (2006). Forest ecosystem C stocks and net annual C stock change were determined according to the stock-difference method, which involved applying C estimation factors to annual forest inventories across time to obtain C stocks and then subtracting between the years to obtain the stock change. The approaches for estimating carbon stocks and stock changes on *Forest Land Remaining Forest Land* were consistent with the methods used in the 1990 through 2015 Inventory and are described in Annex 3.13. Only FIA plots that were used in the 1990 through 2015 Inventory were used in the current Inventory to ensure consistency with the other land use categories and maintain the area estimates reported in the Land Representation, which are a copy of the 1990 through 2015 Inventory area estimates because new area activity data were not compiled for the current Inventory, and 2016 area estimates are held the same as the 2015 values (see Section 6.1 Representation of the U.S. Land Base). As a result, Forest Land area estimates were assumed to remain constant from 2016 to 2017 while carbon stocks and stock changes increased in 2017 consistent with previous years in the time series and based on the FIA plots that were used in the previous (1990 through 2015) Inventory. Forest Land conditions were observed on FIA plots at time t_0 and at a subsequent time t_1=t_0+s, where s is the time step (time measured in years) and is indexed by discrete (e.g., 5 year) forest age classes. The inventory from t_0 was then projected from t_1 to 2017. This projection approach requires simulating changes in the age-class distribution resulting from forest aging and disturbance events and then applying C density estimates for each age class to obtain population estimates for the nation. Harvested wood C estimates were based on factors such as the allocation of wood to various primary and end-use products as well as half-life (the time at which half of the amount placed in use will have been discarded from use) and expected disposition (e.g., product pool, SWDS, combustion). An overview of the different methodologies and data sources used to estimate the C in forest ecosystems or harvested wood products is provided here. See Annex 3.13 for details and additional information related to the methods and data.

Forest Ecosystem Carbon from Forest Inventory

The United States applied the compilation approach described in Woodall et al. (2015a) for the current Inventory which removes the older periodic inventory data, which may be inconsistent with annual inventory data, from the estimation procedures and enables the delineation of forest C accumulation by forest growth, land use change, and natural disturbances such as fire. Development will continue on a system that attributes changes in forest C to disturbances and delineates *Land Converted to Forest Land* from *Forest Land Remaining Forest Land*. As part of this development, C pool science will continue and will be expanded to include C stock transfers from forest land to other land uses, and include techniques to better identify land use change (see the Planned Improvements section below).

Unfortunately, the annual FIA inventory system does not extend into the 1990s, necessitating the adoption of a system to “backcast” the annual C estimates. To facilitate the backcasting of the U.S. annual forest inventory C estimates, the estimation system used in this Inventory is comprised of a forest dynamics module (age transition matrices) and a land use dynamics module (land area transition matrices). The forest dynamics module assesses forest sequestration, forest aging, and disturbance effects (e.g., disturbances such as wind, fire, and floods identified by foresters on inventory plots). The land use dynamics module assesses C stock transfers associated with afforestation and deforestation (Woodall et al. 2015b). Both modules are developed from land use area statistics and C stock change or C stock transfer by age class. The required inputs are estimated from more than 625,000 forest and non-forest observations recorded in the FIA national database (U.S. Forest Service 2016a, b, c). Model predictions prior to the annual inventory period are constructed from the estimation system using the annual estimates. The estimation system is driven by the annual forest inventory system conducted by the FIA program (Frayer and Furnival 1999; Bechtold and Patterson 2005; USDA Forest Service 2016d, 2016a). The FIA program relies on a rotating panel statistical design with a sampling intensity of one 674.5 m^2 ground plot per 2,403 ha of land and water area. A five-panel design, with 20 percent of the field plots typically measured each year within a state, is used in the eastern United States and a ten-panel design, with typically 10 percent of the field plots measured each year within a state, is used in the western United States. The interpenetrating hexagonal design across the U.S. landscape enables the sampling of plots at various intensities in a spatially and temporally unbiased manner. Typically, tree and site attributes are measured with higher sample intensity while other ecosystem attributes such as downed dead wood are sampled during summer months at lower intensities. The first step in incorporating FIA data into the estimation system is to identify annual inventory datasets by state. Inventories include data collected on permanent inventory plots on forest lands and were organized as separate datasets, each representing a complete inventory, or survey, of an individual state at a specified time. Many of the annual inventories reported for states are represented as “moving window” averages, which mean that a portion—but not all—of the previous year’s inventory is updated each year (USDA Forest Service 2016d). Forest C estimates are organized according to these state surveys, and the frequency of surveys varies by state.

Using this FIA data, separate estimates were prepared for the five C storage pools identified by IPCC (2006) and described above. All estimates were based on data collected from the extensive array of permanent, annual forest inventory plots and associated models (e.g., live tree belowground biomass) in the United States (USDA Forest Service 2016b, 2016c). Carbon conversion factors were applied at the disaggregated level of each inventory plot and then appropriately expanded to population estimates.

Carbon in Biomass

Live tree C pools include aboveground and belowground (coarse root) biomass of live trees with diameter at breast height (dbh) of at least 2.54 cm at 1.37 m above the litter. Separate estimates were made for above- and belowground biomass components. If inventory plots included data on individual trees, aboveground and belowground (coarse roots) tree C was based on Woodall et al. (2011a), which is also known as the component ratio method (CRM), and is a function of tree volume, species, and diameter. An additional component of foliage, which was not explicitly included in Woodall et al. (2011a), was added to each tree following the same CRM method.

Understory vegetation is a minor component of biomass, which is defined in the FIA program as all biomass of undergrowth plants in a forest, including woody shrubs and trees less than 2.54 cm dbh. For this Inventory, it was assumed that 10 percent of total understory C mass is belowground (Smith et al. 2006). Estimates of C density were based on information in Birdsey (1996) and biomass estimates from Jenkins et al. (2003). Understory biomass represented over one percent of C in biomass, but its contribution rarely exceeded 2 percent of the total carbon stocks or stock changes across all forest ecosystem C pools each year.

Carbon in Dead Organic Matter

Dead organic matter was initially calculated as three separate pools—standing dead trees, downed dead wood, and litter—with C stocks estimated from sample data or from models as described below. The standing dead tree C pool includes aboveground and belowground (coarse root) biomass for trees of at least 12.7 cm dbh. Calculations followed the basic method applied to live trees (Woodall et al. 2011a) with additional modifications to account for decay and structural loss (Domke et al. 2011; Harmon et al. 2011). Downed dead wood estimates are based on measurement of a subset of FIA plots for downed dead wood (Domke et al. 2013; Woodall and Monleon 2008; Woodall et al. 2013). Downed dead wood is defined as pieces of dead wood greater than 7.5 cm diameter, at transect intersection, that are not attached to live or standing dead trees. This includes stumps and roots of harvested trees. To facilitate the downscaling of downed dead wood C estimates from the state-wide population estimates to individual plots, downed dead wood models specific to regions and forest types within each region are used. Litter C is the pool of organic C (also known as duff, humus, and fine woody debris) above the mineral soil and includes woody fragments with diameters of up to 7.5 cm. A subset of FIA plots are measured for litter C. A modeling approach, using litter C measurements from FIA plots (Domke et al. 2016) was used to estimate litter C for every FIA plot used in the estimation framework.

Carbon in Forest Soil

Soil carbon is the largest terrestrial C sink with much of that C in forest ecosystems. The FIA program has been consistently measuring soil attributes as part of the annual inventory since 2001 and has amassed an extensive inventory of soil measurement data on forest land in the conterminous United States and coastal Alaska (O’Neill et al. 2005). Observations of mineral and organic soil C on forest land from the FIA program and the International Soil Carbon Monitoring Network were used to develop and implement a modeling approach that enabled the prediction of mineral and organic soil C to a depth of 100 cm from empirical measurements to a depth of 20 cm and included site-, stand-, and climate-specific variables that yield predictions of soil C stocks specific to forest land in the United States (Domke et al. 2017). This new approach allowed for separation of mineral and organic soils, also referred to as *Histosols*, in the *Forest Land Remaining Forest Land* category. Note that mineral and organic soil C is reported to a depth of 100 cm for *Forest Land Remaining Forest Land* to remain consistent with past reporting in this category, however for consistency across land-use categories mineral (e.g., cropland, grassland, settlements) soil C is reported to a depth of 30 cm in Section 6.3 *Land Converted to Forest Land*. Estimates of C from organic soils in this section (Table 6-10, Table 6-11, and Table 6-12) do not include emissions from drained organic soils. Estimates of C stock changes from drainage of organic soils from *Forest Land Remaining Forest Land* and *Land Converted to Forest Land* can be found in the Drained Organic Soils section below (Table 6-21 and Table 6-22).

Harvested Wood Carbon

Estimates of the HWP contribution to forest C sinks and emissions (hereafter called “HWP contribution”) were based on methods described in Skog (2008) using the WOODCARB II model. These methods are based on IPCC (2006) guidance for estimating the HWP contribution. IPCC (2006) provides methods that allow for reporting of HWP contribution using one of several different methodological approaches: Production, stock change and atmospheric flow, as well as a default method that assumes there is no change in HWP C stocks (see Annex 3.13 for more details about each approach). The United States uses the production approach to report HWP contribution. Under the production approach, C in exported wood was estimated as if it remains in the United States, and C in imported wood was not included in the estimates. Though reported U.S. HWP estimates are based on the production approach, estimates resulting from use of the two alternative approaches, the stock change and atmospheric flow approaches, are also presented for comparison (see Annex 3.13). Annual estimates of change were calculated by tracking the annual estimated additions to and removals from the pool of products held in end uses (i.e., products in use such as housing or publications) and the pool of products held in SWDS. The C loss from harvest is reported here and for information purposes in the Energy sector, but the non-CO_2 emissions associated with biomass energy are included in the Energy sector emissions (see Chapter 3).

Solidwood products include lumber and panels. End-use categories for solidwood include single and multifamily housing, alteration and repair of housing, and other end uses. There is one product category and one end-use category for paper. Additions to and removals from pools were tracked beginning in 1900, with the exception that additions of softwood lumber to housing, which began in 1800. Solidwood and paper product production and trade data were taken from USDA Forest Service and other sources (Hair and Ulrich 1963; Hair 1958; USDC Bureau of Census 1976; Ulrich 1985, 1989; Steer 1948; AF&PA 2006a, 2006b; Howard 2003, 2007, 2016, In preparation). Estimates for disposal of products reflected the change over time in the fraction of products discarded to SWDS (as opposed to burning or recycling) and the fraction of SWDS that were in sanitary landfills versus dumps.

There are five annual HWP variables that were used in varying combinations to estimate HWP contribution using any one of the three main approaches listed above. These are:

(1A) annual change of C in wood and paper products in use in the United States,

(1B) annual change of C in wood and paper products in SWDS in the United States,

(2A) annual change of C in wood and paper products in use in the United States and other countries where the wood came from trees harvested in the United States,

(2B) annual change of C in wood and paper products in SWDS in the United States and other countries where the wood came from trees harvested in the United States,

(3) C in imports of wood, pulp, and paper to the United States,

(4) C in exports of wood, pulp and paper from the United States, and

(5) C in annual harvest of wood from forests in the United States.

The sum of variables 2A and 2B yielded the estimate for HWP contribution under the production estimation approach. A key assumption for estimating these variables was that products exported from the United States and held in pools in other countries have the same half-lives for products in use, the same percentage of discarded products going to SWDS, and the same decay rates in SWDS as they would in the United States.

Uncertainty and Time-Series Consistency

A quantitative uncertainty analysis placed bounds on current flux for forest ecosystems through a combination of sample-based and model-based approaches to uncertainty for forest ecosystem CO_2 flux (IPCC Approach 1). A Monte Carlo Stochastic Simulation of the Methods described above and probabilistic sampling of C conversion factors were used to determine the HWP uncertainty (IPCC Approach 2). See Annex 3.13 for additional information. The 2016 net annual change for forest C stocks was estimated to be between -919.3 and -423.2 MMT CO_2 Eq. around a central estimate of -671.2 MMT CO_2 Eq. at a 95 percent confidence level. This includes a range of -818.7 to -324.7 MMT CO_2 Eq. around a central estimate of -571.6 MMT CO_2 Eq. for forest ecosystems and -122.1 to -76.3 MMT CO_2 Eq. around a central estimate of -99.6 MMT CO_2 Eq. for HWP.

Table 6-14: Quantitative Uncertainty Estimates for Net CO_2 Flux from *Forest Land Remaining Forest Land*: Changes in Forest C Stocks (MMT CO_2 Eq. and Percent)

Source	Gas	2016 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Forest C Pools[a]	CO_2	(571.6)	(818.7)	(324.7)	-43.2%	43.2%
Harvested Wood Products[b]	CO_2	(99.6)	(122.1)	(76.3)	-22.6%	23.4%
Total Forest	**CO_2**	**(671.2)**	**(919.3)**	**(423.2)**	**-37.0%**	**36.9%**

[a] Range of flux estimates predicted through a combination of sample-based and model-based uncertainty for a 95 percent confidence interval, IPCC Approach 1.

[b] Range of flux estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval, IPCC Approach 2.

Note: Parentheses indicate negative values or net sequestration.

QA/QC and Verification

As discussed above, the FIA program has conducted consistent forest surveys based on extensive statistically-based sampling of most of the forest land in the conterminous United States, dating back to 1952. The FIA program includes numerous quality assurance and quality control (QA/QC) procedures, including calibration among field crews, duplicate surveys of some plots, and systematic checking of recorded data. Because of the statistically-based sampling, the large number of survey plots, and the quality of the data, the survey databases developed by the FIA program form a strong foundation for C stock estimates. Field sampling protocols, summary data, and detailed inventory databases are archived and are publicly available on the Internet (USDA Forest Service 2016d).

General quality control procedures were used in performing calculations to estimate C stocks based on survey data. For example, the C datasets, which include inventory variables such as areas and volumes, were compared to standard inventory summaries such as the forest resource statistics of Oswalt et al. (2014) or selected population estimates generated from the FIA database, which are available at an FIA internet site (USDA Forest Service 2016b). Agreement between the C datasets and the original inventories is important to verify accuracy of the data used. The methods and plots used in the current Inventory were the same as those used in the 1990 through 2015 Inventory. That said, all estimates were compiled again for the entire time series to ensure consistency. As a result, Forest Land area estimates remained constant from 2016 to 2017 while carbon stocks increased in 2017 consistent with previous years in the time series.

Estimates of the HWP variables and the HWP contribution under the production estimation approach use data from U.S. Census and USDA Forest Service surveys of production and trade and other sources (Hair and Ulrich 1963; Hair 1958; USDC Bureau of Census 1976; Ulrich 1985, 1989; Steer 1948; AF&PA 2006a, 2006b; Howard 2003, 2007, 2016, In preparation). Factors to convert wood and paper to units of C are based on estimates by industry and Forest Service published sources (see Annex 3.13). The WOODCARB II model uses estimation methods suggested by IPCC (2006). Estimates of annual C change in solidwood and paper products in use were calibrated to meet two independent criteria. The first criterion is that the WOODCARB II model estimate of C in houses standing in 2001 needs to match an independent estimate of C in housing based on U.S. Census and USDA Forest Service survey data. Meeting the first criterion resulted in an estimated half-life of about 80 years for single family housing built in the 1920s, which is confirmed by other U.S. Census data on housing. The second criterion is that the WOODCARB II model estimate of wood and paper being discarded to SWDS needs to match EPA estimates of discards used in the Waste sector each year over the period 1990 to 2000 (EPA 2006). These criteria help reduce uncertainty in estimates of annual change in C in products in use in the United States and, to a lesser degree, reduce uncertainty in estimates of annual change in C in products made from wood harvested in the United States. In addition, WOODCARB II landfill decay rates have been validated by ensuring that estimates of CH_4 emissions from landfills based on EPA (2006) data are reasonable in comparison to CH_4 estimates based on WOODCARB II landfill decay rates.

Recalculations Discussion

The methods and data used in the current Inventory to compile estimates for forest ecosystem carbon stocks and stock changes, as well as for HWP, from 1990 through 2015 are consistent with those used in the 1990 through 2015 Inventory so recalculations were not necessary.

Planned Improvements

Reliable estimates of forest C stocks and changes across the diverse ecosystems of the United States require a high level of investment in both annual monitoring and associated analytical techniques. Development of improved monitoring/reporting techniques is a continuous process that occurs simultaneously with annual Inventory submissions. Planned improvements can be broadly assigned to the following categories: development of a robust estimation and reporting system, individual C pool estimation, coordination with other land-use categories, and annual inventory data incorporation.

While this is the third Inventory submission to delineate C change by *Forest Land Remaining Forest Land* and *Land Converted to Forest Land* and the second Inventory to report carbon stock changes for all IPCC pools in these two categories, there are many improvements that are still necessary. Since the estimation approach used in the current Inventory operates at the regional scale for the United States, research is underway to leverage auxiliary information (i.e., remotely sensed information) to operate at finer spatial and temporal scales. As in past submissions, emissions and removals associated with natural (e.g., wild fire, insects, and disease) and human (e.g., harvesting) disturbances are implicitly included in the report given the design of the annual forest inventory system, but not explicitly estimated. The transparency and repeatability of estimation and reporting systems will be improved through the dissemination of open source code (e.g., R programming language) in concert with the public availability of the annual forest inventory data (USDA Forest Service 2016b). Also, several FIA database processes are being institutionalized to increase efficiency and QA/QC in reporting and further improve transparency, completeness, consistency, accuracy, and availability of data used in reporting. Finally, a Tier 1 approach was used to estimate uncertainty associated with C stock changes in the *Forest Land Remaining Forest Land* category in this report. There is research underway investigating more robust approaches to total uncertainty (Clough et al. 2016), which will be considered in future Inventory reports.

The modeling framework used to estimate downed dead wood within the dead wood C pool will be updated similar to the litter (Domke et al. 2016) and soil C pools (Domke et al. 2017). Finally, components of other pools, such as C in belowground biomass (Russell et al. 2015) and understory vegetation (Russell et al. 2014; Johnson et al. 2017), are being explored but may require additional investment in field inventories before improvements can be realized with the Inventory report.

The foundation of forest C estimation and reporting is the annual forest inventory system. The ongoing annual surveys by the FIA program are expected to improve the accuracy and precision of forest C estimates as new state surveys become available (USDA Forest Service 2016b), particularly in western states. Hawaii and U.S. Territories will be included when appropriate forest C data are available (only a small number of plots from Hawaii are currently available from the annualized sampling design). A small portion of forest lands in interior Alaska are now included in the annual forest inventory, however alternative methods of estimating C stock change will need to be explored as it will take several years to re-measure newly established plots. To that end, research is underway to incorporate all FIA plot information (both annual and periodic data) and the dense time series of remotely sensed data in a design-based, model-assisted format for estimating greenhouse gas emissions and removals as well as change detection and attribution across the entire reporting period and all managed forest land in the United States. Leveraging this auxiliary information will aid not only the interior Alaska effort but the entire inventory system. In addition to fully inventorying all managed forest land in the United States, the more intensive sampling of fine woody debris, litter, and SOC on a subset of FIA plots continues and will substantially improve resolution of C pools (i.e., greater sample intensity; Westfall et al. 2013) as this information becomes available (Woodall et al. 2011b). Increased sample intensity of some C pools and using annualized sampling data as it becomes available for those states currently not reporting are planned for future submissions. The FIA sampling frame extends beyond the forest land use category (e.g., woodlands and urban areas) with inventory-relevant information for these lands which will likely become increasingly available in coming years.

Box 6-5: Preliminary Estimates of Historical Carbon Stock Change and Methane Emissions from Managed Land in Alaska (Represents Mean for Years 2000 to 2009)

Starting in the 1990s, a forest inventory of south central and southeastern coastal (SCSE) Alaska was initiated following the same approach applied in the conterminous United States. These data have been used to compile Forest Land estimates for SCSE Alaska in the Inventory since 2008. However, there still remain vast expanses of Alaska that are in the U.S. managed land base (See Section 6.1) where forest inventories have only recently been established and thus are not included as part of the greenhouse gas flux reporting in this Inventory. In addition, this Inventory does not report on Grasslands in Alaska due to lack of land use and management data. Recognizing the need to report on these emissions and removals, efforts have been initiated to apply a combination of approaches that will eventually lead to complete reporting for all managed land in Alaska. The most promising near-term option for Forest Lands that would meet the minimum UNFCCC reporting requirements is application of the IPCC Tier 1 Gain-Loss Method. Work is also underway to utilize forest inventory plots in combination with remote sensing to estimate C stock changes. This work was initiated as a pilot study and has now moved fully operational with the annual forest inventory in interior Alaska underway. Full implementation of either of these approaches for reporting in the Inventory is several years in the future.

In order to provide some insight into the greenhouse gas flux in Alaska, preliminary C stock change and CH_4 emissions for Alaska have been developed using data from a recently completed USGS effort overlaid on the Alaskan managed land base to provide a preliminary assessment of the mean historical anthropogenic greenhouse gas flux between 2000 and 2009.

The assessment by the USGS, in collaboration with USDA Forest Service and the University of Alaska in Fairbanks, estimated Alaska C stock changes and CH_4 emissions using an approach that couples modeling, remote sensing analysis, literature and database review (Zhu and McGuire, eds. 2016). Annual variation of soil and vegetation C stocks and associated CO_2 and CH_4 fluxes, in both upland and wetland ecosystems in Alaska, were analyzed from 1950 to 2009, using this USGS modeling framework.

Results of the assessment include C stocks and fluxes from vegetation and soil organic C pools, and CH_4 fluxes. Vegetation C pools included aboveground and belowground biomass. The soil C pool included dead woody debris and C stored in organic and mineral horizons. Carbon dioxide fluxes from vegetation net primary productivity, soil heterotrophic respiration, wildfire emissions and harvest were estimated. Methane fluxes included biogenic and pyrogenic sources. The results of this USGS analysis (i.e., mean values for 2000 to 2009 time period) overlaid on the Alaskan managed land base are presented in Table 6-15.

Table 6-15: Mean C Stocks, CO_2 and CH_4 Fluxes in Alaska between 2000 and 2009

Land Use: C Pool	Area (1,000 ha)[a]	C stock (MMT C)	CO_2 Flux (Change in C stocks) (MMT CO_2 Eq./Year)[b]	CH_4 Flux (MMT CO_2 Eq./Year)
Forest Land	**39,917**	**15,226**	**44.86**	**1.675**
Aboveground Biomass	-	2,130	4.03	-
Belowground Biomass	-	532		-
Soil[c]	-	12,563	40.83	
Grassland[d]	**34,844**	**18,856**	**(30.60)**	**0.102**
Aboveground Vegetation	-	315	(5.83)	-
Belowground Vegetation	-	178		-
Soil[c]	-	18,363	(24.77)	-
Wetland	**12,346**	**3,927**	**17.52**	**23.170**
Aboveground Vegetation	-	264	1.12	-
Belowground Vegetation	-	176		-
Soil[c]	-	3,487	16.41	-
Total	**87,107**	**38,008**	**31.80**	**24.947**

[a] The USGS assessment did not include the Aleutian Islands, Saint Lawrence Island, glacier, bare ground or urban areas, therefore the area data does not match up precisely with the Land Representation analysis in this Inventory (see Section 6.1 for more details).

[b] This assessment considers carbon exported out of the ecosystem from harvesting as a loss, it does not include the contribution to the harvested wood products pool.

[c] Soil pool includes dead woody debris and C stored in organic and mineral horizons.

[d] Grassland also includes heath and shrubland.

Note: Parentheses indicate net sequestration.

Non-CO_2 Emissions from Forest Fires

Emissions of non-CO_2 gases from forest fires were estimated using U.S.-specific data for annual area of forest burned and potential fuel availability as well as the default IPCC (2006) emissions and combustion factors applied to the IPCC methodology. In 2016, emissions from this source were estimated to be 18.5 MMT CO_2 Eq. of CH_4 and 12.2 MMT CO_2 Eq. of N_2O (Table 6-16; kt units provided in Table 6-17). The estimates of non-CO_2 emissions from forest fires include wildfires and prescribed fires in the conterminous 48 states and all managed forest land in Alaska.

Table 6-16: Non-CO_2 Emissions from Forest Fires (MMT CO_2 Eq.)[a]

Gas	1990	2005	2012	2013	2014	2015	2016[b]
CH_4	3.2	9.4	10.8	7.2	7.2	18.5	18.5

N_2O	2.1	6.2	7.1	4.8	4.7	12.2	12.2
Total	**5.3**	**15.6**	**17.9**	**11.9**	**11.9**	**30.7**	**30.7**

[a] These estimates include Non-CO_2 Emissions from Forest Fires on *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.

[b] The data for 2016 were unavailable when these estimates were developed, therefore 2015, the most recent available estimate, is applied to 2016.

Table 6-17: Non-CO_2 Emissions from Forest Fires (kt)[a]

Gas	1990	2005	2012	2013	2014	2015	2016[b]
CH_4	127	377	433	286	289	740	740
N_2O	7	21	24	16	16	41	41
CO	2,880	8,484	9,804	6,624	6,595	16,752	16,752
NO_x	81	239	276	185	185	474	474

[a] These estimates include Non-CO_2 Emissions from Forest Fires on *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.

[b] The data for 2016 were unavailable when these estimates were summarized, therefore 2015, the most recent available estimate, is applied to 2016.

Methodology and Data Sources

Non-CO_2 emissions from forest fires—primarily CH_4 and N_2O emissions—were calculated following IPCC (2006) methodology, which included a combination of U.S. specific data on area burned and potential fuel available for combustion along with IPCC default combustion and emission factors. The estimates were calculated according to Equation 2.27 of IPCC (2006, Volume 4, Chapter 2), which is:

$$\text{Emissions} = \text{Area burned} \times \text{Fuel available} \times \text{Combustion factor} \times \text{Emission factor} \times 10^{-3}$$

where area burned data are based on Monitoring Trends in Burn Severity (MTBS) data summaries (MTBS 2015), fuel estimates are based on current C density estimates obtained from the latest FIA data for each state, and combustion and emission factors are from IPCC (2006, Volume 4, Chapter 2). See Annex 3.13 for further details.

Uncertainty and Time-Series Consistency

In order to quantify the uncertainties for non-CO_2 emissions from wildfires and prescribed burns, a Monte Carlo (IPCC Approach 2) sampling approach was employed to propagate uncertainty based on the model and data applied for U.S. forest land. See IPCC (2006) and Annex 3.13 for the quantities and assumptions employed to define and propagate uncertainty. The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 6-18.

Table 6-18: Quantitative Uncertainty Estimates of Non-CO_2 Emissions from Forest Fires (MMT CO_2 Eq. and Percent)[a]

Source	Gas	2016 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[b] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Non-CO_2 Emissions from Forest Fires	CH_4	18.5	12.2	42.1	-34%	127%
Non-CO_2 Emissions from Forest Fires	N_2O	12.2	4.6	26.9	-62%	120%

[a] These estimates include Non-CO_2 Emissions from Forest Fires on *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.

[b] Range of flux estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2016. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

Tier 1 and Tier 2 QA/QC activities were conducted consistent with the U.S. QA/QC plan. Source-specific quality control measures for estimating non-CO_2 emissions from forest fires included checking input data, documentation, and calculations to ensure data were properly handled through the inventory process. Further, the set of fire emissions estimates using MODIS imagery and post-fire observations developed for Alaska by Veraverbeke et al. (2015) (see Annex 3.13) were compared to the estimates of CO_2 and C emissions from forest fires in Alaska (Table 6-13 and Annex 3.13). These alternate sources of data for annual areas burned and possible fuel availability in Alaska were found to be similar to the data used here. The QA/QC procedures did not reveal any inaccuracies or incorrect input values.

Recalculations Discussion

The methods used in the 1990 through 2016 Inventory to compile estimates of non-CO_2 emissions from forest fires are consistent with those used in the 1990 through 2015 Inventory. New data became available for 2015 and were incorporated in the time series using the same methods as the 1990 through 2015 Inventory. The new data resulted in an increase in both CH_4 and N_2O emissions in 2015.

Planned Improvements

Possible future improvements within the context of this same IPCC (2006) methodology are most likely to involve greater specificity by fire or groups of fires and less reliance on wide regional values or IPCC defaults. Spatially relating potential fuel availability to more localized forest structure is the best example of this. An additional improvement would be the use of combustion factors that are more locally appropriate for the type, location, and intensity of fire, which are currently unused information provided with the MTBS data summaries. All planned improvements depend on future availability of appropriate U.S.-specific data.

N_2O Emissions from N Additions to Forest Soils

Of the synthetic nitrogen (N) fertilizers applied to soils in the United States, no more than one percent is applied to forest soils. Application rates are similar to those occurring on cropland soils, but in any given year, only a small proportion of total forested land receives N fertilizer. This is because forests are typically fertilized only twice during their approximately 40-year growth cycle (once at planting and once midway through their life cycle). While the rate of N fertilizer application for the area of forests that receives N fertilizer in any given year is relatively high, the annual application rate is quite low over the entire forest land area.

N additions to soils result in direct and indirect N_2O emissions. Direct emissions occur on-site due to the N additions. Indirect emissions result from fertilizer N that is transformed and transported to another location in a form other than N_2O (ammonia [NH_3] and nitrogen oxide [NO_x] volatilization, nitrate [NO_3] leaching and runoff), and later converted into N_2O at the off-site location. The indirect emissions are assigned to forest land because the management activity leading to the emissions occurred in forest land.

Direct soil N_2O emissions from *Forest Land Remaining Forest Land* and *Land Converted to Forest Land* in 2016 were 0.3 MMT CO_2 Eq. (1 kt), and the indirect emissions were 0.1 MMT CO_2 Eq. (0.4 kt). Total emissions for 2016 were 0.5 MMT CO_2 Eq. (2 kt) and have increased by 455 percent from 1990 to 2016. Total forest soil N_2O emissions are summarized in Table 6-19.

Table 6-19: N_2O Fluxes from Soils in *Forest Land Remaining Forest Land* and *Land Converted to Forest Land* (MMT CO_2 Eq. and kt N_2O)

	1990		2005		2012	2013	2014	2015	2016
Direct N_2O Fluxes from Soils									
MMT CO_2 Eq.	0.1		0.3		0.3	0.3	0.3	0.3	0.3
kt N_2O	+		1		1	1	1	1	1
Indirect N_2O Fluxes from Soils									
MMT CO_2 Eq.	0.0		0.1		0.1	0.1	0.1	0.1	0.1
kt N_2O	+		+		+	+	+	+	+

Total							
MMT CO_2 Eq.	**0.1**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**
kt N_2O	**+**	**2**	**2**	**2**	**2**	**2**	**2**

+ Does not exceed 0.05 MMT CO_2 Eq. or 0.5 kt.
Note: Totals may not sum due to independent rounding.

Methodology and Data Sources

The IPCC Tier 1 approach is used to estimate N_2O from soils within *Forest Land Remaining Forest Land*. According to U.S. Forest Service statistics for 1996 (USDA Forest Service 2001), approximately 75 percent of trees planted are for timber, and about 60 percent of national total harvested forest area is in the southeastern United States. Although southeastern pine plantations represent the majority of fertilized forests in the United States, this Inventory also accounted for N fertilizer application to commercial Douglas-fir stands in western Oregon and Washington. For the Southeast, estimates of direct N_2O emissions from fertilizer applications to forests are based on the area of pine plantations receiving fertilizer in the southeastern United States and estimated application rates (Albaugh et al. 2007; Fox et al. 2007). Not accounting for fertilizer applied to non-pine plantations is justified because fertilization is routine for pine forests but rare for hardwoods (Binkley et al. 1995). For each year, the area of pine receiving N fertilizer is multiplied by the weighted average of the reported range of N fertilization rates (121 lbs. N per acre). Area data for pine plantations receiving fertilizer in the Southeast are not available for 2005 through 2016, so data from 2004 are used for these years. For commercial forests in Oregon and Washington, only fertilizer applied to Douglas-fir is addressed in the inventory because the vast majority (approximately 95 percent) of the total fertilizer applied to forests in this region is applied to Douglas-fir (Briggs 2007). Estimates of total Douglas-fir area and the portion of fertilized area are multiplied to obtain annual area estimates of fertilized Douglas-fir stands. Similar to the Southeast, data are not available for 2005 through 2016, so data from 2004 are used for these years. The annual area estimates are multiplied by the typical rate used in this region (200 lbs. N per acre) to estimate total N applied (Briggs 2007), and the total N applied to forests is multiplied by the IPCC (2006) default emission factor of one percent to estimate direct N_2O emissions.

For indirect emissions, the volatilization and leaching/runoff N fractions for forest land are calculated using the IPCC default factors of 10 percent and 30 percent, respectively. The amount of N volatilized is multiplied by the IPCC default factor of one percent for the portion of volatilized N that is converted to N_2O off-site. The amount of N leached/runoff is multiplied by the IPCC default factor of 0.075 percent for the portion of leached/runoff N that is converted to N_2O off-site The resulting estimates are summed to obtain total indirect emissions.

Uncertainty and Time-Series Consistency

The amount of N_2O emitted from forests depends not only on N inputs and fertilized area, but also on a large number of variables, including organic C availability, oxygen gas partial pressure, soil moisture content, pH, temperature, and tree planting/harvesting cycles. The effect of the combined interaction of these variables on N_2O flux is complex and highly uncertain. IPCC (2006) does not incorporate any of these variables into the default methodology, except variation in estimated fertilizer application rates and estimated areas of forested land receiving N fertilizer. All forest soils are treated equivalently under this methodology. Furthermore, only synthetic N fertilizers are captured, so applications of organic N fertilizers are not estimated. However, the total quantity of organic N inputs to soils is included in Section 5.4 Agricultural Soil Management and Section 6.9 Settlements Remaining Settlements.

Uncertainties exist in the fertilization rates, annual area of forest lands receiving fertilizer, and the emission factors. Fertilization rates are assigned a default level[28] of uncertainty at ±50 percent, and area receiving fertilizer is assigned a ±20 percent according to expert knowledge (Binkley 2004). The uncertainty ranges around the 2004 activity data and emission factor input variables are directly applied to the 2016 emission estimates. IPCC (2006) provided estimates for the uncertainty associated with direct and indirect N_2O emission factor for synthetic N fertilizer application to soils.

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[28] Uncertainty is unknown for the fertilization rates so a conservative value of ±50 percent is used in the analysis.

Uncertainty is quantified using simple error propagation methods (IPCC 2006). The results of the quantitative uncertainty analysis are summarized in Table 6-20. Direct N_2O fluxes from soils in 2016 are estimated to be between 0.1 and 1.1 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 59 percent below and 211 percent above the 2016 emission estimate of 0.3 MMT CO_2 Eq. Indirect N_2O emissions in 2016 are 0.1 MMT CO_2 Eq. and have a range are between 0.02 and 0.4 MMT CO_2 Eq., which is 86 percent below to 238 percent above the 2016 emission estimate.

Table 6-20: Quantitative Uncertainty Estimates of N_2O Fluxes from Soils in *Forest Land Remaining Forest Land* and *Land Converted to Forest Land* (MMT CO_2 Eq. and Percent)

Source	Gas	2016 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate (MMT CO_2 Eq.)		(%)	
Forest Land Remaining Forest Land			**Lower Bound**	**Upper Bound**	**Lower Bound**	**Upper Bound**
Direct N_2O Fluxes from Soils	N_2O	0.3	0.1	1.1	-59%	+211%
Indirect N_2O Fluxes from Soils	N_2O	0.1	+	0.4	-86%	+238%

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Due to rounding the upper and lower bounds may equal the emission estimate in the above table.

The same methods are applied to the entire time series to ensure time-series consistency from 1990 through 2016, and no recalculations have been done from the previous Inventory. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

The spreadsheet tab containing fertilizer applied to forests and calculations for N_2O and uncertainty ranges are checked and verified.

Planned Improvements

Additional data will be compiled to update estimates of forest areas receiving N fertilizer using surrogate data in the next Inventory. Another improvement is to further disaggregate emissions by state for southeastern pine plantations and northwestern Douglas-fir forests to estimate soil N_2O emission. This improvement is contingent on the availability of state-level N fertilization data for forest land.

CO_2, CH_4, and N_2O Emissions from Drained Organic Soils

Drained organic soils on forest land are identified separately from other forest soils largely because mineralization of the exposed or partially dried organic material results in continuous CO_2 and N_2O emissions (IPCC 2006). In addition, the *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* (IPCC 2014) calls for estimating CH_4 emissions from these drained soils and the ditch networks used to drain them.

Organic soils are identified on the basis of thickness of organic horizon and percent organic matter. All organic soils are assumed to have originally been wet, and drained organic soils are further characterized by drainage or the process of artificially lowering the soil water table, which exposes the organic material to drying and the associated emissions described in this section. The land base considered here is drained inland organic soils that are coincident with forest area as identified by the forest inventory of the USDA Forest Service (USDA Forest Service 2016).

The estimated area of drained organic soils on forest land is 70,849 ha and did not change over the time series based on the data used to compile the estimates in the current Inventory. These estimates are based on permanent plot locations of the forest inventory (USDA Forest Service 2016) coincident with mapped organic soil locations (STATSGO2 2016), which identifies forest land on organic soils. Forest sites that are drained are not explicitly identified in the data, but for this estimate, planted forest stands on sites identified as mesic or xeric (which are identified in USDA Forest Service 2016) are labeled "drained organic soil" sites.

Land use, region, and climate are broad determinants of emissions as are more site specific factors such as nutrient status, drainage level, exposure, or disturbance. Current data are limited in spatial precision and thus lack site specific details. At the same time, corresponding emissions factor data specific to U.S. forests are similarly lacking. Tier 1 estimates are provided here following IPCC (2014). Total annual emissions on forest land with drained organic soils in 2016 are estimated as 0.9 MMT CO_2 Eq. per year (Table 6-21).

The Tier 1 methodology provides methods to estimate C emission as CO_2 from three pathways: direct emissions primarily from mineralization; indirect, or off-site, emissions associated with dissolved organic carbon releasing CO_2 from drainage waters; and emissions from (peat) fires on organic soils. Data about forest fires specifically located on drained organic soils are not currently available; as a result, no corresponding estimate is provided here. Non-CO_2 emissions provided here include CH_4 and N_2O. Methane emissions generally associated with anoxic conditions do occur from the drained land surface but the majority of these emissions originate from ditches constructed to facilitate drainage at these sites. Emission of N_2O can be significant from these drained organic soils in contrast to the very low emissions from wet organic soils.

Table 6-21: Estimated CO_2 and Non-CO_2 Emissions on Drained Organic Forest Soils[a] (MMT CO_2 Eq.)

Source	1990	2005	2012	2013	2014	2015	2016
CO_2, Direct	0.7	0.7	0.7	0.7	0.7	0.7	0.7
CO_2, Dissolved Organic C	0.1	0.1	0.1	0.1	0.1	0.1	0.1
CH_4	+	+	+	+	+	+	+
N_2O	0.1	0.1	0.1	0.1	0. 1	0.1	0.1
Total	**0.9**	**0.9**	**0.9**	**0.9**	**0.9**	**0.9**	**0.9**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] This table includes estimates from *Forest Land Remaining Forest Land* and *Land Converted to Forest Land.*

Table 6-22: Estimated C (MMT C) and Non-CO_2 (kt) Emissions on Drained Organic Forest Soils[a]

Source	1990	2005	2012	2013	2014	2015	2016
C, Direct	0.2	0.2	0.2	0.2	0.2	0.2	0.2
C, Dissolved Organic C	+	+	+	+	+	+	+
CH_4	**1**	**1**	**1**	**1**	**1**	**1**	**1**
N_2O	**+**	**+**	**+**	**+**	**+**	**+**	**+**

+ Does not exceed 0.05 MMT C or 0.5 kt.

[a] This table includes estimates from *Forest Land Remaining Forest Land* and *Land Converted to Forest Land.*

Methodology and Data Sources

The Tier 1 methods for estimating emissions from drained inland organic soils on forest lands follow IPCC (2006), with extensive updates and additional material presented in the *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* (IPCC 2014). With the exception of quantifying area of forest on drained organic soils, which is user-supplied, all quantities necessary for Tier 1 estimates are provided in Chapter 2, Drained Inland Organic Soils of IPCC (2014).

Estimated area of drained organic soils on forest land is 70,849 ha based on analysis of the permanent forest inventory of the USDA Forest Service and did not change over the time series (data downloaded 14 June 2016). The most recent plot data per state within the inventories were used in a spatial overlay with the STATSGO2 (2016) data, and forest plots coincident with the soil order histosol were selected as having organic soils. Information specific to identifying "drained organic" are not in the inventory data so an indirect approach was employed here. Specifically, artificially regenerated forest stands (inventory field STDORGCD=1) on mesic or xeric sites (inventory field $11 \leq \mathrm{PHYSCLCD} \leq 29$) are labeled "drained organic soil" sites. From this selection, forest area and sampling error for forest on drained organic sites are based on the population estimates developed within the inventory data for each state (USDA Forest Service 2016). Eight states, all temperate forests, were identified as having drained organic soils (Table 6-23).

Table 6-23: States identified as having Drained Organic Soils, Area of Forest on Drained Organic Soils, and Sampling Error

State	Forest on Drained Organic Soil (1,000 ha)	Sampling Error (68.3% as ± Percentage of Estimate)
Florida	2.4	79
Georgia	3.7	71
Michigan	18.7	34
Minnesota	30.2	19
North Carolina	1.3	99
Virginia	2.3	102
Washington	2.1	101
Wisconsin	10.1	30
Total	**70.8**	**14**

The Tier 1 methodology provides methods to estimate emissions for three pathways of C emission as CO_2 (Table 6-21 and Table 6-22). Note that subsequent mention of equations and tables in the remainder of this section refer to Chapter 2 of IPCC 2014. The first pathway–direct CO_2 emissions–is calculated according to Equation 2.3 and Table 2.1 as the product of forest area and emission factor for temperate drained forest land. The second pathway–indirect, or off-site, emissions–is associated with dissolved organic carbon releasing CO_2 from drainage waters according to Equation 2.4 and Table 2.2, which represent a default composite of the three pathways for this flux: (1) the flux of dissolved organic carbon (DOC) from natural (undrained) organic soil; (2) the proportional increase in DOC flux from drained organic soils relative to undrained sites; and (3) the conversion factor for the part of DOC converted to CO_2 after export from a site. The third pathway–emissions from (peat) fires on organic soils–assumes that the drained organic soils burn in a fire but not any wet organic soils. However, EPA currently does not include emissions for this pathway because EPA does not have the combined fire and drained organic soils information; this may become available in the future with additional analysis.

Non-CO_2 emissions, according to the Tier 1 method, include methane (CH_4), nitrous oxide (N_2O), and carbon monoxide (CO) (Table 6-16). Emissions associated with peat fires include factors for CH_4 and CO in addition to CO_2, but fire estimates are assumed to be zero for the current Inventory, as discussed above. Methane emissions generally associated with anoxic conditions do occur from the drained land surface but the majority of these emissions originate from ditches constructed to facilitate drainage at these sites. From this, two separate emission factors are used, one for emissions from the area of drained soils and a second for emissions from drainage ditch waterways. Calculations are according to Equation 2.6 and Tables 2.3 and 2.4, which includes the default fraction of the total area of drained organic soil which is occupied by ditches. Emissions of nitrous oxide can be significant from these drained soils in contrast to the very low emissions from wet organic soils. Calculations are according to Equation 2.7 and Table 2.5, which provide the estimate as kg N per year.

Uncertainty and Time-Series Consistency

Uncertainties are based on the sampling error associated with forest area and the uncertainties provided in the Chapter 2 (IPCC 2014) emissions factors (Table 6-24). The estimates and resulting quantities representing uncertainty are based on the Approach 1–error propagation. However, probabilistic sampling of the distributions defined for each emission factor produced a histogram result that contained a mean and 95 percent confidence interval. The primary reason for this approach was to develop a numerical representation of uncertainty with the potential for combining with other forest components. The total emissions in 2016 from drained organic soils on *Forest Land Remaining Forest Land* and *Land Converted to Forest Land* were estimated to be between 0.5 and 1.2 MMT CO_2 Eq. around a central estimate of 0.9 MMT CO_2 Eq. at a 95 percent confidence level.

Table 6-24: Quantitative Uncertainty Estimates for Annual CO_2 and Non-CO_2 Emissions on Drained Organic Forest Soils (MMT CO_2 Eq. and Percent)[a]

Source	2016 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate (MMT CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
CO_2, direct	0.7	0.4	0.9	-39%	39%
CO_2, dissolved organic C	0.1	+	0.1	-56%	56%
CH_4	+	+	+	-76%	76%
N_2O	0.1	+	0.2	-124%	124%
Total	**0.9**	**0.5**	**1.2**	**-38%**	**38%**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Range of flux estimates predicted through a combination of sample-based and IPCC defaults for a 95 percent confidence interval, IPCC Approach 1.

QA/QC and Verification

IPCC (2014) guidance cautions of a possibility of double counting some of these emissions. Specifically, the off-site emissions of dissolved organic C from drainage waters may be double counted if soil C stock and change is based on sampling and this C is captured in that sampling. Double counting in this case is unlikely since plots identified as drained were treated separately in this chapter. Additionally, some of the non-CO_2 emissions may be included in either the Wetlands or sections on N_2O emissions from managed soils. These paths to double counting emissions are unlikely here because these issues are taken into consideration when developing the estimates and this chapter is the only section directly including such emissions on forest land.

Planned Improvements

Additional data will be compiled to update estimates of forest areas on drained organic soils as new reports are made available and new geospatial products become available.

6.3 Land Converted to Forest Land (CRF Category 4A2)

The C stock change estimates for *Land Converted to Forest Land* that are provided in this Inventory include all forest land in an inventory year that had been in another land use(s) during the previous 20 years[29] (USDA NRCS 2012). For example, cropland or grassland converted to forest land during the past 20 years would be reported in this category. Converted lands are in this category for 20 years as recommended in the *2006 IPCC Guidelines* (IPCC 2006), after which they are classified as *Forest Land Remaining Forest Land*. Estimates of C stock changes from all pools (i.e., aboveground and belowground biomass, dead wood, litter and soils), as recommended by IPCC (2006), are included in the *Land Converted to Forest Land* category of this Inventory.

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[29] The 2009 USDA National Resources Inventory (NRI) land-use survey points were classified according to land-use history records starting in 1982 when the NRI survey began. Consequently, the classifications from 1990 to 2001 were based on less than 20 years. Furthermore, the FIA data used to compile estimates of carbon sequestration in this section are based on 5- to 10-yr remeasurements so the exact conversion period was limited to the remeasured data over the time series.

Area of Land Converted to Forest in the United States

Land conversion to and from forests has occurred regularly throughout U.S. history. The 1970s and 1980s saw a resurgence of federally-sponsored forest management programs (e.g., the Forestry Incentive Program) and soil conservation programs (e.g., the Conservation Reserve Program), which have focused on tree planting, improving timber management activities, combating soil erosion, and converting marginal cropland to forests. Recent analyses suggest that net accumulation of forest area continues in areas of the United States, in particular the northeastern United States (Woodall et al. 2015b). Specifically, the annual conversion of land from other land-use categories (i.e., Cropland, Grassland, Wetlands, Settlements, and Other Lands) to Forest Land resulted in a fairly continuous net annual accretion of Forest Land area from 1990 to the present at an average rate of 1 million ha year^{-1}.

Since 1990, the conversion of grassland to forest land resulted in the largest source of C sequestration, accounting for approximately 67 percent of the sequestration in the *Land Converted to Forest Land* category in 2016. However, estimated gains have decreased over the time series due to less Grassland conversion into the Forest Land category in recent years (see Table 6-25). The net flux of C from all forest pool stock changes in 2016 was -75.0 MMT CO_2 Eq. (-20.5 MMT C) (Table 6-25 and Table 6-26). Note that soil C in this Inventory has historically been reported to a depth of 100 cm in the *Forest Land Remaining Forest Land* category (Domke et al. 2017) while other land-use categories report soil C to a depth of 20 or 30 cm. To ensure consistency in the *Land Converted to Forest Land* category where C stock transfers occur between land-use categories, all soil C estimates are based on methods from Ogle et al. (2003, 2006) and IPCC (2006), which are also used in Cropland, Grasslands and Settlements land use categories of this Inventory.

Table 6-25: Net CO_2 Flux from Forest C Pools in *Land Converted to Forest Land* by Land Use Change Category (MMT CO_2 Eq.)

Land Use/Carbon Pool	1990	2005	2012	2013	2014	2015	2016
Cropland Converted to Forest Land	**(16.0)**	**(13.8)**	**(11.8)**	**(11.8)**	**(11.8)**	**(11.8)**	**(11.8)**
Aboveground Biomass	(6.4)	(5.5)	(4.8)	(4.8)	(4.8)	(4.8)	(4.8)
Belowground Biomass	(0.5)	(0.4)	(0.4)	(0.4)	(0.4)	(0.4)	(0.4)
Dead Wood	(3.3)	(2.8)	(2.5)	(2.5)	(2.5)	(2.5)	(2.5)
Litter	(5.8)	(5.0)	(4.1)	(4.1)	(4.1)	(4.1)	(4.1)
Mineral Soil	(+)	(0.1)	+	+	+	+	+
Grassland Converted to Forest Land	**(63.6)**	**(51.2)**	**(50.0)**	**(50.1)**	**(50.1)**	**(50.1)**	**(50.1)**
Aboveground Biomass	(31.5)	(25.0)	(25.5)	(25.5)	(25.5)	(25.5)	(25.5)
Belowground Biomass	7.6	6.3	5.9	5.9	5.9	5.9	5.9
Dead Wood	(14.6)	(11.9)	(11.4)	(11.4)	(11.4)	(11.4)	(11.4)
Litter	(25.0)	(20.3)	(19.1)	(19.1)	(19.1)	(19.1)	(19.1)
Mineral Soil	(0.1)	(0.2)	0.1	0.1	+	+	+
Other Land Converted to Forest Land	**(9.0)**	**(12.5)**	**(9.1)**	**(9.1)**	**(9.1)**	**(9.1)**	**(9.1)**
Aboveground Biomass	(3.8)	(5.4)	(4.2)	(4.2)	(4.2)	(4.2)	(4.2)
Belowground Biomass	(0.7)	(1.0)	(0.8)	(0.8)	(0.8)	(0.8)	(0.8)
Dead Wood	(1.4)	(2.0)	(1.5)	(1.5)	(1.5)	(1.5)	(1.5)
Litter	(3.0)	(4.2)	(2.7)	(2.7)	(2.7)	(2.7)	(2.7)
Mineral Soil	(+)	(+)	+	(+)	(+)	(+)	(+)
Settlements Converted to Forest Land	**(1.3)**	**(1.5)**	**(1.8)**	**(1.8)**	**(1.8)**	**(1.8)**	**(1.8)**
Aboveground Biomass	(0.6)	(0.7)	(0.8)	(0.8)	(0.8)	(0.8)	(0.8)
Belowground Biomass	(0.1)	(0.1)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)
Dead Wood	(0.2)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)
Litter	(0.4)	(0.5)	(0.5)	(0.5)	(0.5)	(0.5)	(0.5)
Mineral Soil	(+)	(+)	+	+	+	+	+
Wetlands Converted to Forest Land	**(2.2)**	**(2.5)**	**(2.2)**	**(2.2)**	**(2.2)**	**(2.2)**	**(2.2)**
Aboveground Biomass	(1.0)	(1.1)	(1.0)	(1.0)	(1.0)	(1.0)	(1.0)
Belowground Biomass	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)
Dead Wood	(0.3)	(0.4)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)
Litter	(0.7)	(0.8)	(0.7)	(0.7)	(0.7)	(0.7)	(0.7)
Mineral Soil	(+)	(+)	+	+	+	+	+

Total Aboveground Biomass Flux	**(43.3)**	**(37.7)**	**(36.3)**	**(36.3)**	**(36.3)**	**(36.3)**	**(36.3)**
Total Belowground Biomass Flux	**6.1**	**4.5**	**4.4**	**4.4**	**4.4**	**4.4**	**4.4**
Total Dead Wood Flux	**(19.8)**	**(17.3)**	**(15.9)**	**(15.9)**	**(15.9)**	**(15.9)**	**(15.9)**
Total Litter Flux	**(34.8)**	**(30.8)**	**(27.2)**	**(27.2)**	**(27.2)**	**(27.2)**	**(27.2)**
Total Mineral Soil Flux	**(0.2)**	**(0.4)**	**0.1**	**0.1**	**0.1**	**+**	**+**
Total Flux	**(92.0)**	**(81.6)**	**(74.9)**	**(74.9)**	**(75.0)**	**(75.0)**	**(75.0)**

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Table 6-26: Net C Flux from Forest C Pools in *Land Converted to Forest Land* by Land Use Change Category (MMT C)

Land Use/Carbon Pool	**1990**	**2005**	**2012**	**2013**	**2014**	**2015**	**2016**
Cropland Converted to Forest Land	**(4.4)**	**(3.8)**	**(3.2)**	**(3.2)**	**(3.2)**	**(3.2)**	**(3.2)**
Aboveground Biomass	(1.7)	(1.5)	(1.3)	(1.3)	(1.3)	(1.3)	(1.3)
Belowground Biomass	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Dead Wood	(0.9)	(0.8)	(0.7)	(0.7)	(0.7)	(0.7)	(0.7)
Litter	(1.6)	(1.4)	(1.1)	(1.1)	(1.1)	(1.1)	(1.1)
Mineral Soil	(+)	(+)	+	+	+	+	+
Grassland Converted to Forest Land	**(17.3)**	**(13.9)**	**(13.6)**	**(13.7)**	**(13.7)**	**(13.7)**	**(13.7)**
Aboveground Biomass	(8.6)	(6.8)	(7.0)	(7.0)	(7.0)	(7.0)	(7.0)
Belowground Biomass	2.1	1.7	1.6	1.6	1.6	1.6	1.6
Dead Wood	(4.0)	(3.2)	(3.1)	(3.1)	(3.1)	(3.1)	(3.1)
Litter	(6.8)	(5.5)	(5.2)	(5.2)	(5.2)	(5.2)	(5.2)
Mineral Soil	(+)	(+)	+	+	+	+	+
Other Land Converted to Forest Land	**(2.4)**	**(3.4)**	**(2.5)**	**(2.5)**	**(2.5)**	**(2.5)**	**(2.5)**
Aboveground Biomass	(1.0)	(1.5)	(1.1)	(1.1)	(1.1)	(1.1)	(1.1)
Belowground Biomass	(0.2)	(0.3)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)
Dead Wood	(0.4)	(0.5)	(0.4)	(0.4)	(0.4)	(0.4)	(0.4)
Litter	(0.8)	(1.1)	(0.7)	(0.7)	(0.7)	(0.7)	(0.7)
Mineral Soil	(+)	(+)	+	(+)	(+)	(+)	(+)
Settlements Converted to Forest Land	**(0.4)**	**(0.4)**	**(0.5)**	**(0.5)**	**(0.5)**	**(0.5)**	**(0.5)**
Aboveground Biomass	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)
Belowground Biomass	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Dead Wood	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Litter	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Mineral Soil	(+)	(+)	+	+	+	+	+
Wetlands Converted to Forest Land	**(0.6)**	**(0.7)**	**(0.6)**	**(0.6)**	**(0.6)**	**(0.6)**	**(0.6)**
Aboveground Biomass	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)
Belowground Biomass	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Dead Wood	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Litter	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)
Mineral Soil	(+)	(+)	+	+	+	+	+
Total Aboveground Biomass Flux	**(11.8)**	**(10.3)**	**(9.9)**	**(9.9)**	**(9.9)**	**(9.9)**	**(9.9)**
Total Belowground Biomass Flux	**1.7**	**1.2**	**1.2**	**1.2**	**1.2**	**1.2**	**1.2**
Total Dead Wood Flux	**(5.4)**	**(4.7)**	**(4.3)**	**(4.3)**	**(4.3)**	**(4.3)**	**(4.3)**
Total Litter Flux	**(9.5)**	**(8.4)**	**(7.4)**	**(7.4)**	**(7.4)**	**(7.4)**	**(7.4)**
Total Mineral Soil Flux	**(+)**	**(0.1)**	**+**	**+**	**+**	**+**	**+**
Total Flux	**(25.1)**	**(22.2)**	**(20.4)**	**(20.4)**	**(20.4)**	**(20.5)**	**(20.5)**

+ Absolute value does not exceed 0.05 MMT C.

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Methodology

The following section includes a description of the methodology used to estimate stock changes in all forest C pools for *Land Converted to Forest Land*. Forest Inventory and Analysis data and IPCC (2006) defaults for reference C stocks were used to compile separate estimates for the five C storage pools. Estimates for Aboveground and

Belowground Biomass, Dead Wood and Litter were based on data collected from the extensive array of permanent, annual forest inventory plots and associated models (e.g., live tree belowground biomass estimates) in the United States (USDA Forest Service 2015b, 2015c). Carbon conversion factors were applied at the disaggregated level of each inventory plot and then appropriately expanded to population estimates. To ensure consistency in the *Land Converted to Forest Land* category where C stock transfers occur between land-use categories, all soil estimates are based on methods from Ogle et al. (2003, 2006) and IPCC (2006).

The approach for estimating carbon stocks and stock changes in the *Land Converted to Forest Land* is consistent with those used in the 1990 through 2015 Inventory and is described in Annex 3.13. Only FIA plots that were used in the 1990 through 2015 Inventory were used in the current Inventory to ensure consistency with the other land use categories and maintain the area estimates reported in the Land Representation, which are consistent with the 1990 through 2015 Inventory area estimates because new area activity data were not compiled for the current Inventory, and 2016 area estimates were assumed to be the same as the 2015 estimates (see Section 6.1 Representation of the U.S. Land Base). Forest Land conditions were observed on FIA plots at time t_0 and at a subsequent time t_1=t_0+s, where s is the time step (time measured in years) and is indexed by discrete (e.g., 5 year) forest age classes. The inventory from t_0 was then projected from t_1 to 2017. This projection approach requires simulating changes in the age-class distribution resulting from forest aging and disturbance events and then applying C density estimates for each age class to obtain population estimates for the nation.

Carbon in Biomass

Live tree C pools include aboveground and belowground (coarse root) biomass of live trees with diameter at breast height (dbh) of at least 2.54 cm at 1.37 m above the forest floor. Separate estimates were made for above and belowground biomass components. If inventory plots included data on individual trees, above- and belowground tree C was based on Woodall et al. (2011a), which is also known as the component ratio method (CRM), and is a function of volume, species, and diameter. An additional component of foliage, which was not explicitly included in Woodall et al. (2011a), was added to each tree following the same CRM method.

Understory vegetation is a minor component of biomass and is defined as all biomass of undergrowth plants in a forest, including woody shrubs and trees less than 2.54 cm dbh. For the current Inventory, it was assumed that 10 percent of total understory C mass is belowground (Smith et al. 2006). Estimates of C density were based on information in Birdsey (1996) and biomass estimates from Jenkins et al. (2003). Understory biomass represented over one percent of C in biomass, but its contribution rarely exceeded 2 percent of the total.

Biomass losses associated with conversion from Grassland and Cropland to Forest Land were assumed to occur in the year of conversion. To account for these losses, IPCC (2006) defaults for aboveground and belowground biomass on Grasslands and aboveground biomass on Croplands were subtracted from sequestration in the year of the conversion. For all other land use (i.e., Other Lands, Settlement, Wetlands) conversions to Forest Land no biomass losses were assumed in the year of the conversion.

Carbon in Dead Organic Matter

Dead organic matter was initially calculated as three separate pools—standing dead trees, downed dead wood, and litter—with C stocks estimated from sample data or from models. The standing dead tree C pool includes aboveground and belowground (coarse root) biomass for trees of at least 12.7 cm dbh. Calculations followed the basic method applied to live trees (Woodall et al. 2011a) with additional modifications to account for decay and structural loss (Domke et al. 2011; Harmon et al. 2011). Downed dead wood estimates are based on measurement of a subset of FIA plots for downed dead wood (Domke et al. 2013; Woodall and Monleon 2008; Woodall et al. 2013). Downed dead wood is defined as pieces of dead wood greater than 7.5 cm diameter, at transect intersection, that are not attached to live or standing dead trees. This includes stumps and roots of harvested trees. To facilitate the downscaling of downed dead wood C estimates from the state-wide population estimates to individual plots, downed dead wood models specific to regions and forest types within each region are used. Litter C is the pool of organic C (also known as duff, humus, and fine woody debris) above the mineral soil and includes woody fragments with diameters of up to 7.5 cm. A subset of FIA plots are measured for litter C. A modeling approach, using litter C measurements from FIA plots (Domke et al. 2016) was used to estimate litter C for every FIA plot used in the estimation framework.

Mineral Soil Carbon Stock Changes

A Tier 2 method is applied to estimate mineral soil C stock changes for *Land Converted to Forest Land* (Ogle et al. 2003, 2006; IPCC 2006). In the current Inventory, a linear regression model with autoregressive moving-average errors was used to estimate the relationship between the surrogate data and the observed 1990 to 2012 data (Brockwell and Davis 2016). Surrogate data are commodity statistics, weather data, or other information that can be used to predict the emissions without compiling a new inventory. This estimate, along with observed surrogate data, is used to predict emissions data for 2013 through 2016 for the Tier 2 method. For this method, land is stratified by climate, soil types, land use, and land management activity, and then assigned reference carbon levels and factors for the forest land and the previous land use. The difference between the stocks is reported as the stock change under the assumption that the change occurs over 20 years. Reference C stocks have been estimated from data in the National Soil Survey Characterization Database (USDA-NRCS 1997), and U.S.-specific stock change factors have been derived from published literature (Ogle et al. 2003, 2006). Land use and land use change patterns are determined from a combination of the Forest Inventory and Analysis Dataset (FIA), the 2012 National Resources Inventory (NRI) (USDA-NRCS 2013), and National Land Cover Dataset (NLCD) (Homer et al. 2007). See Annex 3.12 (Methodology for Estimating N_2O Emissions, CH_4 Emissions and Soil Organic C Stock Changes from Agricultural Soil Management) for more information about this method.

Uncertainty and Time-Series Consistency

A quantitative uncertainty analysis placed bounds on the flux estimates for *Land Converted to Forest Land* through a combination of sample-based and model-based approaches to uncertainty for forest ecosystem CO_2 Eq. flux (IPCC Approach 1). Uncertainty estimates for forest pool C stock changes were developed using the same methodologies as described in the *Forest Land Remaining Forest Land* section for aboveground and belowground biomass, dead wood, and litter. The exception was when IPCC default estimates were used for reference C stocks in certain conversion categories (i.e., *Cropland Converted to Forest Land* and *Grassland Converted to Forest Land*). In those cases, the uncertainties associated with the IPCC (2006) defaults were included in the uncertainty calculations. IPCC Approach 2 was used for mineral soils and is described in the *Cropland Remaining Cropland* section.

Uncertainty estimates are presented in Table 6-27 for each land conversion category and C pool. Uncertainty estimates were obtained using a combination of sample-based and model-based approaches for all non-soil C pools (IPCC Approach 1) and a Monte Carlo approach (IPCC Approach 2) was used for mineral soil. Uncertainty estimates were combined using the error propagation model (IPCC Approach 1). The combined uncertainty for all C stocks in *Land Converted to Forest Land* ranged from 10 percent below to 11 percent above the 2016 C stock change estimate of -75.0 MMT CO_2 Eq.

Table 6-27: Quantitative Uncertainty Estimates for Forest C Pool Stock Changes (MMT CO_2 Eq. per Year) in 2016 from *Land Converted to Forest Land* by Land Use Change

Land Use/Carbon Pool	2016 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Range[a]			
		(MMT CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Cropland Converted to Forest Land	**(11.8)**	**(13.5)**	**(8.5)**	**-14%**	**28%**
Aboveground Biomass	(4.8)	(6.4)	(3.3)	-32%	32%
Belowground Biomass	(0.4)	(0.6)	(0.1)	-76%	76%
Dead Wood	(2.5)	(2.9)	(2.0)	-19%	19%
Litter	(4.1)	(4.6)	(3.7)	-12%	12%
Mineral Soils	+	(0.1)	0.1	-1,136%	1,136%
Grassland Converted to Forest Land	**(50.1)**	**(57.6)**	**(45.9)**	**-15%**	**8%**
Aboveground Biomass	(25.5)	(31.8)	(19.2)	-25%	25%
Belowground Biomass	5.9	4.0	7.8	-31%	31%
Dead Wood	(11.4)	(14.0)	(8.8)	-23%	23%
Litter	(19.1)	(21.7)	(16.6)	-14%	14%
Mineral Soils	+	(0.2)	0.3	-2,684%	2,684%
Other Lands Converted to Forest Land	**(9.1)**	**(10.2)**	**(8.0)**	**-12%**	**12%**
Aboveground Biomass	(4.2)	(5.1)	(3.2)	-23%	23%
Belowground Biomass	(0.8)	(1.0)	(0.6)	-25%	25%

Dead Wood	(1.5)	(1.8)	(1.1)	-24%	24%
Litter	(2.7)	(3.1)	(2.4)	-13%	13%
Mineral Soils	(+)	(0.1)	+	-370%	370%
Settlements Converted to Forest Land	**(1.8)**	**(2.0)**	**(1.5)**	**-13%**	**13%**
Aboveground Biomass	(0.8)	(1.0)	(0.6)	-25%	25%
Belowground Biomass	(0.2)	(0.2)	(0.1)	-27%	27%
Dead Wood	(0.3)	(0.3)	(0.2)	-24%	24%
Litter	(0.5)	(0.6)	(0.4)	-14%	14%
Mineral Soils	+	(+)	+	-800%	800%
Wetlands Converted to Forest Land	**(2.2)**	**(2.5)**	**(2.0)**	**-11%**	**11%**
Aboveground Biomass	(1.0)	(1.2)	(0.8)	-20%	20%
Belowground Biomass	(0.2)	(0.2)	(0.1)	-22%	22%
Dead Wood	(0.3)	(0.4)	(0.3)	-27%	27%
Litter	(0.7)	(0.8)	(0.6)	-13%	13%
Mineral Soils	+	(+)	+	-700%	667%
Total: Aboveground Biomass	**(36.3)**	**(42.9)**	**(29.3)**	**-18%**	**19%**
Total: Belowground Biomass	**4.4**	**2.5**	**6.4**	**-43%**	**44%**
Total: Dead Wood	**(15.9)**	**(18.6)**	**(13.2)**	**-17%**	**17%**
Total: Litter	**(27.2)**	**(29.8)**	**(24.4)**	**-10%**	**10%**
Total: Mineral Soils	**+**	**(0.3)**	**0.3**	**-3,826%**	**3,825%**
Total: Lands Converted to Forest Lands	**(75.0)**	**(82.8)**	**(66.7)**	**-10%**	**11%**

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

[a] Range of flux estimate for 95 percent confidence interval

Note: Parentheses indicate net sequestration.

QA/QC and Verification

See QA/QC and Verification sections under *Forest land Remaining Forest Land* and *Cropland Remaining Cropland.*

Recalculations Discussion

The approach for estimating carbon stock changes in *Land Converted to Forest Land* was consistent with the methods used in the 1990 through 2015 Inventory and is described in Annex 3.13. Only FIA plots that were used in the 1990 through 2015 Inventory were used in the current Inventory to ensure consistency with the other land use categories and maintain the area estimates reported in the Land Representation. While the methods and plots used in the current Inventory were the same as those used in the previous Inventory (i.e., 1990 through 2015), the entire time series was compiled again when estimating the stock changes for 2016 and the estimates over the time series were consistent with those reported in the 1990 through 2015 Inventory report.

Planned Improvements

There are many improvements necessary to improve the estimation of carbons stock changes associated with land use conversion to forest land over the entire time series. First, soil C has historically been reported to a depth of 100 cm in the *Forest Land Remaining Forest Land* category (Domke et al. 2017) while other land-use categories (e.g., Grasslands and Croplands) report soil carbon to a depth of 20 or 30 cm. To ensure greater consistency in the *Land Converted to Forest Land* category where C stock transfers occur between land-use categories, all mineral soil estimates in the *Land Converted to Forest Land* category in this Inventory are based on methods from Ogle et al. (2003, 2006) and IPCC (2006). Methods have recently been developed (Domke et al. 2017) to estimate soil C to depths of 20, 30, and 100 cm in the Forest Land category using in situ measurements from the Forest Inventory and Analysis program within the USDA Forest Service and the International Soil Carbon Network. In subsequent Inventories, a common reporting depth will be defined for all land use conversion categories and Domke et al. (2017) will be used in the *Forest Land Remaining Forest Land* and *Land Converted to Forest Land* categories to ensure consistent reporting across all forest land. Third, due to the 5 to 10-year remeasurement periods within the FIA program and limited land use change information available over the entire time series, estimates presented in this section may not reflect the entire 20-year conversion history. Work is underway to integrate the dense time series of remotely sensed data into a new estimation system, which will facilitate land conversion estimation over the entire time series.

6.4 Cropland Remaining Cropland (CRF Category 4B1)

Carbon (C) in cropland ecosystems occurs in biomass, dead organic matter, and soils. However, C storage in cropland biomass and dead organic matter is relatively ephemeral and may not need to be reported according to the IPCC (2006), with the exception of C stored in perennial woody crop biomass, such as citrus groves and apple orchards, and the biomass, downed wood and dead organic matter in agroforestry systems. Within soils, C is found in organic and inorganic forms of C, but soil organic C (SOC) is the main source and sink for atmospheric CO_2 in most soils. IPCC (2006) recommends reporting changes in SOC stocks due to agricultural land-use and management activities on both mineral and organic soils.[30]

Well-drained mineral soils typically contain from 1 to 6 percent organic C by weight, whereas mineral soils with high water tables for substantial periods during the year may contain significantly more C (NRCS 1999). Conversion of mineral soils from their native state to agricultural land uses can cause up to half of the SOC to be lost to the atmosphere due to enhanced microbial decomposition. The rate and ultimate magnitude of C loss depends on subsequent management practices, climate and soil type (Ogle et al. 2005). Agricultural practices, such as clearing, drainage, tillage, planting, grazing, crop residue management, fertilization, application of biosolids (i.e., sewage sludge) and flooding, can modify both organic matter inputs and decomposition, and thereby result in a net C stock change (Parton et al. 1987; Paustian et al. 1997a; Conant et al. 2001; Ogle et al. 2005). Eventually, the soil can reach a new equilibrium that reflects a balance between C inputs (e.g., decayed plant matter, roots, and organic amendments such as manure and crop residues) and C loss through microbial decomposition of organic matter (Paustian et al. 1997b).

Organic soils, also referred to as *Histosols*, include all soils with more than 12 to 20 percent organic C by weight, depending on clay content (NRCS 1999; Brady and Weil 1999). The organic layer of these soils can be very deep (i.e., several meters), and form under inundated conditions that results in minimal decomposition of plant residues. When organic soils are prepared for crop production, they are drained and tilled, leading to aeration of the soil that accelerates both the decomposition rate and CO_2 emissions.[31] Due to the depth and richness of the organic layers, C loss from drained organic soils can continue over long periods of time, which varies depending on climate and composition (i.e., decomposability) of the organic matter (Armentano and Menges 1986). Due to deeper drainage and more intensive management practices, the use of organic soils for annual crop production (and also settlements) leads to higher C loss rates than drainage of organic soils in grassland or forests (IPCC 2006).

Cropland Remaining Cropland includes all cropland in an Inventory year that has been cropland for a continuous time period of at least 20 years according to the 2012 United States Department of Agriculture (USDA) National Resources Inventory (NRI) land-use survey for non-federal lands (USDA-NRCS 2015) or according to the National Land Cover Dataset for federal lands (Homer et al. 2007; Fry et al. 2011; Homer et al. 2015). Cropland includes all land used to produce food and fiber, in addition to forage that is harvested and used as feed (e.g., hay and silage), and cropland that has been enrolled in the Conservation Reserve Program (CRP) (i.e., considered reserve cropland). Cropland in Alaska is not included in the Inventory, but is a relatively small amount of U.S. cropland area (approximately 28,700 hectares). Some miscellaneous croplands are also not included in the Inventory due to limited understanding of greenhouse gas emissions from these management systems (e.g., aquaculture). This leads to a small discrepancy between the total amount of managed area in *Cropland Remaining Cropland* (see Section 6.1 Representation of the U.S. Land Base) and the cropland area included in the Inventory analysis (1.2 to 1.6 million

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[30] Carbon dioxide emissions associated with liming and urea application are also estimated but are included in the Agriculture chapter of the report.

[31] N_2O emissions from soils are included in the Agricultural Soil Management section.

hectares or 0.8 percent of the total cropland areas in the United States between 1990 and 2015). Improvements are underway to include croplands in Alaska as part of future C inventories.

Carbon dioxide emissions and removals[32] due to changes in mineral soil C stocks are estimated using a Tier 3 method for the majority of annual crops (Ogle et al. 2010). A Tier 2 IPCC method is used for the remaining crops not included in the Tier 3 method (see Methodology section for a list of crops in the Tier 2 and 3 methods) (Ogle et al. 2003, 2006). In addition, a Tier 2 method is used for very gravelly, cobbly, or shaley soils (i.e., classified as soils that have greater than 35 percent of soil volume comprised of gravel, cobbles, or shale) regardless of crop). Emissions from organic soils are estimated using a Tier 2 IPCC method. While a combination of Tier 2 and 3 methods are used to estimate C stock changes across most of the time series, a surrogate data method has been applied to estimate stock changes in the last few years of the Inventory. Stock change estimates based on surrogate data will be recalculated in a future Inventory report using the Tier 2 and 3 methods.

Land-use and land management of mineral soils are the largest contributor to total net C stock change, especially in the early part of the time series (see Table 6-28 and Table 6-29). In 2016, mineral soils are estimated to sequester 39.7 MMT CO_2 Eq. from the atmosphere (10.8 MMT C). This rate of C storage in mineral soils represents about a 44 percent decrease in the rate since the initial reporting year of 1990. Carbon dioxide emissions from organic soils are 29.8 MMT CO_2 Eq. (8.1 MMT C) in 2016, which is a 2 percent decrease compared to 1990. In total, United States agricultural soils in *Cropland Remaining Cropland* sequestered approximately 9.9 MMT CO_2 Eq. (2.7 MMT C) in 2016.

Table 6-28: Net CO_2 Flux from Soil C Stock Changes in *Cropland Remaining Cropland* (MMT CO_2 Eq.)

Soil Type	1990	2005	2012	2013	2014	2015	2016
Mineral Soils	(71.2)	(56.2)	(49.5)	(41.5)	(41.7)	(36.3)	(39.7)
Organic Soils	30.3	29.7	28.1	30.1	29.7	30.0	29.8
Total Net Flux	**(40.9)**	**(26.5)**	**(21.4)**	**(11.4)**	**(12.0)**	**(6.3)**	**(9.9)**

Notes: Estimates after 2012 are based on a surrogate data method (see Methodology section). Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Table 6-29: Net CO_2 Flux from Soil C Stock Changes in *Cropland Remaining Cropland* (MMT C)

Soil Type	1990	2005	2012	2013	2014	2015	2016
Mineral Soils	(19.4)	(15.3)	(13.5)	(11.3)	(11.4)	(9.9)	(10.8)
Organic Soils	8.3	8.1	7.7	8.2	8.1	8.2	8.1
Total Net Flux	**(11.2)**	**(7.2)**	**(5.8)**	**(3.1)**	**(3.3)**	**(1.7)**	**(2.7)**

Notes: Estimates after 2012 are based on a surrogate data method (see Methodology section). Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Soil C stocks increase in *Cropland Remaining Cropland* largely due to sequestration in lands enrolled in CRP (i.e., set-aside program), as well as from conversion of land into hay production, adoption of conservation tillage (i.e., reduced- and no-till practices), and intensification of crop production by limiting the use of bare-summer fallow in semi-arid regions. However, there is a decline in the net amount of C sequestration (i.e., 2016 is 44 percent less than 1990), and this decline is largely due to lower sequestration rates and less annual cropland enrolled in the CRP[33] that was initiated in 1985. Soil C losses from drainage of organic soils are relatively stable across the time series with a small decline associated with the land base declining by 7 percent (based on 2012 estimates) for *Cropland Remaining Cropland* on organic soils since 1990.

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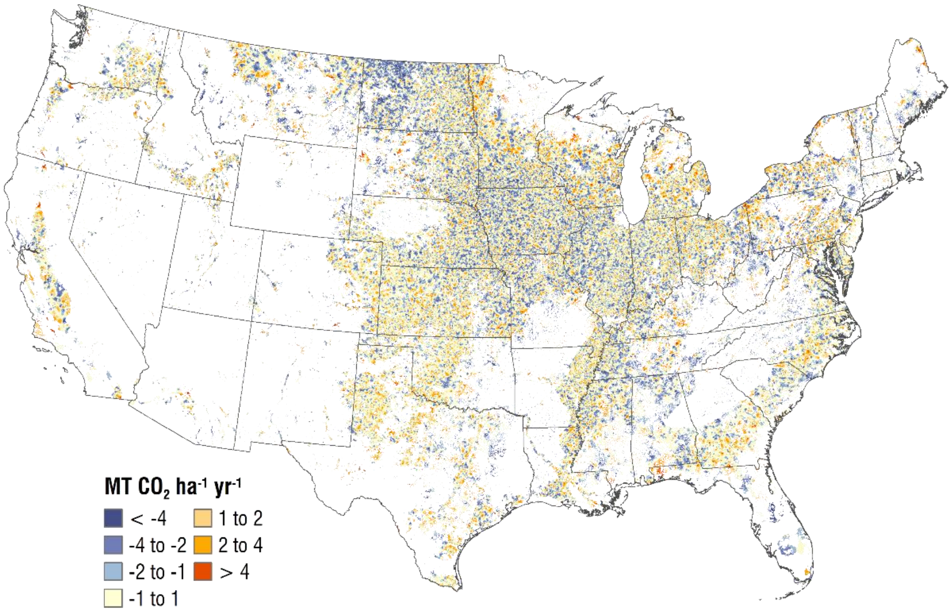
[32] Removals occur through uptake of CO_2 into crop and forage biomass that is later incorporated into soil C pools.

[33] The Conservation Reserve Program (CRP) is a land conservation program administered by the Farm Service Agency (FSA). In exchange for a yearly rental payment, farmers enrolled in the program agree to remove environmentally sensitive land from agricultural production and plant species that will improve environmental health and quality. Contracts for land enrolled in CRP are 10 to 15 years in length. The long-term goal of the program is to re-establish valuable land cover to help improve water quality, prevent soil erosion, and reduce loss of wildlife habitat.

The spatial variability in the 2012 annual soil C stock changes[34] are displayed in Figure 6-5 and Figure 6-6 for mineral and organic soils, respectively. Isolated areas with high rates of C accumulation occur throughout the agricultural land base in the United States, but there are more concentrated areas with gains in the northern Great Plains, which has high rates of CRP enrollment. High rates of net C accumulation in mineral soils also occurred in the Corn Belt region, which is the region with the largest amounts of conservation tillage, along with moderate rates of CRP enrollment. The regions with the highest rates of emissions from drainage of organic soils occur in the Southeastern Coastal Region (particularly Florida), upper Midwest and Northeast surrounding the Great Lakes, and isolated areas along the Pacific Coast (particularly California), which coincides with the largest concentrations of organic soils in the United States that are used for agricultural production.

Figure 6-5: Total Net Annual Soil C Stock Changes for Mineral Soils under Agricultural Management within States, 2012, *Cropland Remaining Cropland*



Note: Only national-scale soil C stock changes are estimated for 2013 to 2016 in the current Inventory using a surrogate data method, and therefore the fine-scale emission patterns in this map are based on inventory data from 2012. Negative values represent a net increase in soil C stocks, and positive values represent a net decrease in soil C stocks.

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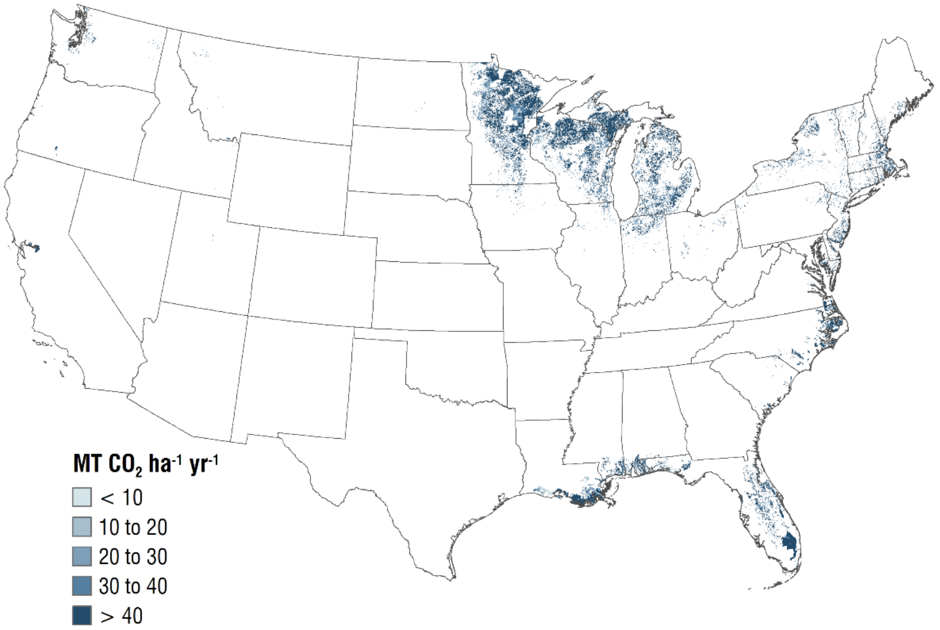
[34] Only national-scale emissions are estimated for 2013 to 2016 in this Inventory using the surrogate data method, and therefore the fine-scale emission patterns in this map are based on inventory data from 2012.

Figure 6-6: Total Net Annual Soil C Stock Changes for Organic Soils under Agricultural Management within States, 2012, *Cropland Remaining Cropland*



Note: Only national-scale soil C stock changes are estimated for 2013 to 2016 in the current Inventory using a surrogate data method, and therefore the fine-scale emission patterns in this map are based on inventory data from 2012.

Methodology

The following section includes a description of the methodology used to estimate changes in soil C stocks for *Cropland Remaining Cropland*, including (1) agricultural land-use and management activities on mineral soils; and (2) agricultural land-use and management activities on organic soils.

Soil C stock changes on non-federal lands are estimated for *Cropland Remaining Cropland* (as well as agricultural land falling into the IPCC categories *Land Converted to Cropland*, *Grassland Remaining Grassland*, and *Land Converted to Grassland*) according to land-use histories recorded in the USDA NRI survey (USDA-NRCS 2015). The NRI is a statistically-based sample of all non-federal land, and includes approximately 609,211 survey locations in agricultural land for the conterminous United States and Hawaii. Each survey location is associated with an "expansion factor" that allows scaling of C stock changes from NRI survey locations to the entire country (i.e., each expansion factor represents the amount of area with the same land-use/management history as the sample point). Land-use and some management information (e.g., crop type, soil attributes, and irrigation) were collected for each NRI point on a 5-year cycle beginning from 1982 through 1997. For cropland, data had been collected for 4 out of 5 years during each survey cycle (i.e., 1979 through 1982, 1984 through 1987, 1989 through 1992, and 1994 through 1997). In 1998, the NRI program began collecting annual data, and the annual data are currently available through 2012 (USDA-NRCS 2015). NRI survey locations are classified as *Cropland Remaining Cropland* in a given year between 1990 and 2012 if the land use had been cropland for a continuous time period of at least 20 years. NRI survey locations are classified according to land-use histories starting in 1979, and consequently the classifications are based on less than 20 years from 1990 to 1998. This may have led to an overestimation of *Cropland Remaining Cropland* in the early part of the time series to the extent that some areas are converted to cropland between 1971 and 1978.

Mineral Soil Carbon Stock Changes

An IPCC Tier 3 model-based approach (Ogle et al. 2010) is applied to estimate C stock changes for mineral soils on the majority of land that is used to produce annual crops in the United States. These crops include alfalfa hay, barley, corn, cotton, dry beans, grass hay, grass-clover hay, lentils, oats, onions, peanuts, peas, potatoes, rice, sorghum, soybeans, sugar beets, sunflowers, tobacco, tomatoes, and wheat, but is not applied to estimate C stock changes from other crops or rotations with other crops. The model-based approach uses the DAYCENT biogeochemical model (Parton et al. 1998; Del Grosso et al. 2001, 2011) to estimate soil C stock changes and soil nitrous oxide (N_2O) emissions from agricultural soil management. Carbon and N dynamics are linked in plant-soil systems through the biogeochemical processes of microbial decomposition and plant production (McGill and Cole 1981). Coupling the two source categories (i.e., agricultural soil C and N_2O) in a single inventory analysis ensures that there is a consistent treatment of the processes and interactions between C and N cycling in soils.

The remaining crops on mineral soils are estimated using an IPCC Tier 2 method (Ogle et al. 2003), including some vegetables, tobacco, perennial/horticultural crops, and crops that are rotated with these crops. The Tier 2 method is also used for very gravelly, cobbly, or shaley soils (greater than 35 percent by volume), and soil C stock changes on federal croplands. Mineral SOC stocks are estimated using a Tier 2 method for these areas because the DAYCENT model, which is used for the Tier 3 method, has not been fully tested for estimating C stock changes associated with these crops and rotations, as well as cobbly, gravelly, or shaley soils. In addition, there is insufficient information to simulate croplands on federal lands using DAYCENT. Further elaboration on the methodology and data used to estimate stock changes from mineral soils are described below and in Annex 3.12.

A surrogate data method is used to estimate soil C stock changes from 2013 to 2016 at the national scale for land areas included in the Tier 2 and Tier 3 methods. Specifically, linear regression models with autoregressive moving-average (ARMA) errors (Brockwell and Davis 2016) are used to estimate the relationship between surrogate data and the 1990 to 2012 stock change data that are derived using the Tier 2 and 3 methods. Surrogate data for these regression models include corn and soybean yields from USDA-NASS statistics,[35] and weather data from the PRISM Climate Group (PRISM 2015). See Box 6-6 for more information about the surrogate data method. Stock change estimates for 2013 to 2016 will be recalculated in future inventories when new NRI data are available.

Box 6-6: Surrogate Data Method

Time series extension is needed because the inventory is currently compiled every two years for many categories in the Agriculture, Forestry, and Other Land Use (AFOLU) sector in order to conserve resources that are needed to implement improvements, and even in years that the inventory is compiled, there are typically gaps at the end of the time series. This is mainly because the NRI, which provides critical data for estimating greenhouse gas emissions and removals, does not release data every year.

A surrogate data method has been used to impute missing emissions at the end of the time series for soil C stock changes in *Cropland Remaining Cropland*, *Land Converted to Cropland*, *Grassland Remaining Grassland*, and *Land Converted to Grassland*. A linear regression model with autoregressive moving-average (ARMA) errors (Brockwell and Davis 2016) is used to estimate the relationship between the surrogate data and the modeled 1990 to 2012 emissions data that has been compiled using the inventory methods described in this section. The model to extend the time series is given by

$$Y = X\beta + \varepsilon,$$

where Y is the response variable (e.g., soil organic carbon), $X\beta$ contains specific surrogate data depending on the response variable, and ε is the remaining unexplained error. Models with a variety of surrogate data were tested, including commodity statistics, weather data, or other relevant information. Parameters are estimated from the emissions data for 1990 to 2012 using standard statistical techniques, and these estimates are used to predict the missing emissions data for 2013 to 2016.

A critical issue in using splicing methods, is to adequately account for the additional uncertainty introduced by predicting emissions with related information without compiling the full inventory. Specifically, uncertainty will increase for years with imputed estimates based on the splicing methods, compared to those years in which the full inventory is compiled. This added uncertainty is quantified within the model framework using a Monte Carlo approach. The approach requires estimating parameters for results in each Monte Carlo simulation for the full inventory (i.e., the surrogate data model is refit with the emissions estimated in each Monte Carlo iteration from the full inventory analysis with data from 1990 to 2012), estimating emissions from each model and deriving confidence

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[35] See <https://quickstats.nass.usda.gov/>.

intervals, which propagates uncertainties through the calculations from the original inventory and the surrogate data method.

Tier 3 Approach. Mineral SOC stocks and stock changes are estimated using the DAYCENT biogeochemical[36] model (Parton et al. 1998; Del Grosso et al. 2001, 2011), which is able to simulate cycling of C, N, and other nutrients in cropland, grassland, forest, and savanna ecosystems. The DAYCENT model utilizes the soil C modeling framework developed in the Century model (Parton et al. 1987, 1988, 1994; Metherell et al. 1993), but has been refined to simulate dynamics at a daily time-step. The modeling approach uses daily weather data as an input, along with information about soil physical properties. Input data on land use and management are specified at a daily resolution and include land-use type, crop/forage type, and management activities (e.g., planting, harvesting, fertilization, manure amendments, tillage, irrigation, and grazing). The model simulates net primary productivity (NPP) using the NASA-CASA production algorithm MODIS Enhanced Vegetation Index (EVI) products, MOD13Q1 and MYD13Q1, for most croplands[37] (Potter et al. 1993, 2007). The model also simulates soil temperature, and water dynamics, in addition to turnover, stabilization, and mineralization of soil organic matter C and nutrients (N, P, K, S). This method is more accurate than the Tier 1 and 2 approaches provided by the IPCC (2006) because the simulation model treats changes as continuous over time as opposed to the simplified discrete changes represented in the default method (see Box 6-7 for additional information).

Box 6-7: Tier 3 Approach for Soil C Stocks Compared to Tier 1 or 2 Approaches

A Tier 3 model-based approach is used to estimate soil C stock changes on the majority of agricultural land on mineral soils. This approach results in a more complete and accurate accounting of soil C stock changes and entails several fundamental differences from the IPCC Tier 1 or 2 methods, as described below.

(1) The IPCC Tier 1 and 2 methods are simplified approaches for estimating soil C stock changes and classify land areas into discrete categories based on highly aggregated information about climate (six regions), soil (seven types), and management (eleven management systems) in the United States. In contrast, the Tier 3 model incorporates the same variables (i.e., climate, soils, and management systems) with considerably more detail both temporally and spatially, and captures multi-dimensional interactions through the more complex model structure.

(2) The IPCC Tier 1 and 2 methods have a coarser spatial resolution in which data are aggregated to soil types in climate regions, of which there about 30 of combinations in the United States. In contrast, the Tier 3 model simulates soil C dynamics at more than 300,000 individual NRI survey locations in individual fields.

(3) The IPCC Tier 1 and 2 methods use a simplified approach to estimating changes in C stocks that assumes a step-change from one equilibrium level of the C stock to another equilibrium level. In contrast, the Tier 3 approach simulates a continuum of C stock changes that may reach a new equilibrium over an extended period of time depending on the environmental conditions (i.e., a new equilibrium often requires hundreds to thousands of years to reach). More specifically, the DAYCENT model (i.e., daily time-step version of the Century model) simulates soil C dynamics (and CO_2 emissions and uptake) on a daily time step based on C emissions and removals from plant production and decomposition processes. These changes in soil C stocks are influenced by multiple factors that affect primary production and decomposition, including changes in land use and management, weather variability and secondary feedbacks between management activities, climate, and soils.

Historical land-use patterns and irrigation histories are simulated with DAYCENT based on the 2012 USDA NRI survey (USDA-NRCS 2015). Additional sources of activity data are used to supplement the land-use information

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[36] Biogeochemical cycles are the flow of chemical elements and compounds between living organisms and the physical environment.

[37] NPP is estimated with the NASA-CASA algorithm for most of the cropland that is used to produce major commodity crops in the central United States from 2000 to 2012. Other regions and years prior to 2000 are simulated with a method that incorporates water, temperature and moisture stress on crop production (see Metherell et al. 1993), but does not incorporate the additional information about crop condition provided with remote sensing data.

from the NRI. The Conservation Technology Information Center (CTIC 2004) provided annual data on tillage activity at the county level for the conterminous United States between 1989 and 2004, and these data are adjusted for long-term adoption of no-till agriculture (Towery 2001). No-till adoption is assumed to remain constant from 2005 through 2012 due to lack of data, but there is a planned improvement to update the tillage histories with a dataset that was recently released by the USDA (Conservation Effects Assessment Program Data, See Planned Improvements section). Information on fertilizer use and rates by crop type for different regions of the United States are obtained primarily from the USDA Economic Research Service. The data collection program was known as the Cropping Practices Surveys through 1995 (USDA-ERS 1997), and then became the Agricultural Resource Management Surveys (ARMS) (USDA-ERS 2015). Additional data are compiled through other sources particularly the National Agricultural Statistics Service (NASS 1992, 1999, 2004). Frequency and rates of manure application to cropland for 1997 are estimated from data compiled by the USDA Natural Resources Conservation Service (Edmonds et al. 2003), and then adjusted using county-level estimates of manure available for application in other years. Specifically, county-scale ratios of manure available for application to soils in other years relative to 1997 are used to adjust the area amended with manure (see Annex 3.12 for further details). Greater availability of managed manure N relative to 1997 is assumed to increase the area amended with manure, while reduced availability of manure N relative to 1997 is assumed to reduce the amended area. Data on the county-level N available for application are estimated for managed systems based on the total amount of N excreted in manure minus N losses during storage and transport, and include the addition of N from bedding materials. Nitrogen losses include direct N_2O emissions, volatilization of ammonia and NO_x, N runoff and leaching, and the N in poultry manure used as a feed supplement. More information on livestock manure production is available in Section 5.2 Manure Management and Annex 3.11.

Daily weather data are another input to the model simulations. These data are based on a 4 kilometer gridded product from the PRISM Climate Group (2015). Soil attributes are obtained from the Soil Survey Geographic Database (SSURGO) (Soil Survey Staff 2016). The C dynamics at each NRI point are simulated 100 times as part of the uncertainty analysis, yielding a total of over 18 million simulation runs for the analysis. Uncertainty in the C stock estimates from DAYCENT associated with parameterization and model algorithms are adjusted using a structural uncertainty estimator accounting for uncertainty in model algorithms and parameter values (Ogle et al. 2007, 2010). Carbon stocks and 95 percent confidence intervals are estimated for each year between 1990 and 2012 using the NRI survey data (which is available through 2012). However, the areas may have changed through the process in which the NRI survey data are reconciled with the Forest Inventory and Analysis (FIA) survey data and the National Land Cover Dataset (Homer et al. 2007; Fry et al. 2011; Homer et al. 2015). This process ensures that the areas of *Forest Land Remaining Forest Land* and *Land Converted to Forest Land* are consistent in all three datasets, and leads to some modification of other lands use areas to ensure the total land area of the United States does not change. For example, if the FIA estimate less *Cropland Converted to Forest Land* than the NRI, then the amount of area for this land use conversion is reduced in the NRI dataset and re-classified as *Cropland Remaining Cropland* (See Section 6.1, Representation of the U.S. Land Base for more information).

Soil C stock changes from 2013 to 2016 are estimated using a surrogate data method that is described in Box 6-6. Future Inventories will be updated with new NRI activity data when the data are made available, and the time series from 2013 to 2016 will be recalculated.

Tier 2 Approach. In the IPCC Tier 2 method, data on climate, soil types, land-use, and land management activity are used to classify land area and apply appropriate soil C stock change factors (Ogle et al. 2003, 2006). Reference C stocks are estimated using the National Soil Survey Characterization Database (NRCS 1997) with cultivated cropland as the reference condition, rather than native vegetation as used in IPCC (2006). Soil measurements under agricultural management are much more common and easily identified in the National Soil Survey Characterization Database (NRCS 1997) than are soils under a native condition, and therefore cultivated cropland provided a more robust sample for estimating the reference condition. U.S.-specific C stock change factors are derived from published literature to determine the impact of management practices on SOC storage (Ogle et al. 2003, 2006). The factors include changes in tillage, cropping rotations, intensification, and land-use change between cultivated and uncultivated conditions. U.S. factors associated with organic matter amendments are not estimated due to an insufficient number of studies in the United States to analyze the impacts. Instead, factors from IPCC (2006) are used to estimate the effect of those activities.

Climate zones in the United States are classified using mean precipitation and temperature (1950 to 2000) variables from the WorldClim data set (Hijmans et al. 2005) and potential evapotranspiration data from the Consortium for

Spatial Information (CGIAR-CSI) (Zomer et al. 2008, 2007) (Figure A-9). IPCC climate zones are then assigned to NRI point locations.

Activity data are primarily based on the historical land-use/management patterns recorded in the 2012 NRI (USDA-NRCS 2015). Each NRI point is classified by land use, soil type, climate region, and management condition. Survey locations on federal lands are included in the NRI, but land use and cropping history are not compiled at these locations in the survey program (i.e., NRI is restricted to data collection on non-federal lands). Land-use patterns at the NRI survey locations on federal lands are based on the National Land Cover Database (NLCD) (Fry et al. 2011; Homer et al. 2007; Homer et al. 2015). Classification of cropland area by tillage practice is based on data from the Conservation Technology Information Center (CTIC 2004; Towery 2001) as described in the Tier 3 approach above. Activity data on wetland restoration of Conservation Reserve Program land are obtained from Euliss and Gleason (2002). Manure N amendments over the inventory time period are based on application rates and areas amended with manure N from Edmonds et al. (2003), in addition to the managed manure production data discussed in the methodology subsection for the Tier 3 approach. Utilizing information from these data sources, SOC stocks for mineral soils are estimated 50,000 times for 1990 through 2012, using a Monte Carlo stochastic simulation approach and probability distribution functions for U.S.-specific stock change factors, reference C stocks, and land-use activity data (Ogle et al. 2002; Ogle et al. 2003; Ogle et al. 2006).

Soil C stock changes from 2013 to 2016 are estimated using a surrogate data method that is described in Box 6-6. As with the Tier 3 method, future inventories will be updated with new NRI activity data when the data are made available, and the time series will be recalculated (see Planned Improvements section).

Organic Soil Carbon Stock Changes

Annual C emissions from drained organic soils in *Cropland Remaining Cropland* are estimated using the Tier 2 method provided in IPCC (2006), with U.S.-specific C loss rates (Ogle et al. 2003) rather than default IPCC rates. The final estimates included a measure of uncertainty as determined from the Monte Carlo Stochastic Simulation with 50,000 iterations. Emissions are based on the annual data for drained organic soils from 1990 to 2012 for *Cropland Remaining Cropland* areas in the 2012 NRI (USDA-NRCS 2015). A surrogate data method is used to estimate annual C emissions from organic soils from 2013 to 2016 as described in Box 6-6 of this section. Estimates for 2013 to 2016 will be recalculated in future inventories when new NRI data are available.

Uncertainty and Time-Series Consistency

Uncertainty associated with the *Cropland Remaining Cropland* land-use category is addressed for changes in agricultural soil C stocks (including both mineral and organic soils). Uncertainty estimates are presented in Table 6-30 for each subsource (mineral soil C stocks and organic soil C stocks) and the methods that are used in the Inventory analyses (i.e., Tier 2 and Tier 3). Uncertainty for the Tier 2 and 3 approaches is derived using a Monte Carlo approach (see Annex 3.12 for further discussion). For 2013 to 2016, there is additional uncertainty propagated through the Monte Carlo Analysis associated with the surrogate data method. Soil C stock changes from the Tier 2 and 3 approaches are combined using the simple error propagation method provided by the IPCC (2006). The combined uncertainty is calculated by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities. The combined uncertainty for soil C stocks in *Cropland Remaining Cropland* ranged from 452 percent below to 452 percent above the 2016 stock change estimate of -9.9 MMT CO_2 Eq. The large relative uncertainty around the 2016 stock change estimate is partly due to variation in soil C stock changes that are not explained by the surrogate data method, leading to high prediction error with this splicing method.

Table 6-30: Approach 2 Quantitative Uncertainty Estimates for Soil C Stock Changes occurring within *Cropland Remaining Cropland* (MMT CO_2 Eq. and Percent)

Source	2016 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate[a] (MMT CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Mineral Soil C Stocks: Cropland Remaining Cropland, Tier 3 Inventory Methodology	(36.3)	(80.2)	7.5	-121%	121%
Mineral Soil C Stocks: Cropland Remaining Cropland, Tier 2 Inventory Methodology	(3.4)	(6.5)	(0.2)	-95%	95%

Organic Soil C Stocks: Cropland Remaining Cropland, Tier 2 Inventory Methodology	29.8	26.6	32.9	-11%	10%
Combined Uncertainty for Flux associated with Agricultural Soil Carbon Stock Change in Cropland Remaining Cropland	**(9.9)**	**(53.8)**	**34.3**	**-452%**	**452%**

[a] Range of C stock change estimates predicted by Monte Carlo Stochastic Simulation with a 95 percent confidence interval.
Note: Parentheses indicate net sequestration.

Methodological recalculations are applied from 2013 to 2015 using the surrogate data method developed with the C stock change estimates from 1990 to 2012, ensuring consistency across the time series. Details on the emission trends through time are described in more detail in the Methodology section.

Uncertainty is also associated with lack of reporting of agricultural woody biomass and dead organic matter C stock changes. The IPCC (2006) does not recommend reporting of annual crop biomass in *Cropland Remaining Cropland* because all of the biomass senesces each year and so there is no long-term storage of C in this pool. For woody plants, biomass C stock changes are likely minor in perennial crops, such as orchards and nut plantations. There will be some removal and replanting of tree crops each year, but the net effect on biomass C stock changes is probably minor because the overall area and tree density is relatively constant across time series. In contrast, agroforestry practices, such as shelterbelts, riparian forests and intercropping with trees, may be significantly changing biomass C stocks over the Inventory time series, at least in some regions of the United States, but there are currently no datasets to evaluate the trends. Changes in litter C stocks are also assumed to be negligible in croplands over annual time frames, although there are certainly significant changes at sub-annual time scales across seasons. However, this trend may change in the future, particularly if crop residue becomes a viable feedstock for bioenergy production.

QA/QC and Verification

Quality control measures included checking input data, model scripts, and results to ensure data are properly handled throughout the inventory process. Inventory reporting forms and text are reviewed and revised as needed to correct transcription errors. Results from the DAYCENT model are compared to field measurements, and a statistical relationship has been developed to assess uncertainties in the predictive capability of the model. The comparisons include 92 long-term experiments, representing about 908 combinations of management treatments across all of the sites (see Ogle et al. 2007 and Annex 3.12 for more information).

Recalculations Discussion

Methodological recalculations are associated with extending the time series from 2013 through 2016 using surrogate data method. C stock change estimates decline by an average of 48 percent from 2013 through 2015 based on the recalculation.

Planned Improvements

New land representation data have not been compiled for the current Inventory, and a surrogate data method has been applied to estimate emissions in the latter part of the time series, which introduces additional uncertainty in the emissions data. Therefore, a key improvement for a future Inventory will be to recalculate the time series for soil C stock changes by applying the Tier 2 and 3 methods with the latest land use data from the National Resources Inventory and related management statistics compiled through the Conservation Effects Assessment Program (discussed below).

There are several other planned improvements underway. The DAYCENT model will be refined to simulate soil organic C stock changes to a depth of at least 30 cm (currently at 20 cm). Improvements are also underway to more accurately simulate plant production. Crop parameters associated with temperature effects on plant production will be further improved in DAYCENT with additional model calibration. Senescence events following grain filling in crops, such as wheat, are being modified based on recent model algorithm development, and will be incorporated. Experimental study sites will continue to be added for quantifying model structural uncertainty.

There is an effort underway to update the time series of management data with information from the USDA-NRCS Conservation Effects Assessment Program (CEAP). This improvement will fill several gaps in the management data including more specific data on fertilizer rates, updated tillage practices, and more information on planting and harvesting dates for crops.

Improvements are underway to simulate crop residue burning in the DAYCENT model based on the amount of crop residues burned according to the data that are used in the Field Burning of Agricultural Residues source category (see Section 5.7). This improvement will more accurately represent the C inputs to the soil that are associated with residue burning.

In the future, the Inventory will include an analysis of C stock changes in Alaska for cropland and managed grassland, using the Tier 2 method for mineral and organic soils that is described earlier in this section. This analysis will initially focus on land use change, which typically has a larger impact on soil C stock changes, but will be further refined over time to incorporate more of the management data that drive C stock changes on long-term cropland.

Many of these improvements are expected to be completed for the 1990 through 2017 Inventory (i.e., 2019 submission to the UNFCCC). However, the time line may be extended if there are insufficient resources to fund all or part of these planned improvements.

6.5 Land Converted to Cropland (CRF Category 4B2)

Land Converted to Cropland includes all cropland in an Inventory year that had been in another land use(s) during the previous 20 years (USDA-NRCS 2015), and used to produce food or fiber, or forage that is harvested and used as feed (e.g., hay and silage). For example, grassland or forest land converted to cropland during the past 20 years would be reported in this category. Recently converted lands are retained in this category for 20 years as recommended by IPCC (2006). This Inventory includes all croplands in the conterminous United States and Hawaii, but does not include a minor amount of *Land Converted to Cropland* in Alaska. Some miscellaneous croplands are also not included in the Inventory due to limited understanding of greenhouse gas dynamics in management systems (e.g., aquaculture) or climate zones (e.g., boreal climates). Consequently, there is a discrepancy between the total amount of managed area in *Land Converted to Cropland* (see Section 6.1 Representation of the U.S. Land Base) and the cropland area included in the Inventory. Improvements are underway to include croplands in Alaska and miscellaneous croplands in future C inventories.

Land use change can lead to large losses of C to the atmosphere, particularly conversions from forest land (Houghton et al. 1983). Moreover, conversion of forest to another land use (i.e., deforestation) is one of the largest anthropogenic sources of emissions to the atmosphere globally (Schimel 1995), although this source may be declining according to a recent assessment (Tubiello et al. 2015).

The *2006 IPCC Guidelines* recommend reporting changes in biomass, dead organic matter and soil organic carbon (SOC) stocks with land use change. All SOC stock changes are estimated and reported for *Land Converted to Cropland*, but reporting of C stock changes for aboveground and belowground biomass, dead wood and litter pools is limited to *Forest Land Converted to Cropland*.[38]

Grassland Converted to Cropland is the largest source of emissions from 1990 to 2016, accounting for approximately 64 percent of the average total loss of C among all of the land use conversions in *Land Converted to Cropland*. The pattern is due to the fact that the area of *Grassland Converted to Cropland* is significantly larger than any of the other land use conversions. The majority of the loss is occurring in the mineral soil C pool. The next largest source of emissions is *Forest Land Converted to Cropland*, which has relatively large losses of woody biomass, accounting for approximately 31 percent of the total emissions (Table 6-31 and Table 6-32).

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[38] Changes in biomass C stocks are not currently reported for other land use conversions (other than forest land) to cropland, but this is a planned improvement for a future inventory. Note: changes in dead organic matter are assumed to negligible for other land use conversions (i.e., other than forest land) to cropland.

The net change in total C stocks for 2016 led to CO_2 emissions to the atmosphere of 23.8 MMT CO_2 Eq. (6.5 MMT C), including 2.1 MMT CO_2 Eq. (0.6 MMT C) from aboveground biomass C losses, 0.6 MMT CO_2 Eq. (0.2 MMT C) from belowground biomass C losses, 0.3 MMT CO_2 Eq. (0.1 MMT C) from dead wood C losses, 0.3 MMT CO_2 Eq. (0.1 MMT C) from litter C losses, 16.9 MMT CO_2 Eq. (4.6 MMT C) from mineral soils and 3.4 MMT CO_2 Eq. (0.9 MMT C) from drainage and cultivation of organic soils. Emissions in 2016 are 45 percent lower than the emissions in the initial reporting year of 1990, largely due to a reduction in the area of *Forest Land Converted to Cropland*.

Table 6-31: Net CO_2 Flux from Soil, Dead Organic Matter and Biomass C Stock Changes in *Land Converted to Cropland* by Land Use Change Category (MMT CO_2 Eq.)

	1990	2005	2012	2013	2014	2015	2016
Grassland Converted to Cropland	**24.5**	**17.3**	**18.1**	**18.0**	**17.9**	**17.8**	**18.4**
Mineral Soils	21.9	13.9	15.1	15.2	15.1	15.0	15.6
Organic Soils	2.5	3.3	3.0	2.9	2.8	2.8	2.8
Forest Land Converted to Cropland	**17.8**	**7.4**	**3.6**	**3.5**	**3.5**	**3.5**	**3.6**
Aboveground Live Biomass	11.3	4.9	2.1	2.1	2.1	2.1	2.1
Belowground Live Biomass	3.2	1.3	0.6	0.6	0.6	0.6	0.6
Dead Wood	1.5	0.6	0.3	0.3	0.3	0.3	0.3
Litter	1.5	0.5	0.3	0.3	0.3	0.3	0.3
Mineral Soils	0.2	0.1	0.1	+	+	+	0.1
Organic Soils	0.1	+	+	+	+	+	+
Other Lands Converted to Cropland	**0.3**	**0.3**	**0.2**	**0.1**	**0.1**	**0.1**	**0.1**
Mineral Soils	0.2	0.2	0.2	0.1	0.1	0.1	0.1
Organic Soils	0.1	0.1	0.0	0.0	0.0	0.0	0.0
Settlements Converted to Cropland	**0.1**	**0.1**	**0.2**	**0.1**	**0.1**	**0.1**	**0.1**
Mineral Soils	0.1	0.1	0.1	+	+	+	+
Organic Soils	+	+	0.1	0.1	0.1	0.1	0.1
Wetlands Converted to Cropland	**0.7**	**0.8**	**0.7**	**1.6**	**1.6**	**1.7**	**1.6**
Mineral Soils	0.1	0.1	0.1	1.2	1.2	1.2	1.1
Organic Soils	0.6	0.7	0.5	0.4	0.5	0.5	0.5
Aboveground Live Biomass	**11.3**	**4.9**	**2.1**	**2.1**	**2.1**	**2.1**	**2.1**
Belowground Live Biomass	**3.2**	**1.3**	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**
Dead Wood	**1.5**	**0.6**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**
Litter	**1.5**	**0.5**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**
Total Mineral Soil Flux	**22.5**	**14.4**	**15.6**	**16.4**	**16.3**	**16.3**	**16.9**
Total Organic Soil Flux	**3.4**	**4.2**	**3.7**	**3.4**	**3.4**	**3.4**	**3.4**
Total Net Flux	**43.3**	**25.9**	**22.7**	**23.3**	**23.2**	**23.2**	**23.8**

+ Does not exceed 0.05 MMT CO_2 Eq.

Notes: Estimates after 2012 for mineral and organic soils are based on a surrogate data method (see Methodology section). The 2016 estimates of biomass, dead wood and litter are assumed the same as estimates derived for 2015 because new activity data have not been analyzed for the current Inventory. Totals may not sum due to independent rounding.

Table 6-32: Net CO_2 Flux from Soil, Dead Organic Matter and Biomass C Stock Changes in *Land Converted to Cropland* (MMT C)

	1990	2005	2012	2013	2014	2015	2016
Grassland Converted to Cropland	**6.7**	**4.7**	**4.9**	**4.9**	**4.9**	**4.9**	**5.0**
Mineral Soils	6.0	3.8	4.1	4.1	4.1	4.1	4.3
Organic Soils	0.7	0.9	0.8	0.8	0.8	0.8	0.8
Forest Land Converted to Cropland	**4.8**	**2.0**	**1.0**	**0.9**	**1.0**	**1.0**	**1.0**
Aboveground Live Biomass	3.1	1.3	0.6	0.6	0.6	0.6	0.6
Belowground Live Biomass	0.9	0.4	0.2	0.2	0.2	0.2	0.2
Dead Wood	0.4	0.2	0.1	0.1	0.1	0.1	0.1
Litter	0.4	0.1	0.1	0.1	0.1	0.1	0.1
Mineral Soils	0.1	+	+	+	+	+	+

Organic Soils	+	+	+	+	+	+	+
Other Lands Converted to Cropland	**0.1**	**0.1**	**0.1**	**+**	**+**	**+**	**+**
Mineral Soils	+	0.1	0.1	+	+	+	+
Organic Soils	+	+	0.0	0.0	0.0	0.0	0.0
Settlements Converted to Cropland	**+**	**+**	**0.1**	**+**	**+**	**+**	**+**
Mineral Soils	+	+	+	+	+	+	+
Organic Soils	+	+	+	+	+	+	+
Wetlands Converted to Cropland	**0.2**	**0.2**	**0.2**	**0.4**	**0.4**	**0.5**	**0.4**
Mineral Soils	+	+	+	0.3	0.3	0.3	0.3
Organic Soils	0.2	0.2	0.1	0.1	0.1	0.1	0.1
Aboveground Live Biomass	**3.1**	**1.3**	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**
Belowground Live Biomass	**0.9**	**0.4**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**
Dead Wood	**0.4**	**0.2**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Litter	**0.4**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Total Mineral Soil Flux	**6.1**	**3.9**	**4.2**	**4.5**	**4.5**	**4.4**	**4.6**
Total Organic Soil Flux	**0.9**	**1.1**	**1.0**	**0.9**	**0.9**	**0.9**	**0.9**
Total Net Flux	**11.8**	**7.1**	**6.2**	**6.4**	**6.3**	**6.3**	**6.5**

+ Does not exceed 0.05 MMT C

Notes: Estimates after 2012 for mineral and organic soils are based on a surrogate data method (see Methodology section). The 2016 estimates of biomass, dead wood and litter are assumed the same as estimates derived for 2015 because new activity data have not been analyzed for the current Inventory. Totals may not sum due to independent rounding.

Methodology

The following section includes a description of the methodology used to estimate C stock changes for *Land Converted to Cropland*, including (1) loss of aboveground and belowground biomass, dead wood and litter C with conversion of forest lands to croplands, as well as (2) the impact from all land use conversions to cropland on mineral and organic soil C stocks.

Biomass, Dead Wood and Litter Carbon Stock Changes

A combination of the Tier 1 and 2 methods is applied to estimate aboveground and belowground biomass, dead wood, and litter C stock changes for *Forest Land Converted to Cropland* from 1990 to 2015. For this method, all annual plots and portions of plots (i.e., conditions; hereafter referred to as plots) from the Forest Inventory and Analysis (FIA) program are evaluated for land use change in the 48 conterminous United States (i.e., all states except Alaska and Hawaii) (USDA Forest Service 2015). Specifically, all annual re-measured FIA plots that are classified as *Forest Land Converted to Cropland* are identified in each state, and C density estimates before conversion are compiled for aboveground biomass, belowground biomass, dead wood, and litter. However, there are exceptions for the Intermountain Region of the Western United States (Arizona, Colorado, Idaho, Montana, New Mexico, Nevada, and Utah), in which there are a small number of plots that are converted from Forest Land to other Land Uses. In this region, all plots identified as a conversion from forest land to another land use are grouped and used to estimate the C densities before conversion, rather than subdividing the plots into specific land use change categories. Furthermore, there are no re-measured annual plots in Wyoming, and so the C densities before conversion are based on data from Colorado, Idaho, Montana, and Utah.

The C density before conversion is estimated for aboveground biomass, belowground biomass, dead wood, and litter C pools. Soil C stock changes are also addressed, but are based on methods discussed in the next section. Individual tree aboveground and belowground C density estimates are based on Woodall et al. (2011). The estimates of aboveground and belowground biomass includes live understory species (i.e., undergrowth plants in a forest) comprised of woody shrubs and trees less than 2.54 cm in diameter at breast height. It is assumed that 10 percent of total understory C mass is belowground (Smith et al. 2006). Estimates of C density are derived from information in Birdsey (1996) and Jenkins et al. (2003). The C density before conversion for standing dead trees is estimated following the basic method applied to live trees (Woodall et al. 2011) with additional modifications to account for decay and structural loss (Domke et al. 2011; Harmon et al. 2011). Downed dead wood is defined as pieces of dead wood greater than 7.5 cm diameter at transect intersections that are not attached to live or standing dead trees, and includes stumps and roots of harvested trees. The C density before conversion for downed dead wood is estimated based on measurements of downed dead wood of a subset of FIA plots (Domke et al. 2013; Woodall and Monleon 2008), and models specific to regions and forest types within each region are used to estimate dead wood C densities. Litter C is the pool of decaying leaves and woody fragments with diameters of up to 7.5 cm that are above the mineral soil (also known as duff, humus, and fine woody debris). A subset of FIA plots are measured for litter C, and a modeling approach is used to estimate litter C density based on the measurements (Domke et al. 2016). See Annex 3.13 for more information about initial C density estimates for Forest Land.

In all states, the initial C in the forest land before conversion to cropland is assumed to be lost to the atmosphere in the year of the conversion (i.e., 0 tonnes dry matter ha^{-1} immediately after conversion), which is consistent with the Tier 1 method in the IPCC guidelines (IPCC 2006). Annual crops (i.e., non-woody crops) are the most common crop type following conversion, and the default IPCC factor for annual crops is used to estimate the growth following conversion (IPCC 2006). It is also assumed that the accumulation of dead wood and litter is negligible in the new cropland. Therefore, total emissions and removals are estimated for biomass based on the new annual crop growth in cropland minus the losses associated with the C before conversion in the forest land. In contrast, changes in dead wood and litter C pools are based solely on the loss of the initial dead wood and litter C pools that existed before conversion of the forest land.

For 2016, C stock changes for biomass, downed wood and dead organic matter are assumed the same as 2015 because new activity data have not been analyzed to determine stock changes in 2016. Future inventories will be updated with new activity data for 2016, and the time series will be recalculated.

Soil Carbon Stock Changes

SOC stock changes are estimated for *Land Converted to Cropland* according to land-use histories recorded in the 2012 USDA NRI survey for non-federal lands (USDA-NRCS 2015). Land-use and some management information (e.g., crop type, soil attributes, and irrigation) had been collected for each NRI point on a 5-year cycle beginning in 1982. In 1998, the NRI program began collecting annual data, which are currently available through 2012 (USDA-NRCS 2015). NRI survey locations are classified as *Land Converted to Cropland* in a given year between 1990 and 2012 if the land use is cropland but had been another use during the previous 20 years. NRI survey locations are classified according to land-use histories starting in 1979, and consequently the classifications are based on less than 20 years from 1990 to 1998, which may have led to an underestimation of *Land Converted to Cropland* in the early part of the time series to the extent that some areas are converted to cropland from 1971 to 1978. For federal lands, the land use history is derived from land cover changes in the National Land Cover Dataset (Homer et al. 2007; Fry et al. 2011; Homer et al. 2015).

Mineral Soil Carbon Stock Changes

An IPCC Tier 3 model-based approach (Ogle et al. 2010) is applied to estimate C stock changes from 1990 to 2012 for mineral soils on the majority of land that is used to produce annual crops in the United States. These crops include alfalfa hay, barley, corn, cotton, dry beans, grass hay, grass-clover hay, lentils, oats, onions, peanuts, peas, potatoes, rice, sorghum, soybeans, sugar beets, sunflowers, tobacco, tomatoes, and wheat. SOC stock changes on the remaining mineral soils are estimated with the IPCC Tier 2 method (Ogle et al. 2003), including land used to produce some vegetables and perennial/horticultural crops and crops rotated with these crops; land on very gravelly, cobbly, or shaley soils (greater than 35 percent by volume); and land converted from another land use or federal ownership.[39]

For the years 2013 to 2016, a surrogate data method is used to estimate soil C stock changes at the national scale for land areas included in the Tier 2 and Tier 3 methods. Specifically, linear regression models with autoregressive moving-average (ARMA) errors (Brockwell and Davis 2016) are used to estimate the relationship between surrogate data and the 1990 to 2012 stock change data from the Tier 2 and 3 methods. Surrogate data for these regression

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[39] Federal land is not a land use, but rather an ownership designation that is treated as grassland for purposes of these calculations. The specific land use on federal lands is not identified in the NRI survey (USDA-NRCS 2015).

models include corn and soybean yields from USDA-NASS statistics,[40] and weather data from the PRISM Climate Group (PRISM 2015). See Box 6-6 in the Methodology Section of *Cropland Remaining Cropland* for more information about the surrogate data method. Stock change estimates for 2013 to 2016 will be recalculated in future inventories when new NRI data are available.

Tier 3 Approach. For the Tier 3 method, mineral SOC stocks and stock changes are estimated using the DAYCENT biogeochemical model (Parton et al. 1998; Del Grosso et al. 2001, 2011). The DAYCENT model utilizes the soil C modeling framework developed in the Century model (Parton et al. 1987, 1988, 1994; Metherell et al. 1993), but has been refined to simulate dynamics at a daily time-step. National estimates are obtained by using the model to simulate historical land-use change patterns as recorded in the USDA NRI (USDA-NRCS 2015). Carbon stocks and 95 percent confidence intervals are estimated for each year between 1990 and 2012. See the *Cropland Remaining Cropland* section for additional discussion of the Tier 3 methodology for mineral soils.

Soil C stock changes from 2013 to 2016 are estimated using the surrogate data method described in Box 6-6 of the Methodology Section in Cropland Remaining Cropland. Future inventories will be updated with new activity data when the data are made available, and the time series will be recalculated (See Planned Improvements section in Cropland Remaining Cropland).

Tier 2 Approach. For the mineral soils not included in the Tier 3 analysis, SOC stock changes are estimated using a Tier 2 Approach, as described in the Tier 2 Approach for mineral soils in *Cropland Remaining Cropland*. This includes application of the surrogate data method that is described in Box 6-6 of the Methodology section in *Cropland Remaining Cropland*. As with the Tier 3 method, future inventories will be updated with new NRI activity data when the data are made available, and the time series will be recalculated.

Organic Soil Carbon Stock Changes

Annual C emissions from drained organic soils in *Land Converted to Cropland* are estimated using the Tier 2 method provided in IPCC (2006), with U.S.-specific C loss rates (Ogle et al. 2003) as described in the *Cropland Remaining Cropland* section for organic soils. This includes application of the surrogate data method that is described in Box 6-6 of the Methodology Section in *Cropland Remaining Cropland*. Estimates will be recalculated in future inventories when new NRI data are available.

Uncertainty and Time-Series Consistency

The uncertainty analysis for biomass, dead wood and litter C losses with *Forest Land Converted to Cropland* is conducted in the same way as the uncertainty assessment for forest ecosystem C flux in the *Forest Land Remaining Forest Land* category. Sample and model-based error are combined using simple error propagation methods provided by the IPCC (2006) by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities. For additional details see the Uncertainty Analysis in Annex 3.13. The uncertainty analyses for mineral soil C stock changes using the Tier 3 and Tier 2 methodologies are based on a Monte Carlo approach that is described for *Cropland Remaining Cropland*. The uncertainty for annual C emission estimates from drained organic soils in *Land Converted to Cropland* is estimated using a Monte Carlo approach, which is also described in the *Cropland Remaining Cropland* section. For 2013 to 2016, there is additional uncertainty propagated through the Monte Carlo Analysis associated with a surrogate data method, which is also described in *Cropland Remaining Cropland*.

Uncertainty estimates are presented in Table 6-33 for each subsource (i.e., biomass C stocks, dead wood C stocks, litter C stocks, mineral soil C stocks and organic soil C stocks) and the method applied in the Inventory analysis (i.e., Tier 2 and Tier 3). Uncertainty estimates for the total C stock changes for biomass, dead organic matter and soils are combined using the simple error propagation methods provided by the IPCC (2006), as discussed in the previous paragraph. The combined uncertainty for total C stocks in *Land Converted to Cropland* ranged from 77 percent below to 77 percent above the 2016 stock change estimate of 23.8 MMT CO_2 Eq. The large relative uncertainty around the 2016 stock change estimate is partly due to variation in soil C stock changes that are not explained by the surrogate data method, leading to high prediction error with this splicing method.

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[40] See <https://quickstats.nass.usda.gov/>.

Table 6-33: Approach 2 Quantitative Uncertainty Estimates for Soil, Dead Organic Matter and Biomass C Stock Changes occurring within *Land Converted to Cropland* (MMT CO_2 Eq. and Percent)

Source	2016 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate[a] (MMT CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Grassland Converted to Cropland	**18.4**	**0.3**	**36.5**	**-98%**	**98%**
Mineral Soil C Stocks: Tier 3	14.6	-3.5	32.7	-124%	124%
Mineral Soil C Stocks: Tier 2	1.0	0.3	1.7	-70%	70%
Organic Soil C Stocks: Tier 2	2.8	1.9	3.7	-33%	33%
Forest Land Converted to Cropland	**3.6**	**0.8**	**6.3**	**-76%**	**76%**
Aboveground Live Biomass	2.1	-0.5	4.7	-121%	121%
Belowground Live Biomass	0.6	0.1	1.2	-80%	80%
Dead Wood	0.3	0.1	0.6	-76%	76%
Litter	0.3	+	0.7	-99%	99%
Mineral Soil C Stocks: Tier 2	0.1	-0.4	0.5	-764%	765%
Organic Soil C Stocks: Tier 2	+	0.0	0.1	-100%	190%
Other Lands Converted to Cropland	**0.1**	**+**	**0.1**	**-97%**	**97%**
Mineral Soil C Stocks: Tier 2	0.1	+	0.1	-97%	97%
Organic Soil C Stocks: Tier 2	0.0	0.0	0.0	0%	0%
Settlements Converted to Cropland	**0.1**	**+**	**0.1**	**-53%**	**53%**
Mineral Soil C Stocks: Tier 2	+	+	+	-211%	211%
Organic Soil C Stocks: Tier 2	0.1	+	0.1	-51%	52%
Wetlands Converted to Croplands	**1.6**	**0.7**	**2.6**	**-59%**	**59%**
Mineral Soil C Stocks: Tier 2	1.1	0.2	2.0	-80%	80%
Organic Soil C Stocks: Tier 2	0.5	0.2	5.5	-66%	66%
Total: Land Converted to Cropland	**23.8**	**5.4**	**42.1**	**-77%**	**77%**
Aboveground Live Biomass	**2.1**	**(0.5)**	**4.7**	**-121%**	**121%**
Belowground Live Biomass	**0.6**	**0.1**	**1.2**	**-80%**	**80%**
Dead Wood	**0.3**	**0.1**	**0.6**	**-76%**	**76%**
Litter	**0.3**	**0.0**	**0.7**	**-99%**	**99%**
Mineral Soil C Stocks: Tier 3	**14.6**	**(3.5)**	**32.7**	**-124%**	**124%**
Mineral Soil C Stocks: Tier 2	**2.3**	**1.0**	**3.5**	**-54%**	**54%**
Organic Soil C Stocks: Tier 2	**3.4**	**2.4**	**4.4**	**-29%**	**29%**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Range of C stock change estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or net sequestration.

Methodological recalculations are applied from 2013 to 2015 using the surrogate data method developed using the C stock change estimates from 1990 to 2012, ensuring consistency across the time series. Details on the emission trends through time are described in more detail in the Methodology section.

Uncertainty is also associated with lack of reporting of agricultural biomass and dead organic matter C stock changes. Biomass C stock changes are likely minor in perennial crops, such as orchards and nut plantations, given the small amount of change in land used to produce these commodities in the United States. In contrast, agroforestry practices, such as shelterbelts, riparian forests and intercropping with trees, may have led to significant changes in biomass C stocks, at least in some regions of the United States. However, there are currently no datasets to evaluate the trends. Changes in dead organic matter C stocks are assumed to be negligible with conversion of land to croplands with the exception of forest lands, which are included in this analysis. This assumption will be further explored in a future analysis.

QA/QC and Verification

See the QA/QC and Verification section in *Cropland Remaining Cropland* for information on QA/QC steps.

Recalculations Discussion

Methodological recalculations are associated with extending the time series from 2013 through 2015 for mineral and organic soils using a surrogate data method. No other recalculations have been implemented in the current Inventory. C stock change estimates increase by an average of 2 percent from 2013 through 2015 based on the recalculation.

Planned Improvements

Soil C stock changes with *Forest Land Converted to Cropland* are undergoing further evaluation to ensure consistency in the time series. Different methods are used to estimate soil C stock changes in forest land and croplands, and while the areas have been reconciled between these land uses, there has been limited evaluation of the consistency in C stock changes with conversion from forest land to cropland. Additional planned improvements are discussed in the *Cropland Remaining Cropland* section.

6.6 Grassland Remaining Grassland (CRF Category 4C1)

Carbon (C) in grassland ecosystems occurs in biomass, dead organic matter, and soils. Soils are the largest pool of C in grasslands, and have the greatest potential for longer-term storage or release of C. Biomass and dead organic matter C pools are relatively ephemeral compared to the soil C pool, with the exception of C stored in tree and shrub biomass, that occurs in grasslands. The *2006 IPCC Guidelines* recommend reporting changes in biomass, dead organic matter and soil organic C (SOC) stocks with land use and management, but there is currently no reporting of C stock changes for aboveground and belowground biomass, dead wood and litter pools.[41] For SOC, the *2006 IPCC Guidelines* (IPCC 2006) recommend reporting changes due to (1) agricultural land-use and management activities on mineral soils, and (2) agricultural land-use and management activities on organic soils.[42]

Grassland Remaining Grassland includes all grassland in an Inventory year that had been grassland for a continuous time period of at least 20 years (USDA-NRCS 2015). Grassland includes pasture and rangeland that are primarily, but not exclusively used for livestock grazing. Rangelands are typically extensive areas of native grassland that are not intensively managed, while pastures are typically seeded grassland (possibly following tree removal) that may also have additional management, such as irrigation or interseeding of legumes. The current Inventory includes all privately-owned and federal grasslands in the conterminous United States and Hawaii, but does not include approximately 50 million hectares of *Grassland Remaining Grassland* in Alaska. This leads to a discrepancy with the total amount of managed area in *Grassland Remaining Grassland* (see Section 6.1 Representation of the U.S. Land Base) and the grassland area included in the Inventory analysis (CRF Category 4C1—Section 6.6).

In *Grassland Remaining Grassland*, there has been considerable variation in soil C stocks between 1990 and 2016. These changes are driven by variability in weather patterns and associated interaction with land management activity. Moreover, changes are small on a per hectare rate basis across the time series even in the years with a larger total change in stocks. Land use and management generally increased soil C in mineral soils for *Grassland Remaining Grassland* between 1990 and 2016. In contrast, organic soils lose a relatively constant amount of C annually from 1990 through 2016. In 2016, soil C stocks are a net sink, sequestering 1.6 MMT CO_2 Eq. (0.4 MMT C), with an increase of 7.2 MMT CO_2 Eq. (2.0 MMT C) in mineral soils, and a loss of 5.5 MMT CO_2 Eq. (1.5 MMT C) from organic soils (Table 6-34 and Table 6-35). Soil C stock changes are 62 percent lower in 2016 compared to 1990, but stock changes are highly variable from 1990 to 2016, with an average annual sequestration of 5.2 MMT

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[41] There are planned improvements to address all C pools in the future, with an initial effort focused on biomass C.

[42] CO_2 emissions associated with liming and urea fertilization are also estimated but included in the Agriculture chapter of the report.

CO_2 Eq. (1.4 MMT C). However, the large inter-annual variability leads to years in which *Grassland Remaining Grassland* is a net sink and others in which it is a net source of CO_2 emissions.

Table 6-34: Net CO_2 Flux from Soil C Stock Changes in *Grassland Remaining Grassland* (MMT CO_2 Eq.)

Soil Type	1990	2005	2012	2013	2014	2015	2016
Mineral Soils	(11.4)	(0.5)	(26.3)	(9.3)	(13.1)	4.1	(7.2)
Organic Soils	7.2	6.0	5.5	5.5	5.5	5.5	5.5
Total Net Flux	**(4.2)**	**5.5**	**(20.8)**	**(3.7)**	**(7.5)**	**9.6**	**(1.6)**

Notes: Estimates after 2012 are based on a surrogate data method (see Methodology section). Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Table 6-35: Net CO_2 Flux from Soil C Stock Changes in *Grassland Remaining Grassland* (MMT C)

Soil Type	1990	2005	2012	2013	2014	2015	2016
Mineral Soils	(3.1)	(0.1)	(7.2)	(2.5)	(3.6)	1.1	(2.0)
Organic Soils	2.0	1.6	1.5	1.5	1.5	1.5	1.5
Total Net Flux	**(1.1)**	**1.5**	**(5.7)**	**(1.0)**	**(2.1)**	**2.6**	**(0.4)**

Notes: Estimates after 2012 are based on a data splicing method (see Methodology section). Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

The spatial variability in the 2012 annual soil C stock changes[43] associated with mineral soils is displayed in Figure 6-7 and organic soils in Figure 6-8. Although relatively small on a per-hectare basis, grassland soils gained C in isolated areas throughout the country, with a larger concentration of grasslands sequestering soil C in Iowa. For organic soils, the regions with the highest rates of emissions coincide with the largest concentrations of organic soils used for managed grassland, including the Southeastern Coastal Region (particularly Florida), upper Midwest and Northeast, and a few isolated areas along the Pacific Coast.

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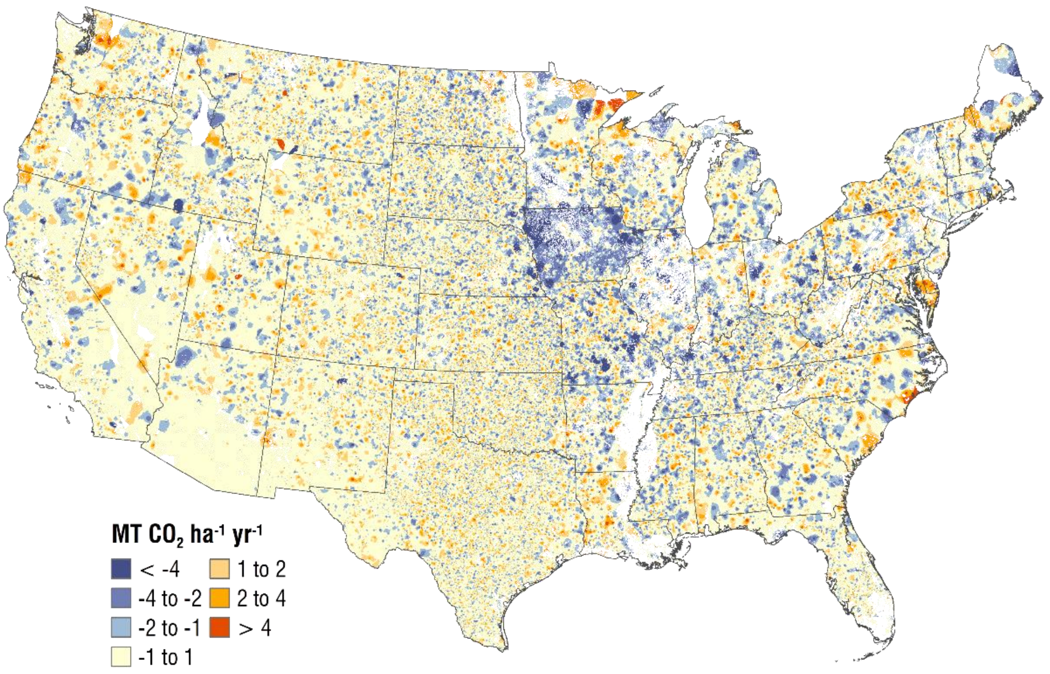
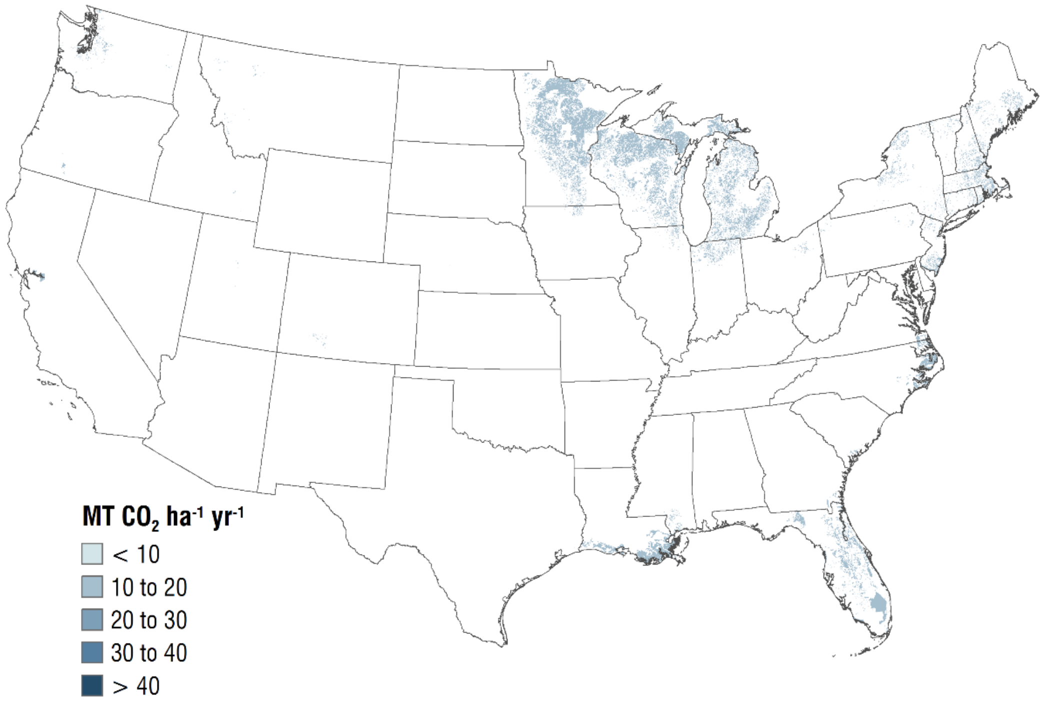
[43] Only national-scale emissions are estimated for 2013 to 2016 in the current Inventory using the surrogate data method, and therefore the fine-scale emission patterns in this map are based on inventory data from 2012.

Figure 6-7: Total Net Annual Soil C Stock Changes for Mineral Soils under Agricultural Management within States, 2012, *Grassland Remaining Grassland*



Note: Only national-scale soil C stock changes are estimated for 2013 to 2016 in the current Inventory using a surrogate data method, and therefore the fine-scale emission patterns in this map are based on inventory data from 2012. Negative values represent a net increase in soil C stocks, and positive values represent a net decrease in soil C stocks.

Figure 6-8: Total Net Annual Soil C Stock Changes for Organic Soils under Agricultural Management within States, 2012, *Grassland Remaining Grassland*



Note: Only national-scale soil carbon stock changes are estimated for 2013 to 2016 in the current Inventory using a surrogate data method, and therefore the fine-scale emission patterns in this map are based on inventory data from 2012.

Methodology

The following section includes a brief description of the methodology used to estimate changes in soil C stocks for *Grassland Remaining Grassland*, including: (1) agricultural land-use and management activities on mineral soils; and (2) agricultural land-use and management activities on organic soils. Further elaboration on the methodologies and data used to estimate stock changes from mineral and organic soils are provided in the *Cropland Remaining Cropland* section and Annex 3.12.

Soil C stock changes are estimated for *Grassland Remaining Grassland* on non-federal lands according to land use histories recorded in the 2012 USDA NRI survey (USDA-NRCS 2015). Land-use and some management information (e.g., grass type, soil attributes, and irrigation) were originally collected for each NRI survey location on a 5-year cycle beginning in 1982. In 1998, the NRI program began collecting annual data, and the annual data are currently available through 2012 (USDA-NRCS 2015). NRI survey locations are classified as *Grassland Remaining Grassland* in a given year between 1990 and 2012 if the land use had been grassland for 20 years. NRI survey locations are classified according to land-use histories starting in 1979, and consequently the classifications are based on less than 20 years from 1990 to 1998. This may have led to an overestimation of *Grassland Remaining Grassland* in the early part of the time series to the extent that some areas are converted to grassland prior between 1971 and 1978. For federal lands, the land use history is derived from land cover changes in the National Land Cover Dataset (Homer et al. 2007; Fry et al. 2011; Homer et al. 2015).

Mineral Soil Carbon Stock Changes

An IPCC Tier 3 model-based approach (Ogle et al. 2010) is applied to estimate C stock changes from 1990 to 2012 for most mineral soils in *Grassland Remaining Grassland*. The C stock changes for the remaining soils are estimated with an IPCC Tier 2 method (Ogle et al. 2003), including gravelly, cobbly, or shaley soils (greater than 35 percent by volume) and additional stock changes associated with biosolids (i.e., sewage sludge) amendments. SOC stock changes on the remaining soils are estimated with the IPCC Tier 2 method (Ogle et al. 2003), including land used to produce some vegetables and perennial/horticultural crops and crops rotated with these crops; land on very gravelly, cobbly, or shaley soils (greater than 35 percent by volume); and land converted from another land use or federal ownership.[44]

A surrogate data method is used to estimate soil C stock changes from 2013 to 2016 at the national scale for land areas included in the Tier 2 and Tier 3 methods. Specifically, linear regression models with autoregressive moving-average (ARMA) errors (Brockwell and Davis 2016) are used to estimate the relationship between surrogate data and the 1990 to 2012 emissions data from the Tier 2 and 3 methods. Surrogate data for these regression models includes weather data from the PRISM Climate Group (PRISM 2015). See Box 6-6 in the Methodology section of *Cropland Remaining Cropland* for more information about the surrogate data method. Stock change estimates for 2013 to 2016 will be recalculated in future inventories when new NRI data are available.

Tier 3 Approach. Mineral SOC stocks and stock changes for *Grassland Remaining Grassland* are estimated using the DAYCENT biogeochemical[45] model (Parton et al. 1998; Del Grosso et al. 2001, 2011), as described in *Cropland Remaining Cropland*. The DAYCENT model utilizes the soil C modeling framework developed in the Century model (Parton et al. 1987, 1988, 1994; Metherell et al. 1993), but has been refined to simulate dynamics at a daily time-step. Historical land-use patterns and irrigation histories are simulated with DAYCENT based on the 2012 USDA NRI survey (USDA-NRCS 2015). Frequency and rates of manure application to grassland during 1997 are estimated from data compiled by the USDA Natural Resources Conservation Service (NRCS) (Edmonds, et al. 2003), and then adjusted using county-level estimates of manure available for application in other years. Specifically, county-scale ratios of manure available for application to soils in other years relative to 1997 are used

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[44] Federal land is not a land use, but rather an ownership designation that is treated as grassland for purposes of these calculations. The specific land use on federal lands is not identified in the NRI survey (USDA-NRCS 2015).

[45] Biogeochemical cycles are the flow of chemical elements and compounds between living organisms and the physical environment.

to adjust the area amended with manure (see *Cropland Remaining Cropland* section and Annex 3.12 for further details). Greater availability of managed manure nitrogen (N) relative to 1997 is assumed to increase the area amended with manure, while reduced availability of manure N relative to 1997 is assumed to reduce the amended area.

The amount of manure produced by each livestock type is calculated for managed and unmanaged waste management systems based on methods described in Section 5.2 Manure Management and Annex 3.11. Manure N deposition from grazing animals (i.e., PRP manure) is an input to the DAYCENT model, and the remainder is deposited on federal lands (i.e., the amount that is not included in DAYCENT simulations is assumed to be applied on federal grasslands). Carbon stocks and 95 percent confidence intervals are estimated for each year between 1990 and 2012 using the NRI survey data.

Soil C stock changes from 2013 to 2016 are estimated using a surrogate data method described in Box 6-6 of the Methodology section in *Cropland Remaining Cropland*. Future inventories will be updated with new activity data when the data are made available, and the time series will be recalculated (See Planned Improvements section in *Cropland Remaining Cropland*).

Tier 2 Approach. The Tier 2 approach is based on the same methods described in the Tier 2 portion of *Cropland Remaining Cropland* section for mineral soils, with the exception of the land use and management data that are used in the Inventory for federal grasslands. The NRI (USDA-NRCS 2015) provides land use and management histories for all non-federal lands, and is the basis for the Tier 2 analysis for these areas. However, NRI does not provide land use information on federal lands. The land use data for federal lands is based on the National Land Cover Database (NLCD) (Fry et al. 2011; Homer et al. 2007; Homer et al. 2015). In addition, the Bureau of Land Management (BLM) manages some of the federal grasslands, and compiles information on grassland condition through the BLM Rangeland Inventory (BLM 2014). To estimate soil C stock changes from federal grasslands, rangeland conditions in the BLM data are aligned with IPCC grassland management categories of nominal, moderately degraded, and severely degraded in order to apply the appropriate emission factors. As with the non-federal lands, the time series for federal lands has been extended from 2013 to 2016 using a surrogate data method described in Box 6-6 of the Methodology Section in *Cropland Remaining Cropland*. Further elaboration on the Tier 2 methodology and data used to estimate C stock changes from mineral soils are described in Annex 3.12.

Additional Mineral C Stock Change Calculations

A Tier 2 method is used to adjust annual C stock change estimates for mineral soils between 1990 and 2016 to account for additional C stock changes associated with biosolid (i.e., sewage sludge) amendments. Estimates of the amounts of biosolids N applied to agricultural land are derived from national data on biosolids generation, disposition, and N content (see Section 7.2, Wastewater Treatment for a detailed discussion of the methodology for estimating sewage sludge available for land application application). Although biosolids can be added to land managed for other land uses, it is assumed that agricultural amendments only occur in *Grassland Remaining Grassland*. Total biosolids generation data for 1988, 1996, and 1998, in dry mass units, are obtained from EPA (1999) and estimates for 2004 are obtained from an independent national biosolids survey (NEBRA 2007). These values are linearly interpolated to estimate values for the intervening years, and linearly extrapolated to estimate values for years since 2004. N application rates from Kellogg et al. (2000) are used to determine the amount of area receiving biosolids amendments. The soil C storage rate is estimated at 0.38 metric tons C per hectare per year for biosolids amendments to grassland as described above. The stock change rate is based on country-specific factors and the IPCC default method (see Annex 3.12 for further discussion).

Organic Soil Carbon Stock Changes

Annual C emissions from drained organic soils in *Grassland Remaining Grassland* are estimated using the Tier 2 method provided in IPCC (2006), which utilizes U.S.-specific C loss rates (Ogle et al. 2003) rather than default IPCC rates. A surrogate data method is used to estimate annual C emissions from organic soils from 2013 to 2016 as described in Box 6-6 of the Methodology section in *Cropland Remaining Cropland*. Estimates for 2013 to 2016 will be updated in future inventories when new NRI data are available. For more information, see the *Cropland Remaining Cropland* section for organic soils.

Uncertainty and Time-Series Consistency

Uncertainty analysis for mineral soil C stock changes using the Tier 3 and Tier 2 methodologies are based on a Monte Carlo approach that is described in the *Cropland Remaining Cropland* section. The uncertainty for annual C emission estimates from drained organic soils in *Grassland Remaining Grassland* is estimated using a Monte Carlo approach, which is also described in the *Cropland Remaining Cropland* section. For 2013 to 2016, there is additional uncertainty propagated through the Monte Carlo Analysis associated with the surrogate data method.

Uncertainty estimates are presented in Table 6-36 for each subsource (i.e., mineral soil C stocks and organic soil C stocks) and the method applied in the inventory analysis (i.e., Tier 2 and Tier 3). Uncertainty estimates from the Tier 2 and 3 approaches are combined using the simple error propagation methods provided by the IPCC (2006), i.e., by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities. The combined uncertainty for soil C stocks in *Grassland Remaining Grassland* ranges from 2503 percent below to 2503 percent above the 2016 stock change estimate of -1.6 MMT CO_2 Eq. The large relative uncertainty is due to limitations in the surrogate data model for capturing inter-annual variability in soil C stock changes, particularly in the mineral soil C pools.

Table 6-36: Approach 2 Quantitative Uncertainty Estimates for C Stock Changes Occurring Within *Grassland Remaining Grassland* (MMT CO_2 Eq. and Percent)

Source	2016 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate[a]			
		(MMT CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Mineral Soil C Stocks Grassland Remaining Grassland, Tier 3 Methodology	(4.2)	(44.8)	36.3	-958%	958%
Mineral Soil C Stocks: Grassland Remaining Grassland, Tier 2 Methodology	(1.4)	(2.9)	0.0	-101%	102%
Mineral Soil C Stocks: Grassland Remaining Grassland, Tier 2 Methodology (Change in Soil C due to Biosolids [i.e., Sewage Sludge] Amendments)	(1.5)	(2.2)	(0.7)	-50%	50%
Organic Soil C Stocks: Grassland Remaining Grassland, Tier 2 Methodology	5.5	5.0	6.1	-9%	9%
Combined Uncertainty for Flux Associated with Agricultural Soil Carbon Stock Change in Grassland Remaining Grassland	**(1.6)**	**(42.2)**	**39.0**	**-2,503%**	**2,503%**

[a] Range of C stock change estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or net sequestration.

Methodological recalculations are applied from 2013 to 2015 using the surrogate data method developed using the C stock change estimates from 1990 to 2012, ensuring consistency across the time series. Details on the emission trends through time are described in more detail in the Methodology section.

Uncertainty is also associated with a lack of reporting on biomass and litter C stock changes. Biomass C stock changes may be significant for managed grasslands with woody encroachment despite not having attained enough tree cover to be considered forest lands. Changes in dead organic matter C stocks are assumed to be negligible in grasslands on an annual basis, although there are certainly significant changes at sub-annual time scales across seasons.

QA/QC and Verification

See the QA/QC and Verification section in *Cropland Remaining Cropland*.

Recalculations Discussion

Methodological recalculations are associated with modifying the approach for extending the time series from 2013 through 2015 for mineral and organic soils using a surrogate data method. C stock change estimates declined by an average of 97 percent from 2013 through 2015 based on the recalculation.

Planned Improvements

Grasslands in Alaska are not currently included in the Inventory. This is a significant planned improvement and estimates are expected to be available in a future Inventory contingent on funding availability. Another key planned improvement is to estimate woody biomass C stock changes for grasslands (See Box 6-8). For information about other improvements, see the Planned Improvements section in *Cropland Remaining Cropland*.

Box 6-8: Grassland Woody Biomass Analysis

An initial analysis of woodland biomass has been conducted for regions in the western United States. Woodlands are areas with trees in a matrix of grass vegetation that does not reach the thresholds for tree cover, diameter at breast height, and/or tree height to be considered forest land. For this pilot effort, carbon stock densities and stock changes are estimated using woodland plots in the Forest Inventory and Analysis (FIA) database. The full set of woodland plots cover 12 states in the western United States, and include two FIA forest type groups, pinyon-juniper and woodland hardwoods. The results suggest that woodlands are sequestering approximately 20 MMT CO_2 Eq. in biomass, dead wood, and litter pools. The analysis will be expanded to the entire time series and reported in a future Inventory.

Non-CO_2 Emissions from Grassland Fires (CRF Source Category 4C1)

Fires are common in grasslands, and are thought to have been a key feature shaping the evolution of the grassland vegetation in North America (Daubenmire 1968; Anderson 2004). Fires can occur naturally through lightning strikes, but are also an important management practice to remove standing dead and improve forage for grazing livestock. Woody and herbaceous biomass will be oxidized in a fire, although currently the focus is primarily on herbaceous biomass in this section.[46] Biomass burning emits a variety of trace gases including non-CO_2 greenhouse gases, CH_4 and N_2O, as well as CO and NO_x that can become greenhouse gases when they react with other gases in the atmosphere (Andreae and Merlet 2001). IPCC (2006) recommends reporting non-CO_2 greenhouse gas emissions from all wildfires and prescribed burning occurring in managed grasslands.

Biomass burning in grassland of the United States is a relatively small source of emissions, but it has increased by 424 percent since 1990. In 2016, CH_4 and N_2O emissions from biomass burning in grasslands were 0.3 MMT CO_2 Eq. (11 kt) and 0.3 MMT CO_2 Eq. (1 kt), respectively. Annual emissions from 1990 to 2016 have averaged approximately 0.3 MMT CO_2 Eq. (12 kt) of CH_4 and 0.3 MMT CO_2 Eq. (1 kt) of N_2O (see Table 6-37 and Table 6-38).

Table 6-37: CH_4 and N_2O Emissions from Biomass Burning in Grassland (MMT CO_2 Eq.)

	1990		2005		2012	2013	2014	2015	2016
CH_4	0.1		0.3		0.6	0.2	0.4	0.3	0.3
N_2O	0.1		0.3		0.6	0.2	0.4	0.3	0.3
Total Net Flux	**0.2**		**0.7**		**1.2**	**0.4**	**0.8**	**0.7**	**0.6**

Notes: Estimates for 2015 and 2016 are based on a splicing method described in the Methodology section. Totals may not sum due to independent rounding.

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[46] A planned improvement is underway to incorporate woodland tree biomass into the Inventory.

Table 6-38: CH_4, N_2O, CO, and NO_x Emissions from Biomass Burning in Grassland (kt)

	1990	2005	2012	2013	2014	2015	2016
CH_4	3	13	23	8	16	13	11
N_2O	+	1	2	1	1	1	1
CO	84	358	657	217	442	356	324
NO_x	5	21	39	13	27	21	19

+ Does not exceed 0.5 kt

Notes: Estimates for 2015 and 2016 are based on a splicing method described in the Methodology section.

Totals may not sum due to independent rounding.

Methodology

The following section includes a description of the methodology used to estimate non-CO_2 greenhouse gas emissions from biomass burning in grassland, including (1) determination of the land base that is classified as managed grassland; (2) assessment of managed grassland area that is burned each year, and (3) estimation of emissions resulting from the fires. For this Inventory, the IPCC Tier 1 method is applied to estimate non-CO_2 greenhouse gas emissions from biomass burning in grassland from 1990 to 2014 (IPCC 2006). A data splicing method is used to estimate the emissions in 2015 and 2016, which is discussed later in this section.

The land area designated as managed grassland is based primarily on the 2012 National Resources Inventory (NRI) (Nusser and Goebel 1997; USDA 2015). NRI has survey locations across the entire United States, but does not classify land use on federally-owned areas. These survey locations are designated as grassland using land cover data from the National Land Cover Dataset (NLCD) (Fry et al. 2011; Homer et al. 2007; Homer et al. 2015) (see Section 6.1 Representation of the U.S. Land Base).

The area of biomass burning in grasslands (*Grassland Remaining Grassland* and *Land Converted to Grassland*) is determined using 30-m fire data from the Monitoring Trends in Burn Severity (MTBS) program for 1990 through 2014.[47] NRI survey locations on grasslands are designated as burned in a year if there is a fire within a 500 m of the survey point according to the MTBS fire data. The area of biomass burning is estimated from the NRI spatial weights and aggregated to the country (Table 6-39).

Table 6-39: Thousands of Grassland Hectares Burned Annually

Year	Thousand Hectares
1990	317
2005	1,343
2012	2,464
2013	815
2014	1,659
2015	NE
2016	NE

Notes: Burned area are not estimated (NE) in 2015 and 2016 but will be updated in a future Inventory.

For 1990 to 2014, the total area of grassland burned is multiplied by the IPCC default factor for grassland biomass (4.1 tonnes dry matter per ha) (IPCC 2006) to estimate the amount of combusted biomass. A combustion factor of 1 is assumed in this Inventory, and the resulting biomass estimate is multiplied by the IPCC default grassland emission factors for CH_4 (2.3 g CH_4 per kg dry matter), N_2O (0.21 g CH_4 per kg dry matter), CO (65 g CH_4 per kg

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[47] See <http://www.mtbs.gov/nationalregional/burnedarea.html>.

dry matter) and NO_x (3.9 g CH_4 per kg dry matter) (IPCC 2006). The Tier 1 analysis is implemented in the Agriculture and Land Use National Greenhouse Gas Inventory (ALU) software (Ogle et al. 2016).[48]

A linear extrapolation of the trend in the time series is applied to estimate the emissions for 2015 and 2016 because new activity data have not been compiled for the current Inventory. Specifically, a linear regression model with autoregressive moving-average (ARMA) errors (Brockwell and Davis 2016) is used to estimate the trend in emissions over time from 1990 to 2014, and the trend is used to approximate the 2015 and 2016 emissions. The Tier 1 method described previously will be applied to recalculate the 2015 and 2016 emissions in a future Inventory.

Uncertainty and Time-Series Consistency

Emissions are estimated using a linear regression model with ARMA errors for 2015 and 2016. The linear regression ARMA model produced estimates of the upper and lower bounds of the emission estimate and the results are summarized in Table 6-40. Methane emissions from Biomass Burning in Grassland for 2016 are estimated to be between 0.0 and 0.7 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 100 percent below and 145 percent above the 2016 emission estimate of 0.3 MMT CO_2 Eq. Nitrous oxide emissions are estimated to be between 0.0 and 0.8 MMT CO_2 Eq., or approximately 100 percent below and 144 percent above the 2016 emission estimate of 0.3 MMT CO_2 Eq.

Table 6-40: Uncertainty Estimates for Non-CO_2 Greenhouse Gas Emissions from Biomass Burning in Grassland (MMT CO_2 Eq. and Percent)

Source	Gas	2016 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Grassland Burning	CH_4	0.3	0.0	0.7	-100%	145%
Grassland Burning	N_2O	0.3	0.0	0.8	-100%	144%

[a] Range of emission estimates predicted by linear regression time-series model for a 95 percent confidence interval.

Uncertainty is also associated with lack of reporting of emissions from biomass burning in grassland of Alaska. Grassland burning emissions could be relatively large in this region of the United States, and therefore extending this analysis to include Alaska is a planned improvement for the Inventory. There is also uncertainty due to lack of reporting combustion of woody biomass, and this is another planned improvement.

QA/QC and Verification

Quality control measures included checking input data, model scripts, and results to ensure data are properly handled throughout the inventory process. Inventory reporting forms and text are reviewed and revised as needed to correct transcription errors. Quality control identified problems with cell references in the spreadsheets, which have been corrected.

Recalculations Discussion

The only recalculation is associated with using the linear regression model with ARMA to estimate emissions in 2015. Non-CO_2 emissions declined by 20 percent for 2015 based on the recalculation.

Planned Improvements

A splicing data method is applied to estimate emissions in the latter part of the time series, which introduces additional uncertainty in the emissions data. Therefore, a key improvement for the next Inventory will be to update the time series with new activity data and recalculate the emissions for 2015 and 2016.

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[48] See <http://www.nrel.colostate.edu/projects/ALUsoftware/>.

Two other planned improvements have been identified for this source category, including a) incorporation of country-specific grassland biomass factors, and b) extending the analysis to include Alaska. In the current Inventory, biomass factors are based on a global default for grasslands that is provided by the IPCC (2006). There is considerable variation in grassland biomass, however, which would affect the amount of fuel available for combustion in a fire. Alaska has an extensive area of grassland and includes tundra vegetation, although some of the areas are not managed. There has been an increase in fire frequency in boreal forest of the region (Chapin et al. 2008), and this may have led to an increase in burning of neighboring grassland areas. There is also an effort under development to incorporate grassland fires into DAYCENT model simulations. Both improvements are expected to reduce uncertainty and lead to more accurate estimates of non-CO_2 greenhouse gas emissions from grassland burning.

6.7 Land Converted to Grassland (CRF Category 4C2)

Land Converted to Grassland includes all grassland in an Inventory year that had been in another land use(s) during the previous 20 years (USDA-NRCS 2015).[49] For example, cropland or forest land converted to grassland during the past 20 years would be reported in this category. Recently-converted lands are retained in this category for 20 years as recommended by IPCC (2006). Grassland includes pasture and rangeland that are used primarily but not exclusively for livestock grazing. Rangelands are typically extensive areas of native grassland that are not intensively managed, while pastures are typically seeded grassland (possibly following tree removal) that may also have additional management, such as irrigation or interseeding of legumes. This Inventory includes all grasslands in the conterminous United States and Hawaii, but does not include *Land Converted to Grassland* in Alaska. Consequently, there is a discrepancy between the total amount of managed area for *Land Converted to Grassland* (see Section 6.1 Representation of the U.S. Land Base) and the grassland area included in the inventory analysis (CRF Category 4C2—Section 6.7).

Land use change can lead to large losses of C to the atmosphere, particularly conversions from forest land (Houghton et al. 1983). Moreover, conversion of forest to another land use (i.e., deforestation) is one of the largest anthropogenic sources of emissions to the atmosphere globally (Schimel 1995), although this source may be declining according to a recent assessment (Tubiello et al. 2015).

IPCC (2006) recommends reporting changes in biomass, dead organic matter, and soil organic C (SOC) stocks due to land use change. All soil C stock changes are estimated and reported for *Land Converted to Grassland*, but there is limited reporting of other pools in this Inventory. Losses of aboveground and belowground biomass, dead wood and litter C from *Forest Land Converted to Grassland* are reported, but these C stock changes are not estimated for other land use conversions to grassland.[50]

The largest C losses with *Land Converted to Grassland* are associated with aboveground biomass, belowground biomass, dead wood and litter C losses from *Forest Land Converted to Grassland* (see Table 6-41 and Table 6-42). These four pools led to net emissions in 2016 of 20.9, 1.7, 3.6, and 6.2 MMT CO_2 Eq. (5.7, 0.5, 1.0, and 1.7 MMT C), respectively. Land use and management of mineral soils in *Land Converted to Grassland* led to an increase in soil C stocks, estimated at 12.0 MMT CO_2 Eq. (3.3 MMT C) in 2016, while drainage of organic soils for grassland management led to CO_2 emissions to the atmosphere of 1.6 MMT CO_2 Eq. (0.4 MMT C). The total net C stock change in 2016 for *Land Converted to Grassland* is estimated as a loss of 22.0 MMT CO_2 Eq. (6.0 MMT C), which is a 23 percent increase in emissions compared to the emissions in the initial reporting year of 1990.

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[49] NRI survey locations are classified according to land-use histories starting in 1979, and consequently the classifications are based on less than 20 years from 1990 to 2001. This may have led to an underestimation of *Land Converted to Grassland* in the early part of the time series to the extent that some areas are converted to grassland between 1971 and 1978.

[50] Changes in biomass C stocks are not currently reported for other conversions to grassland (other than forest land), but this is a planned improvement for a future Inventory. Note: changes in dead organic matter are assumed to negligible for other land use conversions (i.e., other than forest land) to grassland based on the Tier 1 method in IPCC (2006).

Table 6-41: Net CO_2 Flux from Soil, Dead Organic Matter and Biomass C Stock Changes for *Land Converted to Grassland* (MMT CO_2 Eq.)

	1990	2005	2012	2013	2014	2015	2016
Cropland Converted to Grassland	**(7.5)**	**(11.5)**	**(11.3)**	**(8.1)**	**(8.4)**	**(6.2)**	**(7.5)**
Mineral Soils	(8.0)	(12.7)	(12.4)	(9.3)	(9.5)	(7.4)	(8.6)
Organic Soils	0.5	1.1	1.1	1.1	1.1	1.1	1.1
Forest Land Converted to Grassland	**26.1**	**32.0**	**32.3**	**29.8**	**29.7**	**29.5**	**29.4**
Aboveground Live Biomass	18.0	20.2	20.9	20.9	20.9	20.9	20.9
Belowground Live Biomass	0.9	1.9	1.7	1.7	1.7	1.7	1.7
Dead Wood	2.9	3.8	3.6	3.6	3.6	3.6	3.6
Litter	5.1	6.6	6.2	6.2	6.2	6.2	6.2
Mineral Soils	(0.8)	(0.5)	(0.3)	(2.7)	(2.9)	(3.1)	(3.1)
Organic Soils	+	0.1	0.1	0.1	0.1	0.1	0.1
Other Lands Converted Grassland	**(0.5)**	**(1.0)**	**(0.7)**	**(+)**	**(0.1)**	**(0.1)**	**(0.1)**
Mineral Soils	(0.5)	(1.1)	(0.8)	(0.1)	(0.1)	(0.1)	(0.1)
Organic Soils	+	+	0.1	+	+	+	+
Settlements Converted Grassland	**(0.1)**	**(0.1)**	**(0.1)**	**+**	**+**	**+**	**+**
Mineral Soils	(0.1)	(0.1)	(0.1)	(+)	(+)	(+)	(+)
Organic Soils	+	+	+	+	+	+	+
Wetlands Converted Grassland	**(0.2)**	**(0.2)**	**0.2**	**0.2**	**0.2**	**0.1**	**0.1**
Mineral Soils	(0.3)	(0.4)	(0.1)	(0.2)	(0.2)	(0.2)	(0.2)
Organic Soils	0.1	0.3	0.3	0.3	0.3	0.3	0.3
Aboveground Live Biomass	**18.0**	**20.2**	**20.9**	**20.9**	**20.9**	**20.9**	**20.9**
Belowground Live Biomass	**0.9**	**1.9**	**1.7**	**1.7**	**1.7**	**1.7**	**1.7**
Dead Wood	**2.9**	**3.8**	**3.6**	**3.6**	**3.6**	**3.6**	**3.6**
Litter	**5.1**	**6.6**	**6.2**	**6.2**	**6.2**	**6.2**	**6.2**
Total Mineral Soil Flux	**(9.7)**	**(14.8)**	**(13.6)**	**(12.3)**	**(12.6)**	**(10.8)**	**(12.0)**
Total Organic Soil Flux	**0.7**	**1.5**	**1.6**	**1.7**	**1.6**	**1.7**	**1.6**
Total Net Flux	**17.9**	**19.2**	**20.4**	**21.9**	**21.5**	**23.3**	**22.0**

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

Notes: Estimates after 2012 for mineral and organic soils are based on a surrogate data method (see Methodology section). The 2016 estimates of biomass, dead wood and litter are assumed the same as estimates derived for 2015 because new activity data have not been analyzed for the current Inventory. Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Table 6-42: Net CO_2 Flux from Soil, Dead Organic Matter and Biomass C Stock Changes for *Land Converted to Grassland* (MMT C)

	1990	2005	2012	2013	2014	2015	2016
Cropland Converted to Grassland	**(2.0)**	**(3.1)**	**(3.1)**	**(2.2)**	**(2.3)**	**(1.7)**	**(2.0)**
Mineral Soils	(2.2)	(3.5)	(3.4)	(2.5)	(2.6)	(2.0)	(2.3)
Organic Soils	0.1	0.3	0.3	0.3	0.3	0.3	0.3
Forest Land Converted to Grassland	**7.1**	**8.7**	**8.8**	**8.1**	**8.1**	**8.0**	**8.0**
Aboveground Live Biomass	4.9	5.5	5.7	5.7	5.7	5.7	5.7
Belowground Live Biomass	0.2	0.5	0.5	0.5	0.5	0.5	0.5
Dead Wood	0.8	1.0	1.0	1.0	1.0	1.0	1.0
Litter	1.4	1.8	1.7	1.7	1.7	1.7	1.7
Mineral Soils	(0.2)	(0.1)	(0.1)	(0.7)	(0.8)	(0.8)	(0.9)
Organic Soils	+	+	+	+	+	+	+
Other Lands Converted Grassland	**(0.1)**	**(0.3)**	**(0.2)**	**(+)**	**(+)**	**(+)**	**(+)**
Mineral Soils	(0.1)	(0.3)	(0.2)	(+)	(+)	(+)	(+)
Organic Soils	+	+	+	+	+	+	+
Settlements Converted Grassland	**(+)**	**(+)**	**(+)**	**+**	**+**	**+**	**+**
Mineral Soils	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Organic Soils	+	+	+	+	+	+	+
Wetlands Converted Grassland	**(0.1)**	**(+)**	**0.1**	**+**	**+**	**+**	**+**
Mineral Soils	(0.1)	(0.1)	(+)	(+)	(+)	(0.1)	(0.1)

Organic Soils	+	0.1	0.1	0.1	0.1	0.1	0.1
Aboveground Live Biomass	**4.9**	**5.5**	**5.7**	**5.7**	**5.7**	**5.7**	**5.7**
Belowground Live Biomass	**0.2**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**
Dead Wood	**0.8**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**
Litter	**1.4**	**1.8**	**1.7**	**1.7**	**1.7**	**1.7**	**1.7**
Total Mineral Soil Flux	**(2.6)**	**(4.0)**	**(3.7)**	**(3.3)**	**(3.4)**	**(2.9)**	**(3.3)**
Total Organic Soil Flux	**0.2**	**0.4**	**0.4**	**0.5**	**0.4**	**0.5**	**0.4**
Total Net Flux	**4.9**	**5.2**	**5.6**	**6.0**	**5.9**	**6.4**	**6.0**

+ Absolute value does not exceed 0.05 MMT C

Notes: Estimates after 2012 for mineral and organic soils are based on a surrogate data method (see Methodology section). The 2016 estimates of biomass, dead wood and litter are assumed the same as estimates derived for 2015 because new activity data have not been analyzed for the current Inventory. Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Methodology

The following section includes a description of the methodology used to estimate C stock changes for *Land Converted to Grassland*, including (1) loss of aboveground and belowground biomass, dead wood and litter C with conversion of *Forest Land Converted to Grassland*, as well as (2) the impact from all land use conversions to grassland on mineral and organic soil C stocks.

Biomass, Dead Wood and Litter Carbon Stock Changes

A combination of Tier 1 and 2 methods are applied to estimate aboveground and belowground biomass, dead wood, and litter C stock changes for *Forest Land Converted to Grassland* from 1990 to 2015. For this method, all annual plots and portions of plots (i.e., conditions; hereafter referred to as plots) from the Forest Inventory and Analysis (FIA) program are evaluated for land use change in the 48 conterminous United States (i.e., all states except Alaska and Hawaii) (USDA Forest Service 2015). Specifically, all annual re-measured FIA plots that are classified as *Forest Land Converted to Grassland* are identified in each state, and C density estimates before conversion are compiled for aboveground biomass, belowground biomass, dead wood, and litter. However, there are exceptions for the Intermountain Region (Arizona, Colorado, Idaho, Montana, New Mexico, Nevada, and Utah) and the Great Plains Region (Kansas, Nebraska, North Dakota and South Dakota) of the United States, in which there are a relatively small number of re-measured plots that are converted from Forest Land to a specific land use. In this region, all plots identified as a conversion from forest land to another land use are grouped in each state and used to estimate the C densities before conversion, rather than subdividing the plots into specific land use change categories by state. Furthermore, there are no re-measured annual plots in Wyoming, and so the C densities before conversion are based on data from Colorado, Idaho, Montana, and Utah.

The C density before conversion is estimated for aboveground biomass, belowground biomass, dead wood, and litter C pools. Soil C stock changes are also addressed, but are based on methods discussed in the next section. Individual tree aboveground and belowground C density estimates are based on Woodall et al. (2011). The estimates of aboveground and belowground biomass includes live understory species (i.e., undergrowth plants in a forest) comprised of woody shrubs and trees less than 2.54 cm in diameter at breast height. It is assumed that 10 percent of total understory C mass is belowground (Smith et al. 2006). Estimates of C density are obtained from information in Birdsey (1996) and Jenkins et al. (2003). The C density before conversion for standing dead trees is estimated following the basic method applied to live trees (Woodall et al. 2011) with additional modifications to account for decay and structural loss (Domke et al. 2011; Harmon et al. 2011). Downed dead wood is defined as pieces of dead wood greater than 7.5 cm diameter at transect intersections that are not attached to live or standing dead trees, and includes stumps and roots of harvested trees. The C density before conversion for downed dead wood is estimated based on measurements of downed dead wood of a subset of FIA plots (Domke et al. 2013; Woodall and Monleon 2008), and models specific to regions and forest types within each region are used to estimate dead wood C densities. Litter C is the pool of decaying leaves and woody fragments with diameters of up to 7.5 cm that are above the mineral soil (also known as duff, humus, and fine woody debris). A subset of FIA plots are measured for litter C, and a modeling approach is used to estimate litter C density based on the measurements (Domke et al. 2016). See Annex 3.13 for more information about initial C density estimates for Forest Land.

In the Eastern and Central United States, the initial C in the forest land before conversion to grassland is assumed to be lost to the atmosphere in the year of the conversion (i.e., 0 tonnes dry matter ha^{-1} immediately after conversion), which is consistent with the Tier 1 method in the IPCC guidelines (IPCC 2006). Grasses and other herbaceous plants are assumed to dominate these areas following conversion, and the default IPCC factor for grasslands is used to estimate the growth following conversion (IPCC 2006). It is also assumed that the accumulation of dead wood and litter is negligible in the new grasslands. Therefore, total emissions and removals are estimated for biomass based on the new growth in the grassland minus the losses associated with the C before conversion in the forest land. In contrast, changes in dead wood and litter C pools are based solely on the loss of the initial dead wood and litter C pools that existed before conversion of the forest land.

In the Western United States (Arizona, California, Colorado, Idaho, Montana, New Mexico, Nevada, Oregon, Utah, Washington, and Wyoming) and Great Plains Region (Kansas, Nebraska, North Dakota, and South Dakota), there is evidence in the FIA data as well as the published literature that conversion of forest land to grassland is associated with persistent woody biomass (Sims et al. 1978; Scholes and Archer 1997; Breshears et al. 2016). Given the relatively low stocking and tree density on these forest lands, the conversion is likely to equate to a loss of few trees from the aboveground biomass pool in many cases. However, the loss of the few trees is sufficient to reclassify the forest land into grassland in a woodland subcategory based on the land use definitions adopted for land representation in the United States (see Section 6.1, Representation of the U.S. Land Base). Given the evidence from the published literature and the FIA data, the Tier 1 assumption that all C before conversion is lost with land use change seems insufficient and would lead to bias in the estimates. A conclusion was drawn from a synthesis of the literature (Sims et al. 1978; Scholes and Archer 1997; Epstein et al. 2002; Juerna and Archer 2003; Lenihan et al. 2003; Breshears et al. 2016), and an analysis of the FIA data, that approximately 50 percent of the aboveground and belowground biomass, dead wood, and litter C density is lost during the conversion, while all understory biomass remains after conversion to woodlands in these regions. Therefore, the total emissions and removals for *Forest Land Converted to Grassland* in the Western United States and Great Plains Regions are limited to a loss of 50 percent of the live biomass and dead organic matter.

For 2016, C stock changes for biomass, downed wood and dead organic matter are assumed the same as 2015 because new activity data have not been analyzed to determine stock changes in 2016. Future inventories will be updated with new activity data for 2016, and the time series will be recalculated.

Soil Carbon Stock Changes

Soil C stock changes are estimated for *Land Converted to Grassland* according to land use histories recorded in the 2012 USDA NRI survey for non-federal lands (USDA-NRCS 2015). Land use and some management information (e.g., crop type, soil attributes, and irrigation) were originally collected for each NRI survey locations on a 5-year cycle beginning in 1982. In 1998, the NRI Program began collecting annual data, and the annual data are currently available through 2012 (USDA-NRCS 2015). NRI survey locations are classified as *Land Converted to Grassland* in a given year between 1990 and 2012 if the land use is grassland but had been classified as another use during the previous 20 years. NRI survey locations are classified according to land use histories starting in 1979, and consequently the classifications are based on less than 20 years from 1990 to 1998. This may have led to an underestimation of *Land Converted to Grassland* in the early part of the time series to the extent that some areas are converted to grassland between 1971 and 1978. For federal lands, the land use history is derived from land cover changes in the National Land Cover Dataset (Homer et al. 2007; Fry et al. 2011; Homer et al. 2015).

Mineral Soil Carbon Stock Changes

An IPCC Tier 3 model-based approach (Ogle et al. 2010) is applied to estimate C stock changes for *Land Converted to Grassland* on most mineral soils that are classified in this land use change category. C stock changes on the remaining soils are estimated with an IPCC Tier 2 approach (Ogle et al. 2003), including prior cropland used to produce vegetables, tobacco, and perennial/horticultural crops; land areas with very gravelly, cobbly, or shaley soils (greater than 35 percent by volume); and land converted to grassland from another land use other than cropland.

A surrogate data method is used to estimate soil C stock changes from 2013 to 2016 at the national scale for land areas included in the Tier 2 and Tier 3 methods. Specifically, linear regression models with autoregressive moving-average (ARMA) errors (Brockwell and Davis 2016) are used to estimate the relationship between surrogate data and the 1990 to 2012 emissions data that are derived using the Tier 2 and 3 methods. Surrogate data for these regression models include weather data from the PRISM Climate Group (PRISM 2015). See Box 6-6 in the Methodology Section of *Cropland Remaining Cropland* for more information about the surrogate data method. Stock change estimates for 2013 to 2016 will be recalculated in future inventories when new NRI data are available.

Tier 3 Approach. Mineral SOC stocks and stock changes are estimated using the DAYCENT biogeochemical[51] model (Parton et al. 1998; Del Grosso et al. 2001, 2011). The DAYCENT model utilizes the soil C modeling framework developed in the Century model (Parton et al. 1987, 1988, 1994; Metherell et al. 1993), but has been refined to simulate dynamics at a daily time-step. Historical land use patterns and irrigation histories are simulated with DAYCENT based on the 2012 USDA NRI survey (USDA-NRCS 2015). C stocks and 95 percent confidence intervals are estimated for each year between 1990 and 2012. See the *Cropland Remaining Cropland* section and Annex 3.12 for additional discussion of the Tier 3 methodology for mineral soils.

Soil C stock changes from 2013 to 2016 are estimated using a surrogate data method described in Box 6-6 of the Methodology section in *Cropland Remaining Cropland*. Future inventories will be updated with new activity data when the data are made available, and the time series will be recalculated (See Planned Improvements section in *Cropland Remaining Cropland*).

Tier 2 Approach. For the mineral soils not included in the Tier 3 analysis, SOC stock changes are estimated using a Tier 2 Approach, as described in the Tier 2 Approach for mineral soils in *Grassland Remaining Grassland*. This includes application of the surrogate data method that is described in Box 6-6 of the Methodology Section in *Cropland Remaining Cropland*. As with the Tier 3 method, future inventories will be updated with new NRI activity data when the data are made available, and the time series will be recalculated.

Organic Soil Carbon Stock Changes

Annual C emissions from drained organic soils in *Land Converted to Grassland* are estimated using the Tier 2 method provided in IPCC (2006), with U.S.-specific C loss rates (Ogle et al. 2003) as described in the *Cropland Remaining Cropland* section for organic soils. A surrogate data method is used to estimate annual C emissions from organic soils from 2013 to 2016 as described in Box 6-6 of the Methodology section in *Cropland Remaining Cropland*. Estimates for 2013 to 2016 will be recalculated in future inventories when new NRI data are available.

Uncertainty and Time-Series Consistency

The uncertainty analysis for biomass, dead wood and litter C losses with *Forest Land Converted to Grassland* is conducted in the same way as the uncertainty assessment for forest ecosystem C flux in the *Forest Land Remaining Forest Land* category. Sample and model-based error are combined using simple error propagation methods provided by the IPCC (2006), by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities. For additional details see the Uncertainty Analysis in Annex 3.13. The uncertainty analyses for mineral soil C stock changes using the Tier 3 and Tier 2 methodologies are based on a Monte Carlo approach that is described in the *Cropland Remaining Cropland* section. The uncertainty for annual C emission estimates from drained organic soils in *Land Converted to Grassland* is estimated using a Monte Carlo approach, which is also described in the *Cropland Remaining Cropland* section. For 2013 to 2016, there is additional uncertainty propagated through the Monte Carlo Analysis associated with a surrogate data method, which is also described in *Cropland Remaining Cropland*.

Uncertainty estimates are presented in Table 6-43 for each subsource (i.e., biomass C stocks, mineral soil C stocks and organic soil C stocks) and the method applied in the inventory analysis (i.e., Tier 2 and Tier 3). Uncertainty estimates from the Tier 2 and 3 approaches are combined using the simple error propagation methods provided by the IPCC (2006), as discussed in the previous paragraph. The combined uncertainty for total C stocks in *Land Converted to Grassland* ranges from 133 percent below to 134 percent above the 2016 stock change estimate of 22.0 MMT CO_2 Eq. The large relative uncertainty around the 2016 stock change estimate is partly due to variation in soil C stock changes that are not explained by the surrogate data method, leading to high prediction error with this splicing method.

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[51] Biogeochemical cycles are the flow of chemical elements and compounds between living organisms and the physical environment.

Table 6-43: Approach 2 Quantitative Uncertainty Estimates for Soil, Dead Organic Matter and Biomass C Stock Changes occurring within *Land Converted to Grassland* (MMT CO_2 Eq. and Percent)

Source	2016 Flux Estimate[a] (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate[a] (MMT CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Cropland Converted to Grassland	**(7.5)**	**(16.3)**	**1.3**	**-118%**	**118%**
Mineral Soil C Stocks: Tier 3	(8.6)	(17.4)	(0.3)	-103%	103%
Mineral Soil C Stocks: Tier 2	(0.1)	(0.2)	0.1	-343%	343%
Organic Soil C Stocks: Tier 2	1.1	0.8	1.4	-26%	26%
Forest Land Converted to Grassland	**29.4**	**1.4**	**57.5**	**-95%**	**95%**
Aboveground Live Biomass	20.9	(1.9)	43.7	-109%	109%
Belowground Live Biomass	1.7	(10.6)	14.0	-711%	711%
Dead Wood	3.6	(6.5)	13.8	-281%	281%
Litter	6.2	3.1	9.3	-50%	50%
Mineral Soil C Stocks: Tier 2	(3.1)	(5.2)	(1.0)	-68%	68%
Organic Soil C Stocks: Tier 2	0.1	0.1	0.2	-38%	38%
Other Lands Converted to Grassland	**(0.1)**	**(0.2)**	**0.1**	**-250%**	**250%**
Mineral Soil C Stocks: Tier 2	(0.1)	(0.3)	0.1	-154%	154%
Organic Soil C Stocks: Tier 2	+	+	0.1	-36%	37%
Settlements Converted to Grassland	**+**	**+**	**+**	**-69%**	**69%**
Mineral Soil C Stocks: Tier 2	(+)	(+)	+	-500%	525%
Organic Soil C Stocks: Tier 2	+	+	+	-47%	45%
Wetlands Converted to Grasslands	**0.1**	**(0.1)**	**0.3**	**-153%**	**153%**
Mineral Soil C Stocks: Tier 2	(0.2)	(0.3)	(+)	-80%	80%
Organic Soil C Stocks: Tier 2	0.3	0.2	0.4	-38%	38%
Total: Land Converted to Grassland	**22.0**	**(7.4)**	**51.5**	**-133%**	**134%**
Aboveground Live Biomass	**20.9**	**(1.9)**	**43.7**	**-109%**	**109%**
Belowground Live Biomass	**1.7**	**(10.6)**	**14.0**	**-711%**	**711%**
Dead Wood	**3.6**	**(6.5)**	**13.8**	**-281%**	**281%**
Litter	**6.2**	**3.1**	**9.3**	**-50%**	**50%**
Mineral Soil C Stocks: Tier 3	**(8.6)**	**(17.4)**	**(0.3)**	**-103%**	**103%**
Mineral Soil C Stocks: Tier 2	**(3.5)**	**(5.6)**	**(1.3)**	**-62%**	**62%**
Organic Soil C Stocks: Tier 2	**1.6**	**1.3**	**1.9**	**-20%**	**20%**

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

[a] Range of C stock change estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or net sequestration.

Methodological recalculations are applied from 2013 to 2015 using the surrogate data method developed using the C stock change estimates from 1990 to 2012, ensuring consistency across the time series. Details on the emission trends through time are described in more detail in the introductory section, above.

Uncertainty is also associated with a lack of reporting on biomass and dead organic matter C stock changes for *Land Converted to Grassland* with the exception of forest land conversion. Biomass C stock changes may be significant for managed grasslands with woody encroachment despite not having attained enough tree cover to be considered forest lands. Changes in dead organic matter C stocks are assumed to be negligible with conversion of land to grasslands with the exception of forest lands, which are included in this analysis. This assumption will be further explored in a future Inventory.

QA/QC and Verification

See the QA/QC and Verification section in *Cropland Remaining Cropland* for information on QA/QC steps.

Recalculations Discussion

Methodological recalculations are associated with extending the time series from 2013 through 2015 for mineral and organic soils using a surrogate data method. No other recalculations have been implemented in this Inventory. Carbon stock change estimates increase by an average of 9 percent from 2013 through 2015 based on the recalculation.

Planned Improvements

The amount of biomass C that is lost abruptly with *Forest Land Converted to Grasslands* is estimated based on the amount of C before conversion and an assumed level of C left after conversion based on published literature for the Western United States and Great Plains Regions. The amount of C left after conversion needs further investigation, including tree biomass, understory biomass, dead wood and litter C pools. Moreover, there is currently very limited data collection that would capture the slower change in C (i.e., gains or losses of C) that may be occurring in woodlands following the transfer of C from the previous forest land category. One key improvement is to further investigate the abrupt and more gradual changes in biomass C stock changes that are occurring in different regions, particularly in the Western United States and Great Plains.

Soil C stock changes with land use conversion from forest land to grassland are undergoing further evaluation to ensure consistency in the time series. Different methods are used to estimate soil C stock changes in forest land and grasslands, and while the areas have been reconciled between these land uses, there has been limited evaluation of the consistency in C stock changes with conversion from forest land to grassland. In addition, biomass C stock changes will be estimated for *Cropland Converted to Grassland*, and other land use conversions to grassland, to the extent that data are available. One additional planned improvement for the *Land Converted to Grassland* category is to develop an inventory of C stock changes for grasslands in Alaska. For information about other improvements, see the Planned Improvements section in *Cropland Remaining Cropland* and *Grassland Remaining Grassland*.

6.8 Wetlands Remaining Wetlands (CRF Category 4D1)

Wetlands Remaining Wetlands includes all wetland in an Inventory year that had been classified as wetland for the previous 20 years, and in this Inventory includes Peatlands and Coastal Wetlands.

Peatlands Remaining Peatlands

Emissions from Managed Peatlands

Managed peatlands are peatlands that have been cleared and drained for the production of peat. The production cycle of a managed peatland has three phases: land conversion in preparation for peat extraction (e.g., clearing surface biomass, draining), extraction (which results in the emissions reported under *Peatlands Remaining Peatlands*), and abandonment, restoration, or conversion of the land to another use.

Carbon dioxide emissions from the removal of biomass and the decay of drained peat constitute the major greenhouse gas flux from managed peatlands. Managed peatlands may also emit CH_4 and N_2O. The natural production of CH_4 is largely reduced but not entirely shut down when peatlands are drained in preparation for peat extraction (Strack et al. 2004 as cited in the *2006 IPCC Guidelines*). Drained land surface and ditch networks contribute to the CH_4 flux in peatlands managed for peat extraction. Methane emissions were considered insignificant under the IPCC Tier 1 methodology (IPCC 2006), but are included in the emissions estimates for *Peatlands Remaining Peatlands* consistent with the *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* (IPCC 2013). Nitrous oxide emissions from managed peatlands depend on site fertility. In addition, abandoned and restored peatlands continue to release greenhouse gas emissions. Although methodologies are provided for rewetted organic soils (which includes rewetted/restored peatlands) in IPCC (2013) guidelines, information on the areal extent of rewetted/restored peatlands in the United States is currently unavailable. The current Inventory estimates CO_2, CH_4 and N_2O emissions from peatlands managed for peat extraction in accordance with IPCC (2006 and 2013) guidelines.

CO_2, N_2O, and CH_4 Emissions from Peatlands Remaining Peatlands

IPCC (2013) recommends reporting CO_2, N_2O, and CH_4 emissions from lands undergoing active peat extraction (i.e., *Peatlands Remaining Peatlands*) as part of the estimate for emissions from managed wetlands. Peatlands occur where plant biomass has sunk to the bottom of water bodies and water-logged areas and exhausted the oxygen supply below the water surface during the course of decay. Due to these anaerobic conditions, much of the plant matter does not decompose but instead forms layers of peat over decades and centuries. In the United States, peat is extracted for horticulture and landscaping growing media, and for a wide variety of industrial, personal care, and other products. It has not been used for fuel in the United States for many decades. Peat is harvested from two types of peat deposits in the United States: sphagnum bogs in northern states (e.g., Minnesota) and wetlands in states further south (e.g., Florida). The peat from sphagnum bogs in northern states, which is nutrient-poor, is generally corrected for acidity and mixed with fertilizer. Production from more southerly states is relatively coarse (i.e., fibrous) but nutrient-rich.

IPCC (2006 and 2013) recommend considering both on-site and off-site emissions when estimating CO_2 emissions from *Peatlands Remaining Peatlands* using the Tier 1 approach. Current methodologies estimate only on-site N_2O and CH_4 emissions, since off-site N_2O estimates are complicated by the risk of double-counting emissions from nitrogen fertilizers added to horticultural peat, and off-site CH_4 emissions are not relevant given the non-energy uses of peat, so methodologies are not provided in IPCC (2013) guidelines.

On-site emissions from managed peatlands occur as the land is cleared of vegetation and the underlying peat is exposed to sun and weather. As this occurs, some peat deposit is lost and CO_2 is emitted from the oxidation of the peat. Since N_2O emissions from saturated ecosystems tend to be low unless there is an exogenous source of nitrogen, N_2O emissions from drained peatlands are dependent on nitrogen mineralization and therefore on soil fertility. Peatlands located on highly fertile soils contain significant amounts of organic nitrogen in inactive form. Draining land in preparation for peat extraction allows bacteria to convert the nitrogen into nitrates which leach to the surface where they are reduced to N_2O, and contributes to the activity of methanogens and methanotrophs that result in CH_4 emissions (Blodau 2002; Treat et al. 2007 as cited in IPCC 2013). Drainage ditches, which are constructed to drain the land in preparation for peat extraction, also contribute to the flux of CH_4 through *in situ* production and lateral transfer of CH_4 from the organic soil matrix (IPCC 2013).

Off-site CO_2 emissions from managed peatlands occur from waterborne carbon losses and the horticultural and landscaping use of peat. Dissolved organic carbon from water drained off peatlands reacts within aquatic ecosystems and is converted to CO_2, which is then emitted to the atmosphere (Billet et al. 2004 as cited in IPCC 2013). During the horticultural and landscaping use of peat, nutrient-poor (but fertilizer-enriched) peat tends to be used in bedding plants and in greenhouse and plant nursery production, whereas nutrient-rich (but relatively coarse) peat is used directly in landscaping, athletic fields, golf courses, and plant nurseries. Most (nearly 94 percent) of the CO_2 emissions from peat occur off-site, as the peat is processed and sold to firms which, in the United States, use it predominantly for the aforementioned horticultural and landscaping purposes.

Total emissions from *Peatlands Remaining Peatlands* were estimated to be 0.7 MMT CO_2 Eq. in 2016 (see Table 6-44) comprising 0.7 MMT CO_2 Eq. (709 kt) of CO_2, 0.005 MMT CO_2 Eq. (0.18 kt) of CH_4 and 0.001 MMT CO_2 Eq. (0.002 kt) of N_2O. Total emissions in 2016 were about 7 percent less than total emissions in 2015.

Total emissions from *Peatlands Remaining Peatlands* have fluctuated between 0.7 and 1.3 MMT CO_2 Eq. across the time series with a decreasing trend from 1990 until 1993, followed by an increasing trend until reaching peak emissions in 2000. After 2000, emissions generally decreased until 2006 and then increased until 2009. The trend reversed in 2009 and total emissions have generally decreased between 2009 and 2016. Carbon dioxide emissions from *Peatlands Remaining Peatlands* have fluctuated between 0.7 and 1.3 MMT CO_2 across the time series, and these emissions drive the trends in total emissions. Methane and N_2O emissions remained close to zero across the time series. Nitrous oxide emissions showed a decreasing trend from 1990 until 1995, followed by an increasing trend through 2001. Nitrous oxide emissions decreased between 2001 and 2006, followed by a leveling off between 2008 and 2010, and a general decline between 2011 and 2016. Methane emissions decreased from 1990 until 1995, followed by an increasing trend through 2000, a period of fluctuation through 2010, and a general decline between 2010 and 2016.

Table 6-44: Emissions from *Peatlands Remaining Peatlands* (MMT CO_2 Eq.)

Gas	1990	2005	2012	2013	2014	2015	2016
CO_2	**1.1**	**1.1**	**0.8**	**0.8**	**0.8**	**0.8**	**0.7**
Off-site	1.0	1.0	0.8	0.7	0.7	0.7	0.7
On-site	0.1	0.1	0.1	+	0.1	+	0.1
CH_4 (On-site)	+	+	+	+	+	+	+
N_2O (On-site)	+	+	+	+	+	+	+
Total	**1.1**	**1.1**	**0.8**	**0.8**	**0.8**	**0.8**	**0.7**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: These numbers are based on U.S. production data in accordance with Tier 1 guidelines, which does not take into account imports, exports, and stockpiles (i.e., apparent consumption). Off-site N_2O emissions are not estimated to avoid double-counting N_2O emitted from the fertilizer that the peat is mixed with prior to horticultural use (see IPCC 2006). Totals may not sum due to independent rounding.

Table 6-45: Emissions from *Peatlands Remaining Peatlands* (kt)

Gas	1990	2005	2012	2013	2014	2015	2016
CO_2	**1,055**	**1,101**	**812**	**770**	**775**	**763**	**709**
Off-site	985	1,030	760	720	725	713	653
On-site	70	71	53	50	50	49	57
CH_4 (On-site)	+	+	+	+	+	+	+
N_2O (On-site)	+	+	+	+	+	+	+

+ Does not exceed 0.5 kt

Note: These numbers are based on U.S. production data in accordance with Tier 1 guidelines, which does not take into account imports, exports, and stockpiles (i.e., apparent consumption). Off-site N_2O emissions are not estimated to avoid double-counting N_2O emitted from the fertilizer that the peat is mixed with prior to horticultural use (see IPCC 2006). Totals may not sum due to independent rounding.

Methodology

The following methodology sections first describes the steps taken to calculate emissions estimates for the years 1990 through 2015, followed by the simplified methodology used to update 2016 values.

1990-2015 Off-Site CO_2 Emissions

Carbon dioxide emissions from domestic peat production were estimated using a Tier 1 methodology consistent with IPCC (2006). Off-site CO_2 emissions from *Peatlands Remaining Peatlands* were calculated by apportioning the annual weight of peat produced in the United States (Table 6-46) into peat extracted from nutrient-rich deposits and peat extracted from nutrient-poor deposits using annual percentage-by-weight figures. These nutrient-rich and nutrient-poor production values were then multiplied by the appropriate default C fraction conversion factor taken from IPCC (2006) in order to obtain off-site emission estimates. For the lower 48 states, both annual percentages of peat type by weight and domestic peat production data were sourced from estimates and industry statistics provided in the *Minerals Yearbook* and *Mineral Commodity Summaries* from the U.S. Geological Survey (USGS 1995 through 2015; USGS 2016). To develop these data, the U.S. Geological Survey (USGS; U.S. Bureau of Mines prior to 1997) obtained production and use information by surveying domestic peat producers. On average, about 75 percent of the peat operations respond to the survey; and USGS estimates data for non-respondents on the basis of prior-year production levels (Apodaca 2011).

The Alaska estimates rely on reported peat production from the annual *Alaska's Mineral Industry* reports (DGGS 1993 through 2015). Similar to the U.S. Geological Survey, the Alaska Department of Natural Resources, Division of Geological & Geophysical Surveys (DGGS) solicits voluntary reporting of peat production from producers for the *Alaska's Mineral Industry* report. However, the report does not estimate production for the non-reporting producers, resulting in larger inter-annual variation in reported peat production from Alaska depending on the number of producers who report in a given year (Szumigala 2011). In addition, in both the lower 48 states and Alaska, large variations in peat production can also result from variations in precipitation and the subsequent changes in moisture conditions, since unusually wet years can hamper peat production. The methodology estimates Alaska emissions separately from lower 48 emissions because the state conducts its own mineral survey and reports peat production by volume, rather than by weight (Table 6-47). However, volume production data were used to calculate off-site CO_2 emissions from Alaska applying the same methodology but with volume-specific C fraction conversion factors from IPCC (2006).[52] Peat production was not reported for 2015 in *Alaska's Mineral Industry 2014* report (DGGS 2015); and reliable data are not available beyond 2012, so Alaska's peat production in 2013, 2014, and 2015 (reported in cubic yards) was assumed to be equal to the 2012 value.

Consistent with IPCC (2013) guidelines, off-site CO_2 emissions from dissolved organic carbon were estimated based on the total area of peatlands managed for peat extraction, which is calculated from production data using the methodology described in the On-Site CO_2 Emissions section below. CO_2 emissions from dissolved organic C were estimated by multiplying the area of peatlands by the default emissions factor for dissolved organic C provided in IPCC (2013).

The *apparent consumption* of peat, which includes production plus imports minus exports plus the decrease in stockpiles, in the United States is over time the amount of domestic peat production. However, consistent with the Tier 1 method whereby only domestic peat production is accounted for when estimating off-site emissions, off-site CO_2 emissions from the use of peat not produced within the United States are not included in the Inventory. The United States has largely imported peat from Canada for horticultural purposes; from 2011 to 2014, imports of sphagnum moss (nutrient-poor) peat from Canada represented 97 percent of total U.S. peat imports (USGS 2016). Most peat produced in the United States is reed-sedge peat, generally from southern states, which is classified as nutrient-rich by IPCC (2006). Higher-tier calculations of CO_2 emissions from apparent consumption would involve consideration of the percentages of peat types stockpiled (nutrient-rich versus nutrient-poor) as well as the percentages of peat types imported and exported.

Table 6-46: Peat Production of Lower 48 States (kt)

Type of Deposit	1990	2005	2012	2013	2014	2015	2016
Nutrient-Rich	595.1	657.6	409.9	418.5	416.5	409.4	409.4
Nutrient-Poor	55.4	27.4	78.1	46.5	51.5	50.6	50.6
Total Production	**692.0**	**685.0**	**488.0**	**465.0**	**468.0**	**460.0**	**460.0**

Sources: United States Geological Survey (USGS) (1991–2015) *Minerals Yearbook: Peat (1994–2014);* United States Geological Survey (USGS) (2016) *Mineral Commodity Summaries: Peat (2016).*

Table 6-47: Peat Production of Alaska (Thousand Cubic Meters)

	1990	2005	2012	2013	2014	2015	2016
Total Production	49.7	47.8	93.1	93.1	93.1	93.1	93.1

Sources: Division of Geological & Geophysical Surveys (DGGS), Alaska Department of Natural Resources (1997–2015) *Alaska's Mineral Industry Report (1997–2014).*

1990-2015 On-site CO_2 Emissions

IPCC (2006) suggests basing the calculation of on-site emission estimates on the area of peatlands managed for peat extraction differentiated by the nutrient type of the deposit (rich versus poor). Information on the area of land managed for peat extraction is currently not available for the United States, but consistent with IPCC (2006), an average production rate for the industry was applied to derive an area estimate. In a mature industrialized peat industry, such as exists in the United States and Canada, the vacuum method can extract up to 100 metric tons per hectare per year (Cleary et al. 2005 as cited in IPCC 2006).[53] The area of land managed for peat extraction in the lower 48 states of the United States was estimated using nutrient-rich and nutrient-poor production data and the

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[52] Peat produced from Alaska was assumed to be nutrient poor; as is the case in Canada, "where deposits of high-quality [but nutrient poor] sphagnum moss are extensive" (USGS 2008).

[53] The vacuum method is one type of extraction that annually "mills" or breaks up the surface of the peat into particles, which then dry during the summer months. The air-dried peat particles are then collected by vacuum harvesters and transported from the area to stockpiles (IPCC 2006).

assumption that 100 metric tons of peat are extracted from a single hectare in a single year. The annual land area estimates were then multiplied by the IPCC (2013) default emission factor in order to calculate on-site CO_2 emission estimates. Production data are not available by weight for Alaska. In order to calculate on-site emissions resulting from *Peatlands Remaining Peatlands* in Alaska, the production data by volume were converted to weight using annual average bulk peat density values, and then converted to land area estimates using the same assumption that a single hectare yields 100 metric tons. The IPCC (2006) on-site emissions equation also includes a term which accounts for emissions resulting from the change in C stocks that occurs during the clearing of vegetation prior to peat extraction. Area data on land undergoing conversion to peatlands for peat extraction is also unavailable for the United States. However, USGS records show that the number of active operations in the United States has been declining since 1990; therefore, it seems reasonable to assume that no new areas are being cleared of vegetation for managed peat extraction. Other changes in C stocks in living biomass on managed peatlands are also assumed to be zero under the Tier 1 methodology (IPCC 2006 and 2013).

1990-2015 On-site N_2O Emissions

IPCC (2006) suggests basing the calculation of on-site N_2O emission estimates on the area of nutrient-rich peatlands managed for peat extraction. These area data are not available directly for the United States, but the on-site CO_2 emissions methodology above details the calculation of area data from production data. In order to estimate N_2O emissions, the area of nutrient-rich *Peatlands Remaining Peatlands* was multiplied by the appropriate default emission factor taken from IPCC (2013).

1990-2015 On-site CH_4 Emissions

IPCC (2013) also suggests basing the calculation of on-site CH_4 emission estimates on the total area of peatlands managed for peat extraction. Area data is derived using the calculation from production data described in the On-site CO_2 Emissions section above. In order to estimate CH_4 emissions from drained land surface, the area of *Peatlands Remaining Peatlands* was multiplied by the emission factor for direct CH_4 emissions taken from IPCC (2013). In order to estimate CH_4 emissions from drainage ditches, the total area of peatland was multiplied by the default fraction of peatland area that contains drainage ditches, and the appropriate emission factor taken from IPCC (2013).

2016 Emissions

A simplified inventory update was performed for the 1990 through 2016 Inventory using values from the 1990 through 2015 Inventory. Estimates of emissions from peatlands remaining peatlands were forecasted for 2016 and peat production values were set equal to 2015. Excel's FORECAST.ETS function was used to predict a 2016 value using historical data via an algorithm called "Exponential Triple Smoothing." This method smooths out the data to determine the overall trend and provide an appropriate estimate for 2016.

Uncertainty and Time-Series Consistency

A Monte Carlo (Approach 2) uncertainty analysis that was run on the 1990 through 2015 Inventory was applied to estimate the uncertainty of CO_2, CH_4, and N_2O emissions from *Peatlands Remaining Peatlands* for 2016, using the following assumptions:

- The uncertainty associated with peat production data was estimated to be ± 25 percent (Apodaca 2008) and assumed to be normally distributed.
- The uncertainty associated with peat production data stems from the fact that the USGS receives data from the smaller peat producers but estimates production from some larger peat distributors. The peat type production percentages were assumed to have the same uncertainty values and distribution as the peat production data (i.e., ± 25 percent with a normal distribution).
- The uncertainty associated with the reported production data for Alaska was assumed to be the same as for the lower 48 states, or ± 25 percent with a normal distribution. It should be noted that the DGGS estimates that around half of producers do not respond to their survey with peat production data; therefore, the production numbers reported are likely to underestimate Alaska peat production (Szumigala 2008).
- The uncertainty associated with the average bulk density values was estimated to be ± 25 percent with a normal distribution (Apodaca 2008).

- IPCC (2006 and 2013) gives uncertainty values for the emissions factors for the area of peat deposits managed for peat extraction based on the range of underlying data used to determine the emission factors. The uncertainty associated with the emission factors was assumed to be triangularly distributed.
- The uncertainty values surrounding the C fractions were based on IPCC (2006) and the uncertainty was assumed to be uniformly distributed.
- The uncertainty values associated with the fraction of peatland covered by ditches was assumed to be ± 100 percent with a normal distribution based on the assumption that greater than 10 percent coverage, the upper uncertainty bound, is not typical of drained organic soils outside of The Netherlands (IPCC 2013).

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 6-48. Carbon dioxide emissions from *Peatlands Remaining Peatlands* in 2016 were estimated to be between 0.6 and 0.8 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of 16 percent below to 16 percent above the 2016 emission estimate of 0.7 MMT CO_2 Eq. Methane emissions from *Peatlands Remaining Peatlands* in 2016 were estimated to be between 0.002 and 0.008 MMT CO_2 Eq. This indicates a range of 58 percent below to 78 percent above the 2016 emission estimate of 0.005 MMT CO_2 Eq. Nitrous oxide emissions from *Peatlands Remaining Peatlands* in 2016 were estimated to be between 0.0003 and 0.0011 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of 53 percent below to 53 percent above the 2016 emission estimate of 0.0007 MMT CO_2 Eq.

Table 6-48: Approach 2 Quantitative Uncertainty Estimates for CO_2, CH_4, and N_2O Emissions from *Peatlands Remaining Peatlands* (MMT CO_2 Eq. and Percent)

Source	Gas	2016 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Peatlands Remaining Peatlands	CO_2	0.7	0.6	0.8	-16%	16%
Peatlands Remaining Peatlands	CH_4	+	+	+	-58%	78%
Peatlands Remaining Peatlands	N_2O	+	+	+	-53%	53%

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

QA/QC and Verification

A QA/QC analysis was performed to review input data and calculations, and no issues were identified. In addition, the emission trends were analyzed to ensure they reflected activity data trends.

Recalculations Discussion

No recalculations were performed for the 1990 through 2016 Inventory.

Planned Improvements

In order to further improve estimates of CO_2, N_2O, and CH_4 emissions from *Peatlands Remaining Peatlands*, future efforts will investigate if improved data sources exist for determining the quantity of peat harvested per hectare and the total area undergoing peat extraction.

Efforts will also be made to find a new source for Alaska peat production. The current source has not been reliably updated since 2012 and future publication of these data may discontinue.

The *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* describes inventory methodologies for various wetland source categories. In the 1990 through 2013 Inventory, EPA began including updated methods for *Peatlands Remaining Peatlands* to align them with the *2013 IPCC Supplement*. For future inventories, EPA will determine if additional updates are needed to further address the *2013 IPCC Supplement* for *Peatlands Remaining Peatlands*.

The *2006 IPCC Guidelines* do not cover all wetland types; they are restricted to peatlands drained and managed for peat extraction, conversion to flooded lands, and some guidance for drained organic soils. They also do not cover all of the significant activities occurring on wetlands (e.g., rewetting of peatlands). Since this inventory only includes *Peatlands Remaining Peatlands*, additional wetland types and activities found in the *2013 IPCC Supplement* will be reviewed to determine if they apply to the United States. For those that do, available data will be investigated to allow for the estimation of greenhouse gas fluxes in future inventory years.

Coastal Wetlands Remaining Coastal Wetlands

The Inventory recognizes Wetlands as a "land-use that includes land covered or saturated for all or part of the year, in addition to areas of lakes, reservoirs and rivers." Consistent with ecological definitions of wetlands,[54] the United States has historically included under the category of Wetlands those coastal shallow water areas of estuaries and bays that lie within the extent of the Land Representation.

Additional guidance on quantifying greenhouse gas emissions and removals on Coastal Wetlands is provided in the *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands (Wetlands Supplement),* which recognizes the particular importance of vascular plants in sequestering CO_2 from the atmosphere and building soil carbon stocks. Thus, the *Wetlands Supplement* provides specific guidance on quantifying emissions on organic and mineral soils that are covered or saturated for part of the year by tidal freshwater, brackish or saline water and are vegetated by vascular plants and may extend seaward to the maximum depth of vascular plant vegetation.

The United States recognizes both Vegetated Wetlands and Unvegetated Open Water as Coastal Wetlands. Per guidance provided by the *Wetlands Supplement* sequestration of carbon into biomass and soils carbon pools is recognized only in Vegetated Coastal Wetlands and not to occur in Unvegetated Open Water Coastal Wetlands. The United States takes the additional step of recognizing that stock losses occur when Vegetated Coastal Wetlands are converted to Unvegetated Coastal Wetlands.

This Inventory includes all privately-owned and publicly-owned coastal wetlands along the oceanic shores on the conterminous U.S., but does not include *Coastal Wetlands Remaining Coastal Wetlands* in Alaska or Hawaii. Seagrasses are not currently included within the Inventory due to insufficient data on distribution, change through time and carbon (C) stocks or C stock changes as a result of anthropogenic influence.

Under the *Coastal Wetlands Remaining Coastal Wetlands* category, the following emissions and removals are quantified in this chapter:

1) Carbon stock changes and CH_4 emissions on *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands*,
2) Carbon changes on *Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands*,
3) Carbon stock changes on *Unvegetated Open Water Coastal Wetlands Converted to Vegetated Coastal Wetlands*, and
4) *Nitrous Oxide Emissions from Aquaculture in Coastal Wetlands*.

Vegetated coastal wetlands hold C in all five C pools (i.e., aboveground, belowground, dead organic matter [DOM; dead wood and litter], and soil) though typically soil C and, to a lesser extent aboveground- and belowground-biomass, are the dominant pools, depending on wetland type (i.e., forested vs. marsh). Vegetated Coastal Wetlands are net accumulators of soil C as soils accumulate C under anaerobic soil conditions. Emissions from soil C and biomass stocks occur when Vegetated Coastal Wetlands are converted to Unvegetated Open Water Coastal Wetlands (i.e., when managed Vegetated Coastal Wetlands are lost due to subsidence), but are still recognized as Coastal Wetlands in this Inventory. These C emissions resulting from conversion to Unvegetated Open Water Coastal Wetlands, can cause the release of many years of accumulated soil C. Conversion of Unvegetated Open Water Coastal Wetlands to Vegetated Coastal Wetlands initiates the re-building of soil C stocks within soils and biomass. In applying the *2013 IPCC Wetlands Supplement* methodologies for CH_4 emissions, coastal wetlands in salinity conditions less than half that of sea water are sources of CH_4 as result of slow decomposition of organic

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[54] See <https://water.usgs.gov/nwsum/WSP2425/definitions.html>.

matter under freshwater, anaerobic conditions. Conversion of Vegetated Coastal Wetlands to or from Unvegetated Open Water Coastal Wetlands do not result in a change in salinity condition and are assumed to have no impact on CH_4 emissions. The *2013 IPCC Wetlands Supplement* provides methodologies to estimate N_2O emissions on coastal wetlands that occur due to aquaculture. While N_2O emissions can also occur due to anthropogenic N loading from the watershed and atmospheric deposition, these emissions are not reported here to avoid double-counting of indirect N_2O emissions with the Agricultural Soils Management category. The N_2O emissions from Aquaculture result from the N derived from consumption of the applied food stock that is then excreted as N load available for conversion to N_2O.

The *Wetlands Supplement* provides procedures for estimating CO_2 emissions and removals and CH_4 emissions from mangroves, tidal marshes and seagrasses. Depending upon their height and area, emissions and removals from managed mangroves may be reported under the Forest Land category or under Coastal Wetlands. All non-drained, intact coastal marshes are intended to be reported under Coastal Wetlands.

Because of human use and level of regulatory oversight, all coastal wetlands within the conterminous United States are included within the managed land area described in Section 6.1, and as such all estimates of CO_2 emissions and removals, and emissions of CH_4, and N_2O from aquaculture are included in this Inventory. At the present stage of inventory development, Coastal Wetlands are not explicitly shown in the Land Representation analysis while work continues to harmonize data from NOAA's Coastal Change Analysis Program[55] with NRI data used to compile the Land Representation. However, a check was undertaken to confirm that Coastal Wetlands recognized by C-CAP represented a subset of Wetlands recognized by the NRI for marine coastal states.

Emissions and Removals from Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands

The conterminous United States hosts 2.9 million hectares of intertidal *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands* comprised of tidally influenced palustrine emergent marsh (599,145 ha), palustrine scrub shrub (138,748 ha) and estuarine emergent marsh (1,852,842 ha), estuarine scrub shrub (97,098 ha) and estuarine forest (191,551 ha). Mangroves fall under both estuarine forest and estuarine scrub shrub categories depending upon height. Dwarf mangroves, found in Texas, do not attain the height status to be recognized as Forest Land, and are therefore always classified within Vegetated Coastal Wetlands. *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands* are found in cold temperate (52,400 ha), warm temperate (892,297 ha), subtropical (1,878,074 ha) and Mediterranean (56,613 ha) climate zones.

Soils are the largest pool of C in *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands* reflecting long-term removal of atmospheric CO_2 by vegetation and transfer into the soil pool in the form of decaying organic matter. Emissions of soil C are not assumed to occur in coastal wetlands that remain vegetated. In this Inventory, only C stock changes within soils are reported as currently insufficient data exists on C stock changes in biomass, DOM and litter. Methane emissions from decomposition of organic matter in anaerobic conditions are significant at salinity less than half that of sea water. Mineral and organic soils are not differentiated in terms of C removals or CH_4 emissions.

Table 6-49 through Table 6-52 below summarize nationally aggregated soil C stock emissions and removals and CH_4 emissions on Vegetated Coastal Wetlands. Intact *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands* hold a large stock of C (here estimated to be 870 MMT C (3,190 MMT CO_2 Eq.)) within the top 1 meter of soil to which C is accumulated each year at a rate of 12.1 MMT CO_2 Eq. Methane emissions of 3.6 of MMT CO_2 Eq. offset C removals resulting in an annual net C removal rate of 8.5 MMT CO_2 Eq. Due to federal regulatory protection, loss of Vegetated Coastal Wetland area slowed considerably in the 1970s and the current rates of C stock change and CH_4 emissions are relatively constant over time. Losses of Vegetated Coastal Wetlands to Unvegetated Open Water Coastal Wetlands (described later in this chapter) and to other land uses do occur, which because of the depth to which soil C stocks are impacted, do have a significant impact on the net emissions and removals on Coastal Wetlands.

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[55] See <https://coast.noaa.gov/digitalcoast/tools/lca>.

Table 6-49: Net CO_2 Flux from Soil C Stock Changes in *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands* (MMT CO_2 Eq.)

Year	1990	2005	2012	2013	2014	2015	2016
Net Flux	(12.1)	(12.2)	(12.1)	(12.1)	(12.1)	(12.1)	(12.1)

Note: Parentheses indicate net sequestration

Table 6-50: Net CO_2 Flux from Soil C Stock Changes in *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands* (MMT C)

Year	1990	2005	2012	2013	2014	2015	2016
Net Flux	(3.3)	(3.3)	(3.3)	(3.3)	(3.3)	(3.3)	(3.3)

Note: Parentheses indicate net sequestration

Table 6-51: Net CH_4 Flux from *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands* (MMT CO_2 Eq.)

Year	1990	2005	2012	2013	2014	2015	2016
Net Flux	3.4	3.5	3.5	3.6	3.6	3.6	3.6

Table 6-52: Net CH_4 Flux from *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands* (kt CH_4)

Year	1990	2005	2012	2013	2014	2015	2016
Net Flux	138	140	142	142	142	143	143

Methodology

The following section includes a description of the methodology used to estimate changes in soil C stocks and emissions of CH_4 for *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands*.

Soil Carbon Stock Changes

Soil C removals are estimated for *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands* for both mineral and organic soils on wetlands below the elevation of high tides (taken to be mean high water spring tide elevation) and as far seawards as the extent of intertidal vascular plants according to the national LiDAR dataset, the national network of tide gauges and land use histories recorded in the 1996, 2001, 2005 and 2010 NOAA C-CAP surveys.[56] Federal and non-federal lands are represented. Trends in land cover change are extrapolated to 1990 and 2016 from these datasets. Based upon NOAA C-CAP, coastal wetlands are subdivided into freshwater (Palustrine) and saline (Estuarine) classes and further subdivided into emergent marsh, scrub shrub and forest classes.[57] Soil C stock changes, stratified by climate zones and wetland classes, are derived from a synthesis of peer-reviewed literature (Mangrove pool and removals data: Cahoon & Lynch unpublished data; Lynch 1989; Callaway et al. 1997; Chen & Twilley 1999; McKee & Faulkner 2000; Ross et al. 2000; Chmura et al. 2003; Perry & Mendelssohn 2009; Castaneda-Moya et al. 2013; Henry & Twilley 2013; Doughty et al. 2015; Marchio et al. 2016. Tidal marsh pool and removals data: Anisfeld unpublished data; Cahoon unpublished data; Cahoon & Lynch unpublished data; Chmura unpublished data; McCaffrey & Thomson 1980; Hatton 1981; Callaway et al. 1987; Craft et al. 1988; Cahoon & Turner 1989; Patrick & DeLaune 1990; Kearney & Stevenson 1991;Cahoon et al. 1996; Callaway et al. 1997; Roman et al. 1997; Bryant & Chabrek 1998; Orson et al. 1998; Markewich et al. 1998; Anisfeld et al. 1999; Connor et al. 2001; Choi & Wang 2001; Chmura et al. 2003, Hussein et al. 2004; Craft 2007; Miller et al. 2008; Drexler et al. 2009; Perry & Mendelssohn 2009; Loomis & Craft 2010; EPA's NWCA 2011; Callaway et al. 2012; Henry &

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[56] See <https://coast.noaa.gov/digitalcoast/tools/lca.html>.

[57] See <https://coast.noaa.gov/digitalcoast/tools/lca.html>.

Twilley 2013; Weston et al. 2014). To estimate soil C stock changes no differentiation is made between organic and mineral soils.

Tier 2 level estimates of soil C removal associated with annual soil C accumulation from managed *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands* were developed with country-specific soil C removal factors multiplied by activity data of land area for *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands*. The methodology follows Eq. 4.7, Chapter 4 of the *Wetlands Supplement*, and is applied to the area of *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands* on an annual basis. Emission factors were developed from literature references that provided soil C removal factors disaggregated by climate region, vegetation type by salinity range (estuarine or palustrine) as identified using NOAA C-CAP as described above. Quantification of regional coastal wetland above and belowground biomass C stock changes for woody and perennial herbaceous vegetation, DOM (dead wood and litter) C stocks are in development and are not presented this year, though will be included in future reports.

Soil Methane Emissions

Tier 1 estimates of CH_4 emissions for *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands* are derived from the same wetland map used in the analysis of wetland soil C fluxes, produced from C-CAP, LiDAR and tidal data, in combination with default CH_4 emission factors provided in Table 4.14 of the *Wetlands Supplement.* The methodology follows Eq. 4.9, Chapter 4 of the *Wetlands Supplement*, and is applied to the area of *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands* on an annual basis. The AR4 global warming potential factor of 25 was used in converting CH_4 to CO_2 Eq. values.

Uncertainty and Time-Series Consistency

Underlying uncertainties in estimates of soil C stock changes and CH_4 include error in uncertainties associated with Tier 2 literature values of soil C stocks and CH_4 flux, assumptions that underlie the methodological approaches applied and uncertainties linked to interpretation of remote sensing data. Uncertainty specific to *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands* include differentiation of palustrine and estuarine community classes, which determines the soil C stock and CH_4 flux applied. Soil C stocks and CH_4 fluxes applied are determined from vegetation community classes across the coastal zone and identified by NOAA C-CAP. Community classes are further subcategorized by climate zones and growth form (forest, shrub-scrub, marsh). Uncertainties for soil C stock data for all subcategories are not available and thus assumptions were applied using expert judgement about the most appropriate assignment of a soil C stock to a disaggregation of a community class. Because mean soil C stocks for each available community class are in a fairly narrow range, the same overall uncertainty was assigned to each (i.e., applying approach for asymmetrical errors, where the largest uncertainty for any one soil C stock referenced using published literature values for a community class; uncertainty approaches provide that if multiple values are available for a single parameter, the highest uncertainty value should be applied to the propagation of errors; IPCC 2000). Uncertainties for CH_4 flux are the Tier 1 default values reported in the *Wetlands Supplement*. Overall uncertainty of the NOAA C-CAP remote sensing product is 15 percent. This is in the range of remote sensing methods (±10-15 percent; IPCC 2003). However, there is significant uncertainty in salinity ranges for tidal and non-tidal estuarine wetlands and activity data used to apply CH_4 flux emission factors (delineation of an 18 ppt boundary) will need significant improvement to reduce uncertainties.

Table 6-53: Approach 1 Quantitative Uncertainty Estimates for Emissions from C Stock Changes occurring within *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands* (MMT CO_2 Eq. and Percent)

Source	2016 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate (MMT CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Combined Uncertainty for Flux Associated with Wetlands Soil C Stock Change in *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands*	(12.1)	(15.6)	(8.5)	-29.5%	29.5%

Note: Parentheses indicate net sequestration.

Table 6-54: Approach 1 Quantitative Uncertainty Estimates for CH_4 Emissions occurring within *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands* (MMT CO_2 Eq. and Percent)

Source	2016 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate (MMT CO_2 Eq.)		Uncertainty Range Relative to Flux Estimate (%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Combined Uncertainty for Flux Associated with CH_4 emissions in *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands*	3.6	2.5	4.6	-29.8%	29.8%

QA/QC and Verification

NOAA provided National LiDAR Dataset, tide data, and C-CAP land cover and land cover change mapping, all of which are subject to agency internal QA/QC assessment. Acceptance of final datasets into archive and dissemination are contingent upon the product compilation being compliant with mandatory QA/QC requirements (McCombs et al. 2016). QA/QC and verification of soil C stock datasets have been provided by the Smithsonian Environmental Research Center and Coastal Wetland Inventory team leads who reviewed summary tables against reviewed sources. Land cover estimates were assessed to ensure that the total land area did not change over the time series in which the inventory was developed, and verified by a second QA team. A team of two evaluated and verified there were no computational errors within the calculation worksheets. Soil C stock, emissions/removals data are based upon peer-reviewed literature and CH_4 emission factors derived from the IPCC Wetlands Supplement.

Planned Improvements

A USGS/NASA Carbon Monitoring System investigation is in progress to establish a U.S. country-specific database of soil C stock, wetland biomass and CH_4 emissions for coastal wetlands. Refined error analysis combining land cover change and C stock estimates will be provided. Through this work a model is in development to represent changes in soil C stocks. This research effort is due to be completed by November 2017, with plans to include the results from the new model in the 1990 through 2017 Inventory (i.e., 2019 submission to the UNFCCC).

The C-CAP dataset for 2015 is currently under development. Once complete, land use change for 2011 through 2016 will be recalculated with this updated dataset.

With the conclusion of the Blue Carbon Monitoring System Project it is intended that the next (i.e., 1990 through 2017) Inventory will include new data on estuarine emergent biomass C stocks and refined reference soil C stocks and uncertainty analysis based upon an expanded national dataset.

Emissions from Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands

Conversion of intact Vegetated Coastal Wetlands to Unvegetated Open Water Coastal Wetlands is a source of emissions from both soil and biomass C stocks. It is estimated that 8,428 ha of Vegetated Coastal Wetlands were converted to Unvegetated Open Water Coastal Wetlands in 2016. The Mississippi Delta represents more than 40 percent of the total coastal wetland of the United States, and over 90 percent of the conversion of Vegetated Coastal Wetlands to Unvegetated Open Water Coastal Wetlands. The drivers of coastal wetlands loss include legacy human impacts on sediment supply through rerouting river flow, direct impacts of channel cutting on hydrology, salinity and sediment delivery and accelerated subsidence from aquafer extraction. Each of these drivers directly contributes to wetland erosion and subsidence, while also reducing the resilience of the wetland to build with sea level rise or recover from hurricane disturbance. Over recent decades the rate of Mississippi Delta wetland loss has slowed, though episodic mobilization of sediment occurs during hurricane events (Couvillion et al. 2011; Couvillion et al.

2016). The most recent land cover analysis recorded by the C-CAP surveys of 2005 and 2010 coincides with two such events, hurricanes Katrina and Rita both in 2005.

Shallow nearshore open water within the U.S. Land Representation is recognized as falling under the Wetlands category within the U.S. Inventory. Changes in biomass are not presented this year but will be in the future (see Planned Improvements). While high resolution mapping of coastal wetlands provides data to support Tier 2 approaches for tracking land cover change, the depth to which sediment is lost is less clear. This Inventory adopts the Tier 1 methodological guidance from the *Wetlands Supplement* for estimating emissions following the methodology for excavation (see Methodology section, below) when Vegetated Coastal Wetlands are converted to Unvegetated Open Water Coastal Wetlands, assuming a 1 m depth of disturbed soil. This 1 m depth of disturbance is consistent with estimates of wetland C loss provided in the literature (Crooks et al. 2009; Couvillion et al. 2011; Delaune and White 2012; IPCC 2013). A Tier 1 assumption is also adopted that all mobilized C is immediately returned to the atmosphere (as assumed for terrestrial land use categories), rather than redeposited in long-term C storage. The science is currently under evaluation to adopt more refined emissions factors for mobilized coastal wetland C based upon the geomorphic setting of the depositional environment.

Table 6-55: Net CO_2 Flux from Soil C Stock Changes in *Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands* (MMT CO_2 Eq.)

Year	1990		2005		2012	2013	2014	2015	2016
Net Soil Flux	3.5		2.1		3.5	3.5	3.5	3.5	3.5

Table 6-56: Net CO_2 Flux from Soil C Stock Changes in *Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands* (MMT C)

Year	1990		2005		2012	2013	2014	2015	2016
Net Soil Flux	1.0		0.6		1.0	1.0	1.0	1.0	1.0

Methodology

The following section includes a brief description of the methodology used to estimate changes in soil C stocks for *Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands*.

Soil Carbon Stock Changes

Soil C stock changes are estimated for *Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands* on lands below the elevation of high tides (taken to be mean high water spring tide elevation) within the U.S. Land Representation according to the national LiDAR dataset, the national network of tide gauges and land use histories recorded in the 1996, 2001, 2005 and 2010 NOAA C-CAP surveys. Publicly-owned and privately-owned lands are represented. Trends in land cover change are extrapolated to 1990 and 2016 from these datasets. C-CAP provides peer reviewed country-specific mapping to support IPCC Approach 3 quantification of coastal wetland distribution, including conversion to and from open water. Country-specific soil C stocks for mineral and organic soils, stratified by climate zones and wetland classes, are derived from a synthesis of peer-reviewed literature (Mangrove pool and removals data: Cahoon & Lynch unpublished data; Lynch 1989; Callaway et al. 1997; Chen & Twilley 1999; McKee & Faulkner 2000; Ross et al. 2000; Chmura et al. 2003; Perry & Mendelssohn 2009; Castaneda-Moya et al. 2013; Henry & Twilley 2013; Doughty et al. 2015; Marchio et al. 2016. Tidal marsh pool and removals data: Anisfeld unpublished data; Cahoon unpublished data; Cahoon & Lynch unpublished data; Chmura unpublished data; McCaffrey & Thomson 1980; Hatton 1981; Callaway et al. 1987; Craft et al. 1988; Cahoon & Turner 1989; Patrick & DeLaune 1990; Kearney & Stevenson 1991; Cahoon et al. 1996; Callaway et al. 1997; Roman et al. 1997; Bryant & Chabrek 1998; Orson et al. 1998; Markewich et al. 1998; Anisfeld et al. 1999; Connor et al. 2001; Choi & Wang 2001; Chmura et al. 2003, Hussein et al. 2004; Craft 2007; Miller et al. 2008; Drexler et al. 2009; Perry & Mendelssohn 2009; Loomis & Craft 2010; EPA's NWCA 2011; Callaway et al. 2012; Henry & Twilley 2013; Weston et al. 2014). For soil C stock change no differentiation is made between organic and mineral soils. Following the Tier 1 approach for estimating CO_2 emissions with extraction provided within the *Wetlands Supplement*, soil C loss with conversion of Vegetated Coastal Wetlands to Unvegetated Open Water Coastal Wetlands is assumed to affect soil C stock to one-meter depth with all emissions occurring in the year of wetland conversion, and multiplied by activity data of land area for management coastal wetlands. The methodology follows Eq. 4.6. Quantification of regional coastal wetland biomass stock changes for conversion of Vegetated Coastal Wetlands to Unvegetated Open Water Coastal Wetlands are in development and are not presented this year, though will be included in future reports.

Soil Methane Emissions

A Tier 1 assumption has been applied that salinity conditions are unchanged and hence methane emissions are assumed to be zero with conversion of Vegetated Coastal Wetlands to Unvegetated Open Water Coastal Wetlands.

Uncertainty and Time-Series Consistency

Underlying uncertainties in estimates of soil C stock changes associated with Tier 2 literature values of soil C stocks, assumptions that underlie the methodological approaches applied and uncertainties linked to interpretation of remote sensing data are included in this uncertainty assessment. Uncertainty specific to coastal wetlands include differentiation of palustrine and estuarine community classes, which determines the soil C stock applied. Soil C stocks applied are determined from vegetation community classes across the coastal zone and identified by NOAA C-CAP. Community classes are further subcategorized by climate zones and growth form (forest, shrub-scrub, marsh). Soil C stock data for all subcategories are not available and thus assumptions were applied using expert judgement about the most appropriate assignment of a soil C stock to a disaggregation of a community class. Because mean soil C stocks for each available community class are in a fairly narrow range, the same overall uncertainty was assigned to each (i.e., applying approach for asymmetrical errors, where the largest uncertainty for any one soil C stock referenced using published literature values for a community class; uncertainty approaches provide that if multiple values are available for a single parameter, the highest uncertainty value should be applied to the propagation of errors; IPCC 2000). Uncertainties for CH_4 flux are the Tier 1 default values reported in the *Wetlands Supplement*. Overall uncertainty of the NOAA C-CAP remote sensing product is 15 percent. This is in the range of remote sensing methods (±10-15 percent; IPCC 2003).

Table 6-57: Approach 1 Quantitative Uncertainty Estimates for Net CO_2 Flux Occurring within *Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands* (MMT CO_2 Eq. and Percent)

Source	2016 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate (MMT CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Combined Uncertainty for Flux Associated with Soil C Stock Change in *Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands*	3.5	2.0	5.0	-41.7%	41.7%

The C-CAP dataset, consisting of a time series of four time intervals, each five years in length, and two major hurricanes striking the Mississippi Delta in the most recent time interval (2006 to 2010), creates a challenge in utilizing it to represent the annual rate of wetland loss and for extrapolation to 1990 and 2016. Uncertainty in the defining the long-term trend will be improved with release of the 2015 survey, expected in 2018 to 2019.

More detailed research is in development that provides a longer term assessment and more highly refined rates of wetlands loss across the Mississippi Delta (e.g., Couvillion et al. 2016), which could provide a more refined regional Approach 2-3 for assessing wetland loss and support the national-scale assessment provided by C-CAP.

Based upon the IPCC Tier 1 methodological guidance for estimating emissions with excavation in coastal wetlands, it has been assumed that a 1-meter column of soil has been remobilized with erosion and the C released immediately to the atmosphere as CO_2. This depth of disturbance is a simplifying assumption that is commonly applied in the scientific literature to gain a first-order estimate of scale of emissions (e.g., Delaune and White 2012). It is also a simplifying assumption that all that C is released back to the atmosphere immediately and future development of the Tier 2 estimate may refine the emissions both in terms of scale and rate. Given that erosion has been ongoing for multiple decades the assumption that the C eroded is released to the atmosphere the year of erosion is a reasonable simplification that could be further refined.

QA/QC and Verification

Data provided by NOAA (i.e., National LiDAR Dataset, NOS Tide Data, and C-CAP land cover and land cover change mapping) undergo internal agency QA/QC procedures. Acceptance of final datasets into archive and dissemination are contingent upon assurance that the data product is compliant with mandatory NOAA QA/QC requirements (McCombs et al. 2016). QA/QC and Verification of the soil C stock dataset has been provided by the Smithsonian Environmental Research Center and by the Coastal Wetlands project team leads who reviewed the estimates against primary scientific literature. Land cover estimates were assessed to ensure that the total land area did not change over the time series in which the inventory was developed, and were verified by a second QA team. A team of two evaluated and verified there were no computational errors within the calculation worksheets. Two biogeochemists at the USGS, in addition to members of the NASA Carbon Monitoring System Science Team, corroborated the assumption that where salinities are unchanged CH_4 emissions are constant with conversion of Unvegetated Open Water Coastal Wetlands to Vegetated Coastal Wetlands.

Planned Improvements

A refined uncertainty analysis and efforts to improve times series consistency is planned for the 1990 through 2017 Inventory (i.e., 2019 submission to the UNFCCC). An approach for calculating the fraction of remobilized coastal wetland soil C returned to the atmosphere as CO_2 is currently under review and may be included in future reports. Research by USGS is investigating higher resolution mapping approaches to quantify conversion of coastal wetlands is also underway. Such approaches may form the basis of an Approach 3 land representation assessment in future years.

The C-CAP dataset for 2015 is currently under development. Once complete, land use change for 2011 through 2016 will be recalculated with this updated dataset.

With the conclusion of the Blue Carbon Monitoring System Project it is intended that the 1990 through 2017 Inventory will include new data on estuarine emergent biomass C stocks and refined reference soil C stocks and uncertainty analysis based upon an expanded national dataset.

Removals from Unvegetated Open Water Coastal Wetlands Converted to Vegetated Coastal Wetlands

Open Water within the U.S. land base, as described in the Land Representation, is recognized as Wetlands within the Inventory. The appearance of vegetated tidal wetlands on lands previously recognized as open water reflects either the building of new vegetated marsh through sediment accumulation or the transition from other lands uses through an intermediary open water stage as flooding intolerant plants are displaced and then replaced by wetland plants. Biomass and soil C accumulation on *Unvegetated Open Water Coastal Wetlands Converted to Vegetated Coastal Wetlands* begins with vegetation establishment.

Within the United States, conversion of Unvegetated Open Water Coastal Wetlands to Vegetated Coastal Wetlands is predominantly due to engineered activities, which include active restoration of wetlands (e.g., wetlands restoration in San Francisco Bay), dam removals or other means to reconnect sediment supply to the nearshore (e.g., Atchafalaya Delta, Louisiana, Couvillion et al., 2011). Wetlands restoration projects have been ongoing in the United States since the 1970s. Early projects were small, a few hectares in size. By the 1990s, restoration projects, each hundreds of hectares in size, were becoming common in major estuaries. In a number of coastal areas e.g., San Francisco Bay, Puget Sound, Mississippi Delta and south Florida, restoration activities are in planning and implementation phases, each with the goal of recovering tens of thousands of hectares of wetlands.

During wetland restoration, Unvegetated Open Water Coastal Wetland is a common intermediary phase bridging land use transitions from Cropland or Grassland to Vegetated Coastal Wetlands. The time period of open water may last from five to 20 years depending upon the conditions. The conversion of these other land uses to Unvegetated Open Water Coastal Wetland will result in reestablishment of wetland biomass and soil C sequestration and may result in cessation of emissions from drained organic soil. Only changes in soil C stocks are reported in the Inventory at this time, but improvements are being evaluated to include changes from other C pools.

Table 6-58: Net CO_2 Flux from Soil C Stock Changes from *Unvegetated Open Water Coastal Wetlands Converted to Vegetated Coastal Wetlands* (MMT CO_2 Eq.)

Year	1990		2005		2012	2013	2014	2015	2016
Net Soil Flux	(0.01)		(+)		(0.01)	(0.01)	(0.01)	(0.01)	(0.01)

(+) Does not exceed 0.005 MMT CO_2 Eq.
Note: Parentheses indicate net sequestration.

Table 6-59: Net CO_2 Flux from Soil C Stock Changes from *Unvegetated Open Water Coastal Wetlands Converted to Vegetated Coastal Wetlands* (MMT C)

Year	1990		2005		2012	2013	2014	2015	2016
Net Soil Flux	(0.002)		(0.001)		(0.002)	(0.002)	(0.002)	(0.002)	(0.002)

Note: Parentheses indicate net sequestration.

Methodology

The following section includes a brief description of the methodology used to estimate changes in soil C stocks and CH_4 emissions for *Unvegetated Open Water Coastal Wetlands Converted to Vegetated Coastal Wetlands*.

Soil Carbon Stock Change

Soil C removals are estimated for *Unvegetated Open Water Coastal Wetlands Converted to Vegetated Coastal Wetlands* on lands below the elevation of high tides (taken to be mean high water spring tide elevation) according to the national LiDAR dataset, the national network of tide gauges and land use histories recorded in the 1996, 2001, 2005 and 2010 NOAA C-CAP surveys. Privately-owned, and publically-owned lands are represented. Trends in land cover change are extrapolated to 1990 and 2016 from these datasets. C-CAP provides peer reviewed Tier 2 level mapping of coastal wetland distribution, including conversion to and from open water. Country-specific soil C stock change associated with soil C accretion, stratified by climate zones and wetland classes, are derived from a synthesis of peer-reviewed literature (Mangrove pool and removals data*:* Cahoon & Lynch unpublished data; Lynch 1989; Callaway et al. 1997; Chen & Twilley 1999; McKee & Faulkner 2000; Ross et al. 2000; Chmura et al. 2003; Perry & Mendelssohn 2009; Castaneda-Moya et al. 2013; Henry & Twilley 2013; Doughty et al. 2015; Marchio et al. 2016. Tidal marsh pool and removals data: Anisfeld unpublished data; Cahoon unpublished data; Cahoon & Lynch unpublished data; Chmura unpublished data; McCaffrey & Thomson 1980; Hatton 1981; Callaway et al. 1987; Craft et al. 1988; Cahoon & Turner 1989; Patrick & DeLaune 1990; Kearney & Stevenson 1991;Cahoon et al. 1996; Callaway et al. 1997; Roman et al. 1997; Bryant & Chabrek 1998; Orson et al. 1998; Markewich et al. 1998; Anisfeld et al. 1999; Connor et al. 2001; Choi & Wang 2001; Chmura et al. 2003, Hussein et al. 2004; Craft 2007; Miller et al. 2008; Drexler et al. 2009; Perry & Mendelssohn 2009; Loomis & Craft 2010; EPA's NWCA 2011; Callaway et al. 2012; Henry & Twilley 2013; Weston et al. 2014). Soil C removals are stratified based upon wetland class (Estuarine, Palustrine) and subclass (Emergent Marsh, Scrub Shrub). For soil C stock change no differentiation is made for soil type (i.e., mineral, organic).

Tier 2 level estimates of CO_2 removals associated with annual soil C accumulation in managed Vegetated Coastal Wetlands were developed using country-specific soil C removal factors multiplied by activity data on land area for managed coastal wetlands. The methodology follows Eq. 4.7, Chapter 4 of the *Wetlands Supplement*, and is applied to the area of managed Vegetated Coastal Wetlands on an annual basis. Emission factors were developed from literature references that provided soil C removal factors disaggregated by climate region and vegetation type by salinity range (estuarine or palustrine) as identified using NOAA C-CAP as described above. Quantification of regional coastal wetland biomass C stock changes for perennial vegetation are in development and are not presented this year, though will be included in future reports.

Soil Methane Emissions

A Tier 1 assumption has been applied that salinity conditions are unchanged and hence methane emissions are assumed to be zero with conversion of Vegetated Open Water Coastal Wetlands to Vegetated Coastal Wetlands.

Uncertainty and Time-Series Consistency

Underlying uncertainties in estimates of soil C stock changes and methane emissions include error in uncertainties associated with Tier 2 literature values of soil C stocks and methane flux and assumptions that underlie the methodological approaches applied and uncertainties linked to interpretation of remote sensing data. Uncertainty specific to coastal wetlands include differentiation of palustrine and estuarine community classes which determines the soil C stock and methane flux applied. Soil C stocks and methane fluxes applied are determined from vegetation community classes across the coastal zone and identified by NOAA C-CAP. Community classes are further subcategorized by climate zones and growth form (forest, shrub-scrub, marsh). Soil C stock data for all subcategories are not available and thus assumptions were applied using expert judgement about the most appropriate assignment of a soil C stock to a disaggregation of a community class. Because mean soil C stocks for each available community class are in a fairly narrow range, the same overall uncertainty was applied to each (i.e., applying approach for asymmetrical errors, where the largest uncertainty for any one soil C stock referenced using published literature values for a community class; uncertainty approaches provide that if multiple values are available for a single parameter, the highest uncertainty value should be applied to the propagation of errors; IPCC 2000). Uncertainties for CH_4 flux are the Tier 1 default values reported in the *Wetlands Supplement*. Overall uncertainty of the NOAA C-CAP remote sensing product is 15 percent. This is in the range of remote sensing methods (±10 to 15 percent; IPCC 2003). Uncertainties for methane flux include the Tier 1 default values reported in the *Wetlands Supplement* along with the overall uncertainty of the NOAA C-CAP remote sensing product, which is estimated at 15 percent. This is in the typical range of remote sensing methods (±10 to 15; GPG LULUCF, Chapter 3). However, there is significant uncertainty in salinity ranges for tidal and non-tidal estuarine wetlands and activity data used to develop the methane flux (delineation of an 18 ppt boundary) will need significant improvement to reduce uncertainties.

Table 6-60: Approach 1 Quantitative Uncertainty Estimates for C Stock Changes Occurring within *Unvegetated Open Water Coastal Wetlands Converted to Vegetated Coastal Wetlands* (MMT CO_2 Eq. and Percent)

Source	2016 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate (MMT CO_2 Eq.)		Uncertainty Range Relative to Flux Estimate (%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Combined Uncertainty for Flux Associated with Wetlands Soil C Stock Change in *Unvegetated Open Water Coastal Wetlands Converted to Vegetated Coastal Wetlands*	(0.007)	(0.009)	(0.005)	-29.5%	29.5%

Note: Parentheses indicate net sequestration.

QA/QC and Verification

NOAA provided data (i.e., National LiDAR Dataset, NOS Tide Data, and C-CAP land cover and land cover change mapping) undergo internal agency QA/QC assessment procedures. Acceptance of final datasets into the archive for dissemination are contingent upon assurance that the product is compliant with mandatory NOAA QA/QC requirements (McCombs et al. 2016). QA/QC and Verification of soil C stock dataset has been provided by the Smithsonian Environmental Research Center and Coastal Wetlands project team leads who reviewed produced summary tables against primary scientific literature. Land cover estimates were assessed to ensure that the total land area did not change over the time series in which the inventory was developed, and verified by a second QA team. A team of two evaluated and verified there were no computational errors within calculation worksheets. Two biogeochemists at the USGS, also members of the NASA Carbon Monitoring System Science Team, corroborated the simplifying assumption that where salinities are unchanged CH_4 emissions are constant with conversion of Unvegetated Open Water Coastal Wetlands to Vegetated Coastal Wetlands.

Planned Improvements

A USGS/NASA Carbon Monitoring System investigation is in progress to establish a U.S. country-specific database of published measurement data quantifying soil C stock, wetland biomass and CH_4 emissions. Refined error analysis combining land cover change and soil and biomass C stock estimates will be provided. Under this investigation a model is in development to represent changes in soil C stocks. This investigation is to be completed by November 2017 and will be included in the 1990 through 2017 Inventory.

The C-CAP dataset for 2015 is currently under development. Once complete, land use change for 2011 through 2016 will be recalculated with this updated dataset.

With the conclusion of the Blue Carbon Monitoring System Project it is intended that the 1990 through 2017 Inventory will include new data on estuarine emergent biomass C stocks and refined reference soil C stocks and uncertainty analysis based upon an expanded national dataset.

N_2O Emissions from Aquaculture in Coastal Wetlands

Shrimp and fish cultivation in coastal areas increases nitrogen loads resulting in direct emissions of N_2O. Nitrous oxide is generated and emitted as a byproduct of the conversion of ammonia (contained in fish urea) to nitrate through nitrification and nitrate to N_2 gas through denitrification (Hu et al. 2012). Nitrous oxide emissions can be readily estimated from data on fish production (IPCC 2013 *Wetlands Supplement*).

Overall, aquaculture production in the United States has fluctuated slightly from year to year though it is essentially at a similar level since 2011 as in 1990. Data for 2016 are not yet available and emissions have been held constant with 2014 at 0.14 MMT CO_2 Eq.

Table 6-61: Net N_2O Emissions from Aquaculture in Coastal Wetlands (MMT CO_2 Eq.)

Year	1990	2005	2012	2013	2014	2015	2016
Flux	0.13	0.18	0.14	0.14	0.14	0.14	0.14

Table 6-62: Net N_2O Emissions from Aquaculture in Coastal Wetlands (kt N_2O)

Year	1990	2005	2012	2013	2014	2015	2016
Flux	0.44	0.59	0.46	0.48	0.47	0.47	0.47

Methodology

The methodology to estimate N_2O emissions from Aquaculture in Coastal Wetlands follows guidance in the *2013 IPCC Wetlands Supplement* by applying country-specific fisheries production data and the IPCC Tier 1 default emission factor.

Each year NOAA Fisheries document the status of U.S. marine fisheries in the annual report of *Fisheries of the United States*, from which activity data for this analysis is derived.[58] The fisheries report has been produced in various forms for more than 100 years, primarily at the national level, on U.S. recreational catch and commercial fisheries landings and values. In addition, data are reported on U.S. aquaculture production, the U.S. seafood processing industry, imports and exports of fish-related products, and domestic supply and per capita consumption of fisheries products. Within the aquaculture chapter mass of production for Catfish, Striped bass, Tilapia, Trout, Crawfish, Salmon and Shrimp are reported. While some of these fisheries are produced on land and some in open water cages, all have data on the quantity of food stock produced, which is the activity data that is applied to the IPCC Tier 1 default emissions factor to estimate emissions of N_2O from aquaculture. It is not apparent from the data as to the amount of aquaculture occurring above the extent of high tides on river floodplains. While some aquaculture likely occurs on coastal lowland floodplains this is likely a minor component of tidal aquaculture production because of the need for a regular source of water for pond flushing. The estimation of N_2O emissions

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[58] See <https://www.st.nmfs.noaa.gov/st1/publications.html>

from aquaculture is not sensitive to salinity using IPCC approaches and as such the location of aquaculture ponds on the landscape does not influence the calculations.

Other open water shellfisheries for which no food stock is provided, and thus no additional N inputs, are not applicable for estimating N_2O emissions (e.g., Clams, Mussels and Oysters) and have not been included in the analysis. The IPCC Tier 1 default emissions factor of 0.00169 kg N_2O-N per kg of fish produced (95 percent confidence interval – 0,0038) is applied to the activity data to calculate total N_2O emissions. The AR4 global warming potential value of 298 is applied in deriving CO_2 Eq. values from N_2O emissions.

Uncertainty and Time-Series Consistency

Uncertainty estimates are based upon the Tier 1 default 95 percent confidence interval provided within the *Wetlands Supplement* for N_2O emissions. Uncertainties in N_2O emissions from aquaculture are based on expert judgement for the NOAA *Fisheries of the United States* fisheries production data (± 100 percent) multiplied by default uncertainty level for N_2O emissions found in Table 4.15, chapter 4 of the *Wetlands Supplement*. Given the overestimate of fisheries production from coastal wetland areas due to the inclusion of fish production in non-coastal wetland areas, this is a reasonable initial first approximation for an uncertainty range.

Table 6-63: Approach 1 Quantitative Uncertainty Estimates for N_2O Emissions for Aquaculture Production in Coastal Wetlands (MMT CO_2 Eq. and Percent)

Source	2016 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emissions Estimate[a] (MMT CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Combined Uncertainty for Flux Associated with N_2O Emissions for Aquaculture Production in Coastal Wetlands	0.14	0.00	0.30	-116%	116%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

QA/QC and Verification

NOAA provided internal QA/QC review of reported fisheries data. The Coastal Wetlands Inventory team consulted with the Coordinating Lead Authors of the Coastal Wetlands chapter of the *2013 IPCC Wetlands Supplement* to assess which fisheries production data to include in estimating emissions from aquaculture. It was concluded that N_2O emissions estimates should be applied to any fish production to which food supplement is supplied be they pond or open water and that salinity conditions were not a determining factor in production of N_2O emissions.

6.9 Land Converted to Wetlands (CRF Category 4D2)

Emissions and Removals from Land Converted to Vegetated Coastal Wetlands

Land Converted to Vegetated Coastal Wetlands occurs as a result of inundation of unprotected low-lying coastal areas with gradual sea level rise, flooding of previously drained land behind hydrological barriers, and through active restoration and creation of coastal wetlands through removal of hydrological barriers. All other land categories (i.e., Forest Land, Cropland, Grassland, Settlements and Other Lands) are identified has having some area converting to Vegetated Coastal Wetlands. Between 1990 and 2016 the rate of annual transition for *Land Converted to Vegetated Coastal Wetlands* ranged from 2,619 ha/year to 5,316 ha/year. Conversion rates were higher during the period 2010 through 2016 than during the earlier part of the time series.

However, at the present stage of Inventory development, Coastal Wetlands are not explicitly shown in the Land Representation analysis while work continues harmonizing data from NOAA’s Coastal Change Analysis Program[59] with NRI data used to compile the Land Representation. As a QC step a check was undertaken to confirm that Coastal Wetlands recognized by C-CAP represented a subset of Wetlands recognized by the NRI for marine coastal states. Delineating Vegetated Coastal Wetlands from ephemerally flooded upland Grasslands represents a particular challenge in remote sensing. Moreover, at the boundary between wetlands and uplands, which may be gradual on low lying coastlines, the presence of wetlands may be ephemeral depending upon weather and climate cycles and as such results in the emissions and removals vary over these time frames.

Following conversion to Vegetated Coastal Wetlands there are increases in biomass and soil C storage. Additionally, at salinities less than half that of seawater the transition from upland dry soils to wetland soils results in CH_4 emissions. In this Inventory analysis, soil C stock changes and CH_4 emissions are quantified. Estimates of biomass C stock changes will be included in subsequent reports. Estimates of emissions and removals are based on emission factor data that have been applied to estimate changes in soil C stock for *Land Converted to Vegetated Coastal Wetlands*.

Table 6-64: Net CO_2 Flux from Soil C Stock Changes in *Land Converted to Vegetated Coastal Wetlands* (MMT CO_2 Eq.)

Year	1990	2005	2012	2013	2014	2015	2016
Net Soil Flux	(0.02)	(0.01)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)

Note: Parentheses indicate net sequestration.

Table 6-65: Net CO_2 Flux from Soil C Stock Changes in *Land Converted to Vegetated Coastal Wetlands* (MMT C)

Year	1990	2005	2012	2013	2014	2015	2016
Net Soil Flux	(0.01)	(+)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)

+ Does not exceed 0.005 MMT C.
Note: Parentheses indicate net sequestration.

Table 6-66: Net CH_4 Flux in *Land Converted to Vegetated Coastal Wetlands* (MMT CO_2 Eq.)

Soil Type	1990	2005	2012	2013	2014	2015	2016
Net Flux	0.01	0.01	0.01	0.01	0.01	0.01	0.01

Table 6-67: Net CH_4 Flux from Soil C Stock Changes in *Land Converted to Vegetated Coastal Wetlands* (kt CH_4)

Soil Type	1990	2005	2012	2013	2014	2015	2016
Net Flux	0.57	0.48	0.48	0.48	0.48	0.48	0.48

Methodology

The following section includes a brief description of the methodology used to estimate changes in soil C removals and CH_4 emissions for *Land Converted to Vegetated Coastal Wetlands*.

Soil Carbon Stock Changes

Soil C removals are estimated for *Land Converted to Vegetated Coastal Wetlands* for land below the elevation of high tides (taken to be mean high water spring tide elevation) and as far seawards as the extent of intertidal vascular plants within the U.S. Land Representation according to the national LiDAR dataset, the national network of tide

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[59] See <https://coast.noaa.gov/digitalcoast/tools/lca>.

gauges and land use histories recorded in the 1996, 2001, 2005 and 2010 NOAA C-CAP surveys.[60] As noted above, the NOAA C-CAP dataset has yet to be harmonized with the NRI dataset from which the Land Representation is derived. Federal and non-federal lands are represented. Trends in land cover change are extrapolated to 1990 and 2016 from these datasets. Based upon NOAA C-CAP, wetlands are subdivided into freshwater (Palustrine) and saline (Estuarine) classes and further subdivided into Emergent marsh, scrub shrub and forest classes. Soil C stock changes, stratified by climate zones and wetland classes, are derived from a synthesis of peer-reviewed literature (Mangrove pool and removals data: Cahoon & Lynch unpublished data; Lynch 1989; Callaway et al. 1997; Chen & Twilley 1999; McKee & Faulkner 2000; Ross et al. 2000; Chmura et al. 2003; Perry & Mendelssohn 2009; Castaneda-Moya et al. 2013; Henry & Twilley 2013; Doughty et al. 2015; Marchio et al. 2016. Tidal marsh pool and removals data: Anisfeld unpublished data; Cahoon unpublished data; Cahoon & Lynch unpublished data; Chmura unpublished data; McCaffrey & Thomson 1980; Hatton 1981; Callaway et al. 1987; Craft et al. 1988; Cahoon & Turner 1989; Patrick & DeLaune 1990; Kearney & Stevenson 1991;Cahoon et al. 1996; Callaway et al. 1997; Roman et al. 1997; Bryant & Chabrek 1998; Orson et al. 1998; Markewich et al. 1998; Anisfeld et al. 1999; Connor et al. 2001; Choi & Wang 2001; Chmura et al. 2003, Hussein et al. 2004; Craft 2007; Miller et al. 2008; Drexler et al. 2009; Perry & Mendelssohn 2009; Loomis & Craft 2010; EPA's NWCA 2011; Callaway et al. 2012; Henry & Twilley 2013; Weston et al. 2014). To estimate soil C stock changes no differentiation is made for soil type (i.e., mineral, organic).

Tier 2 level estimates of soil C removal associated with annual soil C accumulation from *Land Converted to Vegetated Coastal Wetlands* were developed using country-specific soil C removal factors multiplied by activity data of land area for *Land Converted to Vegetated Coastal Wetlands*. The methodology follows Eq. 4.7, Chapter 4 of the *IPCC Wetlands Supplement*, and applied to the area of *Land Converted to Vegetated Coastal Wetlands* on an annual basis. Emission factors were developed from literature references that provided soil C removal factors disaggregated by climate region, vegetation type by salinity range (estuarine or palustrine) as identified using NOAA C-CAP as described above. Quantification of regional coastal wetland biomass C stock changes for perennial vegetation are in development and are not presented this year, though will be included in future reports.

Soil Methane Emissions

Tier 1 estimates of CH_4 emissions for *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands* are derived from the same wetland map used in the analysis of wetland soil C fluxes, produced from C-CAP, LiDAR and tidal data, in combination with default CH_4 emission factors provided in Table 4.14 of the *IPCC Wetlands Supplement.* The methodology follows Eq. 4.9, Chapter 4 of the *IPCC Wetlands Supplement*, and is applied to the total area of *Land Converted to Vegetated Coastal Wetlands* on an annual basis. The AR4 global warming potential factor of 25 was used in converting CH_4 to CO_2 Eq. values.

Uncertainty and Time-Series Consistency

Underlying uncertainties in estimates of soil C removal factors and CH_4 include error in uncertainties associated with Tier 2 literature values of soil C removal estimates and CH_4 flux, assumptions that underlie the methodological approaches applied and uncertainties linked to interpretation of remote sensing data.

Uncertainty specific to coastal wetlands include differentiation of palustrine and estuarine community classes which determines the soil C removal and CH_4 flux applied. Soil C removal and CH_4 fluxes applied are determined from vegetation community classes across the coastal zone and identified by NOAA C-CAP. Community classes are further subcategorized by climate zones and growth form (forest, shrub-scrub, marsh). Soil C removal data for all subcategories are not available and thus assumptions were applied using expert judgement about the most appropriate assignment of a soil C removal factor to a disaggregation of a community class. Because mean soil C removal for each available community class are in a fairly narrow range, the same overall uncertainty was assigned to each, (i.e., applying approach for asymmetrical errors, the largest uncertainty for any soil C stock value should be applied in the calculation of error propagation; IPCC 2000). Uncertainties for CH_4 flux are the Tier 1 default values reported in the *IPCC Wetlands Supplement*. Overall uncertainty of the NOAA C-CAP remote sensing product is 15 percent. This is in the range of remote sensing methods (±10-15 percent; IPCC 2003). However, there is significant

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[60] See <https://coast.noaa.gov/digitalcoast/tools/lca>.

uncertainty in salinity ranges for tidal and non-tidal estuarine wetlands and activity data used to estimate the CH_4 flux (e.g., delineation of an 18 ppt boundary), which will need significant improvement to reduce uncertainties.

Table 6-68: Approach 1 Quantitative Uncertainty Estimates for Net CO_2 Flux Changes occurring within *Land Converted to Vegetated Coastal Wetlands* (MMT CO_2 Eq. and Percent)

Source	2016 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate[a] (MMT CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Combined Uncertainty for Flux Associated with *Land Converted to Vegetated Coastal Wetlands*	(0.02)	(0.03)	(0.02)	-29.5%	29.5%

[a] Range of flux estimates based on error propagation at 95 percent confidence interval.

Table 6-69: Approach 1 Quantitative Uncertainty Estimates for CH_4 Emissions occurring within *Land Converted to Vegetated Coastal Wetlands* (MMT CO_2 Eq. and Percent)

Source	2016 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate[a] (MMT CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Combined Uncertainty for Flux Associated with *Land Converted to Vegetated Coastal Wetlands*	0.01	0.01	0.02	-29.8%	29.8%

[a] Range of flux estimates based on error propagation at 95 percent confidence interval.

QA/QC and Verification

NOAA provided National LiDAR Dataset, tide data, and C-CAP land cover and land cover change mapping, all of which are subject to agency internal mandatory QA/QC assessment (McCombs et al. 2016). QA/QC and verification of soil C stock dataset has been provided by the Smithsonian Environmental Research Center and Coastal Wetland Inventory team leads. Land cover estimates were assessed to ensure that the total land area did not change over the time series in which the inventory was developed, and verified by a second QA team. A team of two evaluated and verified there were no computational errors within the calculation worksheets. Soil C stock, emissions/removals data where based upon peer-reviewed literature and CH_4 emission factors derived from the *IPCC Wetlands Supplement*.

Planned Improvements

A USGS/NASA Carbon Monitoring System investigation is in progress to establish a U.S. country-specific database of soil C stocks, wetland biomass and CH_4 emissions. Refined error analysis combining land cover change and C stock estimates will be provided. Under this investigation, a model is in development to represent changes in soil C stocks. This investigation is due to be completed by November 2017. Future improvements will thus include estimates of estuarine emergent biomass C stocks, refined soil C stocks and uncertainty analysis.

The C-CAP dataset for 2015 is currently under development. Once complete, land use change for 2011 through 2016 will be recalculated with this updated dataset.

With the conclusion of the Blue Carbon Monitoring System Project it is intended that the 1990 through 2017 Inventory will include new data on estuarine emergent biomass C stocks and refined reference soil C stocks and uncertainty analysis based upon an expanded national dataset.

6.10 Settlements Remaining Settlements (CRF Category 4E1)

Soil Carbon Stock Changes (CRF Category 4E1)

Drainage of organic soils is common when wetland areas have been developed for settlements. Organic soils, also referred to as *Histosols*, include all soils with more than 12 to 20 percent organic C by weight, depending on clay content (NRCS 1999, Brady and Weil 1999). The organic layer of these soils can be very deep (i.e., several meters), and form under inundated conditions that results in minimal decomposition of plant residues. Drainage of organic soils leads to aeration of the soil that accelerates decomposition rate and CO_2 emissions.[61] Due to the depth and richness of the organic layers, C loss from drained organic soils can continue over long periods of time, which varies depending on climate and composition (i.e., decomposability) of the organic matter (Armentano and Menges 1986). The United States does not estimate changes in soil organic C stocks for mineral soils on *Settlements Remaining Settlements*, which is consistent with the assumption of the Tier 1 method in the IPCC guidelines (2006). This assumption may be evaluated in the future if funding and resources are available to conduct an analysis of soil C stock changes in mineral soils of *Settlements Remaining Settlements*.

Settlements Remaining Settlements includes all areas that have been settlements for a continuous time period of at least 20 years according to the 2012 United States Department of Agriculture (USDA) National Resources Inventory (NRI) (USDA-NRCS 2015)[62] or according to the National Land Cover Dataset (NLCD) for federal lands (Homer et al. 2007; Fry et al. 2011; Homer et al. 2015). The Inventory includes settlements on privately-owned lands in the conterminous United States and Hawaii. Alaska and the small amount of settlements on federal lands are not included in this Inventory even though these areas are part of the U.S. managed land base. This leads to a discrepancy with the total amount of managed area in *Settlements Remaining Settlements* (see Section 6.1 Representation of the U.S. Land Base) and the settlements area included in the Inventory analysis. There is a planned improvement to include settlements on organic soils in these areas as part of a future Inventory.

CO_2 emissions from drained organic soils in settlements are 1.3 MMT CO_2 Eq. (0.4 MMT C) in 2016. Although the flux is relatively small, the amount has increased by over 800 percent since 1990.

Table 6-70: Net CO_2 Flux from Soil C Stock Changes in *Settlements Remaining Settlements* (MMT CO_2 Eq.)

Soil Type	1990		2005		2012	2013	2014	2015	2016
Organic Soils	0.1		0.5		1.3	1.3	1.3	1.3	1.3

Note: Estimates after 2012 are based on a data splicing method (see Methodology section).

Table 6-71: Net CO_2 Flux from Soil C Stock Changes in *Settlements Remaining Settlements* (MMT C)

Soil Type	1990		2005		2012	2013	2014	2015	2016
Organic Soils	+		0.1		0.4	0.4	0.4	0.4	0.4

+ Does not exceed 0.05 MMT C

Note: Estimates after 2012 are based on a data splicing method (see Methodology section).

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[61] N_2O emissions from soils are included in the N_2O Emissions from Settlement Soils section.

[62] NRI survey locations are classified according to land-use histories starting in 1979, and consequently the classifications are based on less than 20 years from 1990 to 1998. This may have led to an overestimation of *Settlements Remaining Settlements* in the early part of the time series to the extent that some areas are converted to settlements between 1971 and 1978.

Methodology

An IPCC Tier 2 method is used to estimate soil organic C stock changes for organic soils in *Settlements Remaining Settlements* (IPCC 2006). Organic soils in *Settlements Remaining Settlements* are assumed to be losing C at a rate similar to croplands due to deep drainage, and therefore emission rates are based on country-specific values for cropland (Ogle et al. 2003). The following section includes a description of the methodology, including (1) determination of the land base that is classified as settlements; and (2) estimation of emissions from drained organic soils.

The land area designated as settlements is based primarily on the 2012 NRI (USDA 2015) with additional information from the NLCD (Fry et al. 2011; Homer et al. 2007; Homer et al. 2015). It is assumed that all settlement area on organic soils is drained, and those areas are provided in Table 6-72 (See Section 6.1, Representation of the U.S. Land Base for more information). The area of drained organic soils is estimated from the NRI spatial weights and aggregated to the country (Table 6-72). The area of land on organic soils in *Settlements Remaining Settlements* has increased from 3 thousand hectares in 1990 to over 28 thousand hectares in 2012. The area of land on organic soils are not available from NRI for *Settlements Remaining Settlements* after 2012.

Table 6-72: Thousands of Hectares of Drained Organic Soils in *Settlements Remaining Settlements*

Year	Area (Thousand Hectares)
1990	3
2005	10
2012	28
2013	ND
2014	ND
2015	ND
2016	ND

Note: No NRI data are available after 2012.
ND (No data).

To estimate CO_2 emissions from drained organic soils across the time series from 1990 to 2012, the total area of organic soils in *Settlements Remaining Settlements* is multiplied by the country-specific emission factors for *Cropland Remaining Cropland* under the assumption that there is deep drainage of the soils. The emission factors are 11.2 MT C per ha in cool temperate regions, 14.0 MT C per ha in warm temperate regions, and 14.3 MT C per ha in subtropical regions (see Annex 3.12 for more information).

A linear extrapolation of the trend in the time series is applied to estimate the emissions from 2013 to 2016 because NRI activity data are not available for these years to determine the area of drained organic soils in *Settlements Remaining Settlements*. Specifically, a linear regression model with autoregressive moving-average (ARMA) errors (Brockwell and Davis 2016) is used to estimate the trend in emissions over time from 1990 to 2012, and in turn, the trend is used to approximate the 2013 to 2016 emissions. The Tier 2 method described previously will be applied in future inventories to recalculate the estimates beyond 2012 as activity data becomes available.

Uncertainty and Time-Series Consistency

Uncertainty for the Tier 2 approach is derived using a Monte Carlo approach, along with additional uncertainty propagated through the Monte Carlo Analysis for 2013 to 2016 based on the linear time series model. The results of the Approach 2 Monte Carlo uncertainty analysis are summarized in Table 6-73. Soil C losses from drained organic soils in *Settlements Remaining Settlements* for 2016 are estimated to be between 0.8 and 1.8 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 35 percent below and 35 percent above the 2016 emission estimate of 1.3 MMT CO_2 Eq.

Table 6-73: Uncertainty Estimates for CO_2 Emissions from Drained Organic Soils in *Settlements Remaining Settlements* (MMT CO_2 Eq. and Percent)

Source	Gas	2016 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Organic Soils	CO_2	1.3	0.8	1.8	-35%	35%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological recalculations are applied from 2013 to 2015 using the linear time series model described above. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

Quality control measures included checking input data, model scripts, and results to ensure data are properly handled throughout the inventory process. Inventory reporting forms and text are reviewed and revised as needed to correct transcription errors.

Recalculations Discussion

Methodological recalculations are associated with extending the time series from 2013 through 2016 using a linear time series model. The recalculation had a minor effect on the time series overall with C losses from drainage of organic soils increasing by less than 1 percent on average.

Planned Improvements

This source will be extended to include CO_2 emissions from drainage of organic soils in settlements of Alaska and federal lands in order to provide a complete inventory of emissions for this category. New land representation data will also be compiled, and the time series recalculated for the latter years that are estimated using the data splicing method in the current Inventory.

Changes in Carbon Stocks in Urban Trees (CRF Category 4E1)

Urban forests constitute a significant portion of the total U.S. tree canopy cover (Dwyer et al. 2000). Urban areas (cities, towns, and villages) are estimated to cover over 3 percent of the United States (U.S. Census Bureau 2012). With an average tree canopy cover of 35 percent, urban areas account for approximately 5 percent of total tree cover in the continental United States (Nowak and Greenfield 2012). Trees in urban areas of the United States were estimated to account for an average annual net sequestration of 77.6 MMT CO_2 Eq. (21.2 MMT C) over the period from 1990 through 2016. Net C flux from urban trees in 2016 was estimated to be -92.9 MMT CO_2 Eq. (-25.3 MMT C). Annual estimates of CO_2 flux (Table 6-74) were developed based on periodic (1990, 2000, and 2010) U.S. Census data on urbanized area. The estimate of urbanized area is smaller than the area categorized as *Settlements* in the Representation of the U.S. Land Base developed for this report: over the 1990 through 2016 time series the Census urban area totaled, on average, about 63 percent of the *Settlements* area.

In 2016, Census urban area totaled about 69 percent of the total area defined as *Settlements*. Census area data are preferentially used to develop C flux estimates for this source category since these data are more applicable for use with the available peer-reviewed data on urban tree canopy cover and urban tree C sequestration. Annual sequestration increased by 54 percent between 1990 and 2016 due to increases in urban land area. Data on C storage and urban tree coverage were collected since the early 1990s and have been applied to the entire time series in this report. As a result, the estimates presented in this chapter are not truly representative of changes in C stocks in urban trees for *Settlements* areas, but are representative of changes in C stocks in urban trees for Census urban area. The method used in this report does not attempt to scale these estimates to the *Settlements* area. Therefore, the estimates presented in this chapter are likely an underestimate of the true changes in C stocks in urban trees in all *Settlements* areas—i.e., the changes in C stocks in urban trees presented in this chapter are a subset of the changes in C stocks in urban trees in all *Settlements* areas.

Urban trees often grow faster than forest trees because of the relatively open structure of the urban forest (Nowak and Crane 2002). Because tree density in urban areas is typically much lower than in forested areas, the C storage per hectare of land is in fact smaller for urban areas than for forest areas. To quantify the C stored in urban trees, the methodology used here requires analysis per unit area of tree cover, rather than per unit of total land area (as is done for Forestlands). When expressed as per unit of tree cover, areas covered by urban trees actually have a greater C density than do forested areas (Nowak and Crane 2002). Expressed per unit of land area, however, the situation is the opposite: because tree density is so much lower in urban areas, these areas have a smaller C density per unit land area than forest areas.

Table 6-74: Net C Flux from Urban Trees (MMT CO_2 Eq. and MMT C)

Year	MMT CO_2 Eq.	MMT C
1990	(60.4)	(16.5)
2005	(80.5)	(22.0)
2012	(88.4)	(24.1)
2013	(89.5)	(24.4)
2014	(90.6)	(24.7)
2015	(91.7)	(25.0)
2016	(92.9)	(25.3)

Note: Parentheses indicate net sequestration.

Methodology

Methods for quantifying urban tree biomass, C sequestration, and C emissions from tree mortality and decomposition were taken directly from Nowak et al. (2013), Nowak and Crane (2002), and Nowak (1994). In general, the methodology used by Nowak et al. (2013) to estimate net C sequestration in urban trees followed three steps, each of which is explained further in the paragraphs below. First, field data from cities and states were used to estimate C in urban tree biomass from field data on measured tree dimensions. Second, estimates of annual tree growth and biomass increment were generated from published literature and adjusted for tree condition, crown competition, and growing season to generate estimates of gross C sequestration in urban trees for all 50 states and the District of Columbia. Third, estimates of C emissions due to mortality and decomposition were subtracted from gross C sequestration values to derive estimates of net C sequestration.

For the current Inventory, net C sequestration estimates for all 50 states and the District of Columbia, that were generated using the Nowak et al. (2013) methodology and expressed in units of C sequestered per unit area of tree cover, were then used to estimate urban tree C sequestration in the United States. To accomplish this, EPA used urban area estimates from U.S. Census data together with urban tree cover percentage estimates for each state and the District of Columbia from remote sensing data, an approach consistent with Nowak et al. (2013).

This approach is also consistent with the default IPCC Gain-Loss methodology in IPCC (2006), although sufficient field data are not yet available to separately determine interannual gains and losses in C stocks in the living biomass of urban trees. Instead, the methodology applied here uses estimates of net C sequestration based on modeled estimates of decomposition, as given by Nowak et al. (2013).

The first step in the methodology is to estimate C in urban tree biomass. To develop urban tree carbon estimates Nowak et al. (2013) and previously published research (Nowak and Crane 2002; and Nowak 1994, 2007b, and 2009) collected field measurements in a number of U.S. cities between 1989 and 2012. For a random sample of trees in representative cities, tree data were collected regarding stem diameter, tree height, crown height and crown width, tree location, species, and canopy condition. The data for each tree were converted into total dry-weight biomass estimates using allometric equations, a root-to-shoot ratio to convert aboveground biomass estimates to whole tree biomass, and wood moisture content. Total dry weight biomass was converted to C by dividing by two (50 percent carbon content). An adjustment factor of 0.8 was used for open grown trees to account for urban trees having less aboveground biomass for a given stem diameter than predicted by allometric equations based on forest trees (Nowak 1994). Carbon storage estimates for deciduous trees include only C stored in wood. Estimated C storage was divided by tree cover in the area to estimate carbon storage per square meter of tree cover. The second step in the methodology is to estimate rates of tree growth for urban trees in the United States. In the Nowak et al. (2013) methodology that is applied here, growth rates were standardized for open-grown trees in areas with 153 days of frost free length based on measured data on tree growth. These growth rates were then adjusted to local tree conditions based on length of frost free season, crown competition (as crown competition increased, growth rates decreased), and tree condition (as tree condition decreased, growth rates decreased). For each tree, the difference in C storage estimates between year 1 and year (x + 1) represents the gross amount of C sequestered. These annual gross C sequestration rates for each tree were then scaled up to city estimates using tree population information. The area of assessment for each city or state was defined by its political boundaries; parks and other forested urban areas were thus included in sequestration estimates (Nowak 2011).

Most of the field data used to develop the methodology of Nowak et al. (2013) were analyzed using the U.S. Forest Service's i-Tree Eco model (formerly Urban Forest Effects (UFORE) model). The i-Tree Eco computer model uses standardized field data from randomly located plots, along with local hourly air pollution and meteorological data to quantify urban forest structure, values of the urban forest, and environmental effects, including total C stored and annual C sequestration. The model was used with field data from randomly sampled plots in each city or urban areas in states to quantify the characteristics of the urban forest (Nowak et al. 2013).

Where gross C sequestration accounts for all carbon sequestered, net C sequestration for urban trees takes into account C emissions associated with tree death and removals. In the third step in the methodology developed by Nowak et al. (2002; 2013), estimates of net C emissions from urban trees were derived by applying estimates of annual mortality based on tree condition, and assumptions about whether dead trees were removed from the site. Estimates of annual mortality rates by diameter class and condition class were derived from a study of street-tree mortality (Nowak 1986). Different decomposition rates were applied to dead trees left standing compared with those removed from the site. For removed trees, different rates were applied to the removed/aboveground biomass in contrast to the belowground biomass. The estimated annual gross C emission rates for each plot were then scaled up to city estimates using tree population information.

The data for all 50 states and the District of Columbia are described in Nowak et al. (2013) and reproduced in Table 6-75, which builds upon previous research, including: Nowak and Crane (2002), Nowak et al. (2007), Nowak and Greenfield (2012), and references cited therein. The full methodology development is described in the underlying literature, and key details and assumptions were made as follows. The allometric equations applied to the field data for the Nowak methodology for each tree were taken from the scientific literature (see Nowak 1994, Nowak et al. 2002), but if no allometric equation could be found for the particular species, the average result for the genus or botanical relative was used. The adjustment (0.8) to account for less live tree biomass in open-grown urban trees was based on information in Nowak (1994). Measured tree growth rates for street (Frelich 1992; Fleming 1988; Nowak 1994), park (deVries 1987), and forest (Smith and Shifley 1984) trees were standardized to an average length of growing season (153 frost free days) and adjusted for site competition and tree condition. Standardized growth rates of trees of the same species or genus were then compared to determine the average difference between standardized street tree growth and standardized park and forest growth rates. Crown light exposure (CLE) measurements (number of sides and/or top of tree exposed to sunlight) were used to represent forest, park, and open (street) tree growth conditions. Local tree base growth rates (BG) were then calculated as the average standardized growth rate for open-grown trees multiplied by the number of frost free days divided by 153. Growth rates were then adjusted for CLE. The CLE adjusted growth rate was then adjusted based on tree health and tree condition to determine the final growth rate. Assumptions for which dead trees would be removed versus left standing were developed specific to each land use and were based on expert judgment of the authors. Decomposition rates were based on literature estimates (Nowak et al. 2013).

Estimates of gross and net sequestration rates for each of the 50 states and the District of Columbia (Table 6-75) were compiled in units of C sequestration per unit area of tree canopy cover. These rates were used in conjunction with estimates of state urban area and urban tree cover data (Nowak and Greenfield 2012) to calculate each state's annual net C sequestration by urban trees. This method was described in Nowak et al. (2013) and has been modified here to incorporate U.S. Census data.

Specifically, urban area estimates were based on 1990, 2000, and 2010 U.S. Census data. The 1990 U.S. Census defined urban land as "urbanized areas," which included land with a population density greater than 1,000 people per square mile, and adjacent “urban places,” which had predefined political boundaries and a population total greater than 2,500. In 2000, the U.S. Census replaced the “urban places” category with a new category of urban land called an “urban cluster,” which included areas with more than 500 people per square mile. In 2010, the Census updated its definitions to have “urban areas” encompassing Census tract delineated cities with 50,000 or more people, and “urban clusters” containing Census tract delineated locations with between 2,500 and 50,000 people. Urban land area increased by approximately 23 percent from 1990 to 2000 and 14 percent from 2000 to 2010; Nowak et al. (2005) estimate that the changes in the definition of urban land are responsible for approximately 20 percent of the total reported increase in urban land area from 1990 to 2000. Under all Census (i.e., 1990, 2000, and 2010) definitions, the urban category encompasses most cities, towns, and villages (i.e., it includes both urban and suburban areas). *Settlements* area, as assessed in the Representation of the U.S. Land Base developed for this report, encompassed all developed parcels greater than 0.1 hectares in size, including rural transportation corridors, and as previously mentioned represents a larger area than the Census-derived urban area estimates. However, the smaller, Census-derived urban area estimates were deemed to be more suitable for estimating national urban tree cover given the data available in the peer-reviewed literature (i.e., the data set available is consistent with Census urban rather than *Settlements* areas), and the recognized overlap in the changes in C stocks between urban forest and non-urban forest (see Planned Improvements below). U.S. Census urban area data are reported as a series of continuous blocks of urban area in each state. The blocks or urban area were summed to create each state’s urban area estimate.

Net annual C sequestration estimates were derived for all 50 states and the District of Columbia by multiplying the gross annual emission estimates by 0.74, the standard ratio for net/gross sequestration set out in Table 3 of Nowak et al. (2013) (unless data existed for both gross and net sequestration for the state in Table 2 of Nowak et. al. (2013), in which case they were divided to get a state-specific ratio). The gross and net annual C sequestration values for each state were multiplied by each state’s area of tree cover, which was the product of the state’s urban/community area as defined in the U.S. Census (2012) and the state’s urban/community tree cover percentage. The urban/community tree cover percentage estimates for all 50 states were obtained from Nowak and Greenfield (2012). The urban/community tree cover percentage estimate for the District of Columbia was obtained from Nowak et al. (2013). The urban area estimates were taken from the 2010 U.S. Census (2012). The equation, used to calculate the summed carbon sequestration amounts, can be written as follows:

Net annual C sequestration = Gross sequestration rate × Net to Gross sequestration ratio × Urban Area × % Tree Cover

Table 6-75: Annual C Sequestration (Metric Tons C/Year), Tree Cover (Percent), and Annual C Sequestration per Area of Tree Cover (kg C/m^2-yr) for 50 states plus the District of Columbia (2016)

State	Gross Annual Sequestration	Net Annual Sequestration	Tree Cover	Gross Annual Sequestration per Area of Tree Cover	Net Annual Sequestration per Area of Tree Cover	Net: Gross Annual Sequestration Ratio
Alabama	1,207,204	893,331	55.2	0.343	0.254	0.74
Alaska	44,593	32,999	39.8	0.168	0.124	0.74
Arizona	402,045	297,513	17.6	0.354	0.262	0.74
Arkansas	438,481	324,476	42.3	0.331	0.245	0.74
California	2,119,770	1,568,630	25.1	0.389	0.288	0.74
Colorado	158,608	117,370	18.5	0.197	0.146	0.74
Connecticut	775,500	573,870	67.4	0.239	0.177	0.74
Delaware	142,326	105,321	35.0	0.335	0.248	0.74
DC	14,561	11,571	35.0	0.263	0.209	0.79
Florida	3,528,013	2,610,730	35.5	0.475	0.352	0.74
Georgia	2,684,691	1,986,671	54.1	0.353	0.261	0.74
Hawaii	251,232	185,911	39.9	0.581	0.430	0.74
Idaho	26,407	19,541	10.0	0.184	0.136	0.74
Illinois	773,115	572,105	25.4	0.283	0.209	0.74
Indiana	415,255	383,968	23.7	0.250	0.231	0.92
Iowa	122,216	90,440	19.0	0.240	0.178	0.74
Kansas	189,999	147,851	25.0	0.283	0.220	0.78
Kentucky	249,995	184,997	22.1	0.286	0.212	0.74
Louisiana	771,314	570,772	34.9	0.397	0.294	0.74
Maine	108,310	80,150	52.3	0.221	0.164	0.74

Maryland	609,241	450,838	34.3	0.323	0.239	0.74
Massachusetts	1,324,939	980,455	65.1	0.254	0.188	0.74
Michigan	748,782	554,099	35.0	0.220	0.163	0.74
Minnesota	359,271	265,861	34.0	0.229	0.169	0.74
Mississippi	508,818	376,525	47.3	0.344	0.255	0.74
Missouri	509,564	377,077	31.5	0.285	0.211	0.74
Montana	55,205	40,852	36.3	0.184	0.136	0.74
Nebraska	52,156	44,013	15.0	0.238	0.201	0.84
Nevada	46,396	34,333	9.6	0.207	0.153	0.74
New Hampshire	256,348	189,697	66.0	0.217	0.161	0.74
New Jersey	1,209,144	894,766	53.3	0.294	0.218	0.74
New Mexico	71,215	52,699	12.0	0.263	0.195	0.74
New York	1,103,216	816,380	42.6	0.240	0.178	0.74
North Carolina	2,163,326	1,600,861	51.1	0.312	0.231	0.74
North Dakota	15,520	7,375	13.0	0.223	0.106	0.48
Ohio	943,793	698,407	31.5	0.248	0.184	0.74
Oklahoma	373,957	276,728	31.2	0.332	0.246	0.74
Oregon	264,655	195,844	36.6	0.242	0.179	0.74
Pennsylvania	1,287,482	952,736	41.0	0.244	0.181	0.74
Rhode Island	137,454	101,716	51.0	0.258	0.191	0.74
South Carolina	1,152,059	852,523	48.9	0.338	0.250	0.74
South Dakota	22,340	19,373	14.0	0.236	0.205	0.87
Tennessee	1,095,753	979,732	43.8	0.303	0.271	0.89
Texas	2,904,124	2,149,052	31.4	0.368	0.272	0.74
Utah	95,804	70,895	16.4	0.215	0.159	0.74
Vermont	47,031	34,803	53.0	0.213	0.158	0.74
Virginia	856,934	634,131	39.8	0.293	0.217	0.74
Washington	582,070	430,732	34.6	0.258	0.191	0.74
West Virginia	261,146	193,248	61.0	0.241	0.178	0.74
Wisconsin	372,818	275,885	31.8	0.225	0.167	0.74
Wyoming	19,680	14,563	19.9	0.182	0.135	0.74
Total	**33,873,873**	**25,324,418**				

Uncertainty and Time-Series Consistency

Uncertainty associated with changes in C stocks in urban trees includes the uncertainty associated with urban area, percent urban tree coverage, and estimates of gross and net C sequestration for each of the 50 states and the District of Columbia. A 10 percent uncertainty was associated with urban area estimates based on expert judgment. Uncertainty associated with estimates of percent urban tree coverage for each of the 50 states was based on standard error estimates reported by Nowak and Greenfield (2012). Uncertainty associated with estimate of percent urban tree coverage for the District of Columbia was based on the standard error estimate reported by Nowak et al. (2013). Uncertainty associated with estimates of gross and net C sequestration for each of the 50 states and the District of Columbia was based on standard error estimates for each of the state-level sequestration estimates reported by Nowak et al. (2013). These estimates are based on field data collected in each of the 50 states and the District of Columbia, and uncertainty in these estimates increases as they are scaled up to the national level.

Additional uncertainty is associated with the biomass equations, conversion factors, and decomposition assumptions used to calculate C sequestration and emission estimates (Nowak et al. 2002). These results also exclude changes in soil C stocks, and there is some overlap between the urban tree C estimates and the forest tree C estimates as detailed in Nowak et al. (2013). Due to data limitations, urban soil flux is not quantified as part of this analysis, while reconciliation of urban tree and forest tree estimates will be addressed through the land-representation effort described in the Planned Improvements section of this chapter.

A Monte Carlo (Approach 2) uncertainty analysis was applied to estimate the overall uncertainty of the sequestration estimate in 2015. This uncertainty was updated in 2016 based on proportional allocation of changes between the 2015 and 2016 flux estimate. The results of this adjusted quantitative uncertainty analysis are summarized in Table 6-76. The net C flux from changes in C stocks in urban trees in 2016 was estimated to be between -136.9 and -47.9 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 47 percent more sequestration to 48 percent less sequestration than the 2016 flux estimate of -92.9 MMT CO_2 Eq.

Table 6-76: Approach 2 Quantitative Uncertainty Estimates for Net C Flux from Changes in C Stocks in Urban Trees (MMT CO_2 Eq. and Percent)

Source	Gas	2016 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Changes in C Stocks in Urban Trees	CO_2	(92.9)	(136.9)	(47.9)	-47%	48%

[a] Range of uncertainty in emissions was estimated based on proportional allocation of 2015 to 2016 flux values to the 2015 uncertainty estimates. Range of flux estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Note: Parentheses indicate negative values or net sequestration.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2016. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

Tier 1 and Tier 2 QA/QC activities were conducted consistent with the U.S. QA/QC plan. Source-specific quality control measures for urban trees included checking input data, documentation, and calculations to ensure data were properly handled through the inventory process. Errors that were found during this process were corrected as necessary.

Planned Improvements

A consistent representation of the managed land base in the United States is discussed in Section 6.1 Representation of the U.S. Land Base, and discusses a planned improvement by the USDA Forest Service to reconcile the overlap between urban forest and non-urban forest greenhouse gas inventories. Because some plots defined as “forest” in the Forest Inventory and Analysis (FIA) program of the USDA Forest Service actually fall within the boundaries of the areas also defined as Census urban, there may be “double counting” of these land areas in estimates of C stocks and fluxes for this report. Specifically, Nowak et al. (2013) estimates that 1.5 percent of forest plots measured by the FIA program fall within land designated as Census urban, suggesting that approximately 1.5 percent of the C reported in the Forest source category might also be counted in the Urban Trees source category.

Future research may also enable more complete coverage of changes in the C stock in urban trees for all *Settlements* land. To provide estimates for all *Settlements*, research would need to establish the extent of overlap between the areas of land included in the *Settlements* land use category and Census-defined urban areas, and would have to separately characterize sequestration on non-urban *Settlements* land.

To provide more accurate emissions estimates in the urban forest greenhouse gas inventories, the following actions will be taken:

a) Development of a national definition of “settlements”. Settlements are defined as including “all developed land, including transportation infrastructure and human settlements of any size, unless they are already included under other categories. This should be consistent with the selection of national definitions”. In the United States, different types of classifications can be used to determine settlements e.g., Census urban, Census urban/community, National Land Cover Dataset, and National Resources Inventory. A combination of these data will be used to encompass settlement areas and improve consistency with Section 6.1, Representation of the U.S. Land Base;

b) For settlement areas, estimates of land area will be obtained for 1990, 2000 and 2010 and projections developed for annual growth during the 2010 to 2020 period;

c) 2,500 random points will be laid on aerial images using Google Earth imagery to estimate tree cover in the settlement areas circa 1990, 2000 and 2010. Trends in tree cover change will be used to estimate tree cover in settlement between 2010 and 2020;

d) Photo interpretation of settlement tree cover will be updated bi-annually to update tree cover estimates and trends;
e) A review of recent literature will be performed to update C storage, sequestration and net-to-gross sequestration rates per unit tree cover;
f) C rates per unit tree cover will be applied to tree cover estimates within estimated settlement areas annually to estimate past and current C values; and
g) Settlement areas will be updated approximately every 10 years based on updated data from the U.S. Census and NLCD developed land.

N_2O Emissions from Settlement Soils (CRF Source Category 4E1)

Of the synthetic N fertilizers applied to soils in the United States, approximately 3.1 percent are currently applied to lawns, golf courses, and other landscaping within settlement areas. Application rates are lower than those occurring on cropped soils, and, therefore, account for a smaller proportion of total U.S. soil N_2O emissions per unit area. In addition to synthetic N fertilizers, a portion of surface applied biosolids (i.e., sewage sludge) is applied to settlement areas, and drained organic soils (i.e., soils with high organic matter content, known as *Histosols*) also contribute to emissions of soil N_2O.

N additions to soils result in direct and indirect N_2O emissions. Direct emissions occur on-site due to the N additions in the form of synthetic fertilizers and biosolids as well as enhanced mineralization of N in drained organic soils. Indirect emissions result from fertilizer and sludge N that is transformed and transported to another location in a form other than N_2O (ammonia [NH_3] and nitrogen oxide [NO_x] volatilization, nitrate [NO_3^-] leaching and runoff), and later converted into N_2O at the off-site location. The indirect emissions are assigned to settlements because the management activity leading to the emissions occurred in settlements.

Total N_2O emissions from soils in *Settlements Remaining Settlements*[63] are 2.5 MMT CO_2 Eq. (8 kt of N_2O) in 2016. There is an overall increase of 75 percent from 1990 to 2016 due to an expanding settlement area leading to more synthetic N fertilizer applications. Inter-annual variability in these emissions is directly attributable to variability in total synthetic fertilizer consumption, area of drained organic soils, and biosolids applications in the United States. Emissions from this source are summarized in Table 6-77.

Table 6-77: N_2O Emissions from Soils in *Settlements Remaining Settlements* (MMT CO_2 Eq. and kt N_2O)

	1990	2005	2012	2013	2014	2015	2016
MMT CO_2 Eq.							
Direct N_2O Emissions from Soils	**1.1**	**1.9**	**2.1**	**2.0**	**2.0**	**2.0**	**1.9**
Synthetic Fertilizers	0.8	1.6	1.7	1.7	1.7	1.6	1.6
Biosolids	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Drained Organic Soils	0.1	0.1	0.2	0.2	0.2	0.2	0.2
Indirect N_2O Emissions from Soils	**0.4**	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**
Total	**1.4**	**2.5**	**2.7**	**2.6**	**2.6**	**2.5**	**2.5**
kt N_2O							
Direct N_2O Emissions from Soils	**4**	**6**	**7**	**7**	**7**	**7**	**7**
Synthetic Fertilizers	3	5	6	6	6	6	5
Biosolids	1	1	1	1	1	1	1
Drained Organic Soils	+	1	1	1	1	1	1
Indirect N_2O Emissions from Soils	1	**2**	**2**	**2**	**2**	**2**	**2**
Total	**5**	**8**	**9**	**9**	**9**	**9**	**8**

+ Does not exceed 0.5 kt

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[63] Estimates of Soil N_2O for *Settlements Remaining Settlements* include emissions from *Land Converted to Settlements* because it was not possible to separate the activity data.

Notes: Estimates after 2012 are based on a data splicing method (see Methodology section), except for biosolids. Totals may not sum due to independent rounding. Estimates of Soil N_2O for *Settlements Remaining Settlements* include emissions from *Land Converted to Settlements* because it was not possible to separate the activity data.

Methodology

For settlement soils, the IPCC Tier 1 approach is used to estimate soil N_2O emissions from synthetic N fertilizer, biosolids additions, and drained organic soils. Estimates of direct N_2O emissions from soils in settlements are based on the amount of N in synthetic commercial fertilizers applied to settlement soils, the amount of N in biosolids applied to non-agricultural land and surface disposal (see Section 7.2, Wastewater Treatment for a detailed discussion of the methodology for estimating biosolids application), and the area of drained organic soils within settlements.

Nitrogen applications to settlement soils are estimated using data compiled by the USGS (Ruddy et al. 2006). The USGS estimated on-farm and non-farm fertilizer use is based on sales records at the county level from 1982 through 2001 (Ruddy et al. 2006). Non-farm N fertilizer is assumed to be applied to settlements and forest lands; values for 2002 through 2012 are based on 2001 values adjusted for annual total N fertilizer sales in the United States because there is no new activity data on application after 2001. Settlement application is calculated by subtracting forest application from total non-farm fertilizer use. Biosolids applications are derived from national data on biosolids generation, disposition, and N content (see Section 7.2, Wastewater Treatment for further detail). The total amount of N resulting from these sources is multiplied by the IPCC default emission factor for applied N (one percent) to estimate direct N_2O emissions (IPCC 2006) for 1990 to 2012. The IPCC (2006) Tier 1 method is also used to estimate direct N_2O emissions due to drainage of organic soils in settlements at the national scale. Estimates of the total area of drained organic soils are obtained from the 2012 NRI (USDA-NRCS 2015) using soils data from the Soil Survey Geographic Database (SSURGO) (Soil Survey Staff 2011). To estimate annual emissions from 1990 to 2012, the total area is multiplied by the IPCC default emission factor for temperate regions (IPCC 2006). This Inventory does not include soil N_2O emissions from drainage of organic soils in Alaska and federal lands, although this is a planned improvement for a future Inventory.

For indirect emissions, the total N applied from fertilizer and sludge is multiplied by the IPCC default factors of 10 percent for volatilization and 30 percent for leaching/runoff to calculate the amount of N volatilized and the amount of N leached/runoff. The amount of N volatilized is multiplied by the IPCC default factor of one percent for the portion of volatilized N that is converted to N_2O off-site and the amount of N leached/runoff is multiplied by the IPCC default factor of 0.075 percent for the portion of leached/runoff N that is converted to N_2O off-site. The resulting estimates are summed to obtain total indirect emissions from 1990 to 2012.

A linear extrapolation of the trend in the time series is applied to estimate the direct and indirect N_2O emissions from 2013 to 2016 from synthetic fertilizers and drained organic soils because new activity data for these two sources have not been compiled for the latter part of the time series. Specifically, a linear regression model with autoregressive moving-average (ARMA) errors (Brockwell and Davis 2016) is used to estimate the trend in emissions over time from 1990 to 2012, and in turn, the trend is used to approximate the 2013 to 2016 emissions. The time series will be recalculated for the years beyond 2012 in a future inventory with the methods described above for 1990 to 2012. This Inventory does incorporate updated activity data on biosolids application in settlements through 2016.

Uncertainty and Time-Series Consistency

The amount of N_2O emitted from settlement soils depends not only on N inputs and area of drained organic soils, but also on a large number of variables that can influence rates of nitrification and denitrification, including organic C availability; rate, application method, and timing of N input; oxygen gas partial pressure; soil moisture content; pH; temperature; and irrigation/watering practices. The effect of the combined interaction of these variables on N_2O emissions is complex and highly uncertain. The IPCC default methodology does not explicitly incorporate any of these variables, except variations in the total amount of fertilizer N and biosolids applications. All settlement soils are treated equivalently under this methodology.

Uncertainties exist in both the fertilizer N and biosolids application rates in addition to the emission factors. Uncertainty in fertilizer N application is assigned a default level of ±50 percent.[64] Uncertainty in drained organic soils is based on the estimated variance from the NRI survey (USDA-NRCS 2015). For 2013 to 2016, there is also additional uncertainty associated with the surrogate data method. Uncertainty in the amounts of biosolids applied to non-agricultural lands and used in surface disposal is derived from variability in several factors, including: (1) N content of biosolids; (2) total sludge applied in 2000; (3) wastewater existing flow in 1996 and 2000; and (4) the biosolids disposal practice distributions to non-agricultural land application and surface disposal. Uncertainty in the direct and indirect emission factors is provided by IPCC (2006).

Uncertainty is propagated through the calculations of N_2O emissions from fertilizer N and drainage of organic soils using a Monte Carlo analysis. The results are combined with the uncertainty in N_2O emissions from the biosolids application using simple error propagation methods (IPCC 2006). The results are summarized in Table 6-78. Direct N_2O emissions from soils in *Settlements Remaining Settlements* in 2016 are estimated to be between 1.4 and 2.7 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 28 percent below to 38 percent above the 2016 emission estimate of 1.9 MMT CO_2 Eq. Indirect N_2O emissions in 2016 are between 0.4 and 0.7 MMT CO_2 Eq., ranging from a -24 percent to 24 percent around the estimate of 0.6 MMT CO_2 Eq.

Table 6-78: Quantitative Uncertainty Estimates of N_2O Emissions from Soils in *Settlements Remaining Settlements* (MMT CO_2 Eq. and Percent)

Source	Gas	2016 Emissions (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
Settlements Remaining Settlements			**Lower Bound**	**Upper Bound**	**Lower Bound**	**Upper Bound**
Direct N_2O Emissions from Soils	N_2O	1.9	1.4	2.7	-28%	38%
Indirect N_2O Emissions from Soils	N_2O	0.6	0.4	0.7	-24%	24%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.
Note: These estimates include direct and indirect N_2O emissions from *Settlements Remaining Settlements* and *Land Converted to Settlements* because it was not possible to separate the activity data.

Methodological recalculations are applied from 2013 to 2015 using the linear time series model described above. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

The spreadsheet containing fertilizer, drainage of organic soils, and biosolids applied to settlements and calculations for N_2O and uncertainty ranges have been checked and verified.

Recalculations Discussion

Methodological recalculations are associated with extending the time series from 2013 through 2016 using a linear time series model. The recalculation had a minor effect on the time series overall with N_2O emissions declining by less than 1 percent on average.

Planned Improvements

This source will be extended to include soil N_2O emissions from drainage of organic soils in settlements of Alaska and federal lands in order to provide a complete inventory of emissions for this category. Updated data on fertilizer amount and area of drained organic soils will be compiled to update emissions estimates for estimates beyond 2012 in a future Inventory.

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[64] No uncertainty is provided with the USGS fertilizer consumption data (Ruddy et al. 2006) so a conservative ±50 percent is used in the analysis. Biosolids data are also assumed to have an uncertainty of ±50 percent.

Changes in Yard Trimmings and Food Scrap Carbon Stocks in Landfills (CRF Category 4E1)

In the United States, yard trimmings (i.e., grass clippings, leaves, and branches) and food scraps account for a significant portion of the municipal waste stream, and a large fraction of the collected yard trimmings and food scraps are put in landfills. Carbon (C) contained in landfilled yard trimmings and food scraps can be stored for very long periods.

Carbon storage estimates within the Inventory are associated with particular land uses. For example, harvested wood products are reported under *Forest Land Remaining Forest Land* because these wood products originated from the forest ecosystem. Similarly, C stock changes in yard trimmings and food scraps are reported under *Settlements Remaining Settlements* because the bulk of the C, which comes from yard trimmings, originates from settlement areas. While the majority of food scraps originate from cropland and grassland, in this Inventory they are reported with the yard trimmings in the *Settlements Remaining Settlements* section. Additionally, landfills are considered part of the managed land base under settlements (see Section 6.1 Representation of the U.S. Land Base), and reporting these C stock changes that occur entirely within landfills fits most appropriately within the *Settlements Remaining Settlements* section.

Both the estimated amount of yard trimmings collected annually and the fraction that is landfilled have declined over the last decade. In 1990, over 53 million metric tons (wet weight) of yard trimmings and food scraps are estimated to have been generated (i.e., put at the curb for collection to be taken to disposal sites or to composting facilities) (EPA 2016). Since then, programs banning or discouraging yard trimmings disposal have led to an increase in backyard composting and the use of mulching mowers, and a consequent estimated 1.4 percent decrease between 1990 and 2015 in the tonnage of yard trimmings generated (i.e., collected for composting or disposal in landfills). At the same time, an increase in the number of municipal composting facilities has reduced the proportion of collected yard trimmings that are discarded in landfills—from 72 percent in 1990 to 31 percent in 2015.[65] The net effect of the reduction in generation and the increase in composting is a 57 percent decrease in the quantity of yard trimmings disposed of in landfills since 1990.[66]

Food scrap generation has grown by an estimated 61 percent since 1990, and while the proportion of total food scraps generated that are eventually discarded in landfills has decreased slightly, from an estimated 82 percent in 1990 to 76 percent in 2015, the tonnage disposed of in landfills has increased considerably (by an estimated 50 percent) due to the increase in food scrap generation. Although the total tonnage of food scraps disposed of in landfills has increased from 1990 to 2015, the difference in the amount of food scraps added from one year to the next generally decreased, and consequently the annual carbon stock *net changes* from food scraps have generally decreased as well (as shown in Table 6-79 and Table 6-80). As described in the Methodology section, the carbon stocks are modeled using data on the amount of food scraps landfilled since 1960. These food scraps decompose over time, producing CH_4 and CO_2. Decomposition happens at a higher rate initially, then decreases. As decomposition decreases, the carbon stock becomes more stable. Because the cumulative carbon stock left in the landfill from previous years is (1) not decomposing as much as the carbon introduced from food scraps in a single more recent year; and (2) is much larger than the carbon introduced from food scraps in a single more recent year, the total carbon stock in the landfill is primarily driven by the more stable 'older' carbon stock, thus resulting in less annual change in later years."[67]

Overall, the decrease in the landfill disposal rate of yard trimmings has more than compensated for the increase in food scrap disposal in landfills, and the net result is a decrease in annual *net change* landfill C storage from 26.0 MMT CO_2 Eq. (7.1 MMT C) in 1990 to 12.1 MMT CO_2 Eq. (3.3 MMT C) in 2016 (Table 6-79 and Table 6-80).

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[65] Updated data for 2016 were not included for the current Inventory, therefore the trend analysis is based on the latest data through 2015

[66] Landfilled yard trimming amounts were not estimated for 2016; the values are estimated from 1990 through 2015.

[67] Food scrap generation was not estimated for 2016; the values are estimated from 1990 through 2015.

Table 6-79: Net Changes in Yard Trimmings and Food Scrap Carbon Stocks in Landfills (MMT CO_2 Eq.)

Carbon Pool	1990	2005	2012	2013	2014	2015	2016
Yard Trimmings	**(21.0)**	**(7.4)**	**(9.1)**	**(8.4)**	**(8.3)**	**(8.3)**	**(8.4)**
Grass	(1.8)	(0.6)	(0.9)	(0.8)	(0.8)	(0.8)	(0.8)
Leaves	(9.0)	(3.4)	(4.1)	(3.9)	(3.8)	(3.8)	(3.9)
Branches	(10.2)	(3.4)	(4.1)	(3.8)	(3.7)	(3.7)	(3.8)
Food Scraps	**(5.0)**	**(4.0)**	**(3.1)**	**(3.2)**	**(3.6)**	**(3.4)**	**(3.7)**
Total Net Flux	**(26.0)**	**(11.4)**	**(12.2)**	**(11.6)**	**(11.9)**	**(11.8)**	**(12.1)**

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Table 6-80: Net Changes in Yard Trimmings and Food Scrap Carbon Stocks in Landfills (MMT C)

Carbon Pool	1990	2005	2012	2013	2014	2015	2016
Yard Trimmings	**(5.7)**	**(2.0)**	**(2.5)**	**(2.3)**	**(2.3)**	**(2.3)**	**(2.3)**
Grass	(0.5)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)
Leaves	(2.5)	(0.9)	(1.1)	(1.1)	(1.0)	(1.0)	(1.1)
Branches	(2.8)	(0.9)	(1.1)	(1.0)	(1.0)	(1.0)	(1.0)
Food Scraps	**(1.4)**	**(1.1)**	**(0.9)**	**(0.9)**	**(1.0)**	**(0.9)**	**(1.0)**
Total Net Flux	**(7.1)**	**(3.1)**	**(3.3)**	**(3.2)**	**(3.3)**	**(3.2)**	**(3.3)**

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Methodology

When wastes of biogenic origin (such as yard trimmings and food scraps) are landfilled and do not completely decompose, the C that remains is effectively removed from the C cycle. Empirical evidence indicates that yard trimmings and food scraps do not completely decompose in landfills (Barlaz 1998, 2005, 2008; De la Cruz and Barlaz 2010), and thus the stock of C in landfills can increase, with the net effect being a net atmospheric removal of C. Estimates of net C flux resulting from landfilled yard trimmings and food scraps were developed by estimating the change in landfilled C stocks between inventory years, based on methodologies presented for the *Land Use, Land-Use Change, and Forestry* sector in IPCC (2003) and the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006). Carbon stock estimates were calculated by determining the mass of landfilled C resulting from yard trimmings and food scraps discarded in a given year; adding the accumulated landfilled C from previous years; and subtracting the mass of C that was landfilled in previous years and has since decomposed.

To determine the total landfilled C stocks for a given year, the following were estimated: (1) The composition of the yard trimmings; (2) the mass of yard trimmings and food scraps discarded in landfills; (3) the C storage factor of the landfilled yard trimmings and food scraps; and (4) the rate of decomposition of the degradable C. The composition of yard trimmings was assumed to be 30 percent grass clippings, 40 percent leaves, and 30 percent branches on a wet weight basis (Oshins and Block 2000). The yard trimmings were subdivided, because each component has its own unique adjusted C storage factor (i.e., moisture content and C content) and rate of decomposition. The mass of yard trimmings and food scraps disposed of in landfills was estimated by multiplying the quantity of yard trimmings and food scraps discarded by the proportion of discards managed in landfills. Data on discards (i.e., the amount generated minus the amount diverted to centralized composting facilities) for both yard trimmings and food scraps were taken primarily from *Advancing Sustainable Materials Management: Facts and Figures 2014* (EPA 2016), which provides data for 1960, 1970, 1980, 1990, 2000, 2005, 2009 and 2011 through 2013. To provide data for some of the missing years, detailed backup data were obtained from historical data tables that EPA developed for 1960 through 2013 (EPA 2015). Remaining years in the time series for which data were not provided were estimated using linear interpolation. Due to the limited update this inventory year, data for 2015 was set equal to 2014 values, and 2016 was not estimated. The EPA (2016) report and historical data tables (EPA 2015) do not subdivide the discards (i.e., total generated minus composted) of individual materials into masses landfilled and combusted, although it provides a mass of overall waste stream discards managed in landfills[68] and combustors with energy recovery (i.e., ranging from 67 percent and 33 percent, respectively, in 1960 to 92 percent and 8 percent, respectively, in 1985); it is assumed that the proportion of each individual material (food scraps, grass, leaves, branches) that is landfilled is the same as the proportion across the overall waste stream.

The amount of C disposed of in landfills each year, starting in 1960, was estimated by converting the discarded landfilled yard trimmings and food scraps from a wet weight to a dry weight basis, and then multiplying by the initial (i.e., pre-decomposition) C content (as a fraction of dry weight). The dry weight of landfilled material was calculated using dry weight to wet weight ratios (Tchobanoglous et al. 1993, cited by Barlaz 1998) and the initial C contents and the C storage factors were determined by Barlaz (1998, 2005, 2008) (Table 6-81).

The amount of C remaining in the landfill for each subsequent year was tracked based on a simple model of C fate. As demonstrated by Barlaz (1998, 2005, 2008), a portion of the initial C resists decomposition and is essentially persistent in the landfill environment. Barlaz (1998, 2005, 2008) conducted a series of experiments designed to measure biodegradation of yard trimmings, food scraps, and other materials, in conditions designed to promote decomposition (i.e., by providing ample moisture and nutrients). After measuring the initial C content, the materials were placed in sealed containers along with methanogenic microbes from a landfill. Once decomposition was complete, the yard trimmings and food scraps were re-analyzed for C content; the C remaining in the solid sample can be expressed as a proportion of the initial C (shown in the row labeled “C Storage Factor, Proportion of Initial C Stored (%)” in Table 6-81).

The modeling approach applied to simulate U.S. landfill C flows builds on the findings of Barlaz (1998, 2005, 2008). The proportion of C stored is assumed to persist in landfills. The remaining portion is assumed to degrade over time, resulting in emissions of CH_4 and CO_2. (The CH_4 emissions resulting from decomposition of yard trimmings and food scraps are reported in the *Waste* chapter.) The degradable portion of the C is assumed to decay according to first-order kinetics. The decay rates for each of the materials are shown in Table 6-81.

The first-order decay rates, *k*, for each refuse type were derived from De la Cruz and Barlaz (2010). De la Cruz and Barlaz (2010) calculate first-order decay rates using laboratory data published in Eleazer et al. (1997), and a correction factor, *f*, is calculated so that the weighted average decay rate for all components is equal to the EPA AP-42 default decay rate (0.04) for mixed MSW for regions that receive more than 25 inches of rain annually (EPA 1995). Because AP-42 values were developed using landfill data from approximately 1990, 1990 waste composition for the United States from EPA’s *Characterization of Municipal Solid Waste in the United States: 1990 Update* (EPA 1991) was used to calculate *f*. This correction factor is then multiplied by the Eleazer et al. (1997) decay rates of each waste component to develop field-scale first-order decay rates.

De la Cruz and Barlaz (2010) also use other assumed initial decay rates for mixed MSW in place of the AP-42 default value based on different types of environments in which landfills in the United States are located, including dry conditions (less than 25 inches of rain annually, k=0.02) and bioreactor landfill conditions (moisture is controlled for rapid decomposition, k=0.12). As in the Landfills section of the Inventory (Section 7.1), which estimates CH_4 emissions, the overall MSW decay rate is estimated by partitioning the U.S. landfill population into three categories based on annual precipitation ranges of: (1) Less than 20 inches of rain per year, (2) 20 to 40 inches of rain per year, and (3) greater than 40 inches of rain per year. These correspond to overall MSW decay rates of 0.020, 0.038, and 0.057 year^{-1}, respectively.

De la Cruz and Barlaz (2010) calculate component-specific decay rates corresponding to the first value (0.020 year^{-1}), but not for the other two overall MSW decay rates. To maintain consistency between landfill methodologies across the Inventory, the correction factors (*f*) were developed for decay rates of 0.038 and 0.057 year^{-1} through linear interpolation. A weighted national average component-specific decay rate was calculated by assuming that waste generation is proportional to population (the same assumption used in the landfill methane emission estimate), based on population data from the 2000 U.S. Census. The component-specific decay rates are shown in Table 6-81.

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[68] EPA (2016 and 2015) reports discards in two categories: “combustion with energy recovery” and “landfill, other disposal,” which includes combustion without energy recovery. For years in which there is data from previous EPA reports on combustion without energy recovery, EPA assumes these estimates are still applicable. For 2000 to present, EPA assumes that any combustion of MSW that occurs includes energy recovery, so all discards to “landfill, other disposal” are assumed to go to landfills.

For each of the four materials (grass, leaves, branches, food scraps), the stock of C in landfills for any given year is calculated according to Equation 1:

$$LFC_{i,t} = \sum_{n}^{t} W_{i,n} \times (1 - MC_i) \times ICC_i \times \{[CS_i \times ICC_i] + [(1 - (CS_i \times ICC_i)) \times e^{-k(t-n)}]\}$$

where,

t = Year for which C stocks are being estimated (year),
i = Waste type for which C stocks are being estimated (grass, leaves, branches, food scraps),
$LFC_{i,t}$ = Stock of C in landfills in year t, for waste i (metric tons),
$W_{i,n}$ = Mass of waste i disposed of in landfills in year n (metric tons, wet weight),
n = Year in which the waste was disposed of (year, where $1960 < n < t$),
MC_i = Moisture content of waste i (percent of water),
CS_i = Proportion of initial C that is stored for waste i (percent),
ICC_i = Initial C content of waste i (percent),
e = Natural logarithm, and
k = First-order decay rate for waste i, (year^{-1}).

For a given year t, the total stock of C in landfills ($TLFC_t$) is the sum of stocks across all four materials (grass, leaves, branches, food scraps). The annual flux of C in landfills (F_t) for year t is calculated in as the change in C stock compared to the preceding year according to Equation 2:

$$F_t = TLFC_t - TLFC_{(t-1)}$$

Thus, as seen in Equation 1, the C placed in a landfill in year n is tracked for each year t through the end of the inventory period. For example, disposal of food scraps in 1960 resulted in depositing about 1,135,000 metric tons of C in landfills. Of this amount, 16 percent (179,000 metric tons) is persistent; the remaining 84 percent (956,000 metric tons) is degradable. By 1965, more than half of the degradable portion (518,000 metric tons) decomposes, leaving a total of 617,000 metric tons (the persistent portion, plus the remainder of the degradable portion).

Continuing the example, by 2015, the total food scraps C originally disposed of in 1960 had declined to 179,000 metric tons (i.e., virtually all degradable C had decomposed). By summing the C remaining from 1960 with the C remaining from food scraps disposed of in subsequent years (1961 through 2015), the total landfill C from food scraps in 2015 was 42.6 million metric tons. This value is then added to the C stock from grass, leaves, and branches to calculate the total landfill C stock in 2015, yielding a value of 268.0 million metric tons (as shown in Table 6-82).[69] In the same way total net flux is calculated for forest C and harvested wood products, the total net flux of landfill C for yard trimmings and food scraps for a given year (Table 6-80) is the difference in the landfill C stock for that year and the stock in the preceding year. For example, the net change in 2016 shown in Table 6-80 (3.3 MMT C) is equal to the stock in 2016 (271.3 MMT C) minus the stock in 2015 (268.0 MMT C). The C stocks calculated through this procedure are shown in Table 6-82.

Table 6-81: Moisture Contents, C Storage Factors (Proportions of Initial C Sequestered), Initial C Contents, and Decay Rates for Yard Trimmings and Food Scraps in Landfills

Variable	Yard Trimmings			Food Scraps
	Grass	Leaves	Branches	
Moisture Content (% H_2O)	70	30	10	70
C Storage Factor, Proportion of Initial C Stored (%)	53	85	77	16
Initial C Content (%)	45	46	49	51
Decay Rate (year^{-1})	0.323	0.185	0.016	0.156

Note: The decay rates are presented as weighted averages based on annual precipitation categories and population residing in each precipitation category.

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[69] Carbon stock mass and decomposition was not estimated for 2016; the values are only estimated from 1990 to 2015.

Table 6-82: C Stocks in Yard Trimmings and Food Scraps in Landfills (MMT C)

Carbon Pool	1990		2005		2012	2013	2014	2015	2016
Yard Trimmings	**155.8**		**202.9**		**218.6**	**220.9**	**223.1**	**225.4**	**227.7**
Branches	14.5		18.1		19.5	19.7	19.9	20.2	20.4
Leaves	66.7		87.3		94.5	95.5	96.6	97.6	98.7
Grass	74.6		97.5		104.5	105.6	106.6	107.6	108.6
Food Scraps	**17.6**		**32.8**		**39.8**	**40.7**	**41.6**	**42.6**	**43.6**
Total Carbon Stocks	**173.5**		**235.6**		**258.3**	**261.5**	**264.8**	**268.0**	**271.3**

Note: Totals may not sum due to independent rounding.

To develop the 2016 estimate, a simplified inventory update was performed using values from the 1990 through 2015 Inventory. Estimates of yard trimming and food scrap carbon stocks were forecasted for 2016, which were then used to calculate net changes in carbon stocks. Excel's FORECAST.ETS function was used to predict a 2016 value using historical data via an algorithm called "Exponential Triple Smoothing". This method smooths out the data to determine the overall trend and provide an appropriate estimate for 2016.

Uncertainty and Time-Series Consistency

The uncertainty analysis for landfilled yard trimmings and food scraps includes an evaluation of the effects of uncertainty for the following data and factors: disposal in landfills per year (tons of C), initial C content, moisture content, decay rate, and proportion of C stored. The C storage landfill estimates are also a function of the composition of the yard trimmings (i.e., the proportions of grass, leaves and branches in the yard trimmings mixture). There are respective uncertainties associated with each of these factors.

A Monte Carlo (Approach 2) uncertainty analysis that was run on the previous (i.e., 1990 through 2015) Inventory was applied to estimate the overall uncertainty of the sequestration estimate for 2016. The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 6-83. Total yard trimmings and food scraps CO_2 flux in 2016 was estimated to be between -19.0 and -4.8 MMT CO_2 Eq. at a 95 percent confidence level (or 19 of 20 Monte Carlo stochastic simulations). This indicates a range of 56 percent below to 61 percent above the 2016 flux estimate of -12.1 MMT CO_2 Eq.

Table 6-83: Approach 2 Quantitative Uncertainty Estimates for CO_2 Flux from Yard Trimmings and Food Scraps in Landfills (MMT CO_2 Eq. and Percent)

Source	Gas	2016 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Yard Trimmings and Food Scraps	CO_2	(12.1)	(19.0)	(4.8)	-56%	61%

[a] Range of flux estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Note: Parentheses indicate negative values or net C sequestration.

QA/QC and Verification

Tier 1 and Tier 2 QA/QC activities were conducted consistent with the U.S. QA/QC plan. Source-specific quality control measures for *Landfilled Yard Trimmings and Food Scraps* included checking that input data were properly transposed within the spreadsheet, checking calculations were correct, and confirming that all activity data and calculations documentation was complete and updated to ensure data were properly handled through the inventory process.

Order of magnitude checks and checks of time-series consistency were performed to ensure data were updated correctly and any changes in emissions estimates were reasonable and reflected changes in activity data. An annual change trend analysis was also conducted to ensure the validity of the emissions estimates. Errors that were found during this process were corrected as necessary.

Recalculations Discussion

No recalculations were performed for the 1990 through 2015 estimates in this Inventory.

Planned Improvements

Future work is planned to evaluate the consistency between the estimates of C storage described in this chapter and the estimates of landfill CH_4 emissions described in the Waste chapter. For example, the Waste chapter does not distinguish landfill CH_4 emissions from yard trimmings and food scraps separately from landfill CH_4 emissions from total bulk (i.e., municipal solid) waste, which includes yard trimmings and food scraps.

In addition, additional data from recent peer-reviewed literature will be evaluated that may modify the default C storage factors, initial C contents, and decay rates for yard trimmings and food scraps in landfills. Based upon this evaluation, changes may be made to the default values. Updating of the weighted national average component-specific decay rate using new U.S. Census data will also be evaluated, if any are available.

Yard waste composition will also be investigated to determine if changes need to be made based on changes in residential practices, a review of available literature will be conducted to determine if there are changes in the allocation of yard trimmings. For example, leaving grass clippings in place is becoming a more common practice, thus reducing the percentage of grass clippings in yard trimmings disposed in landfills. In addition, agronomists may be consulted for determining the mass of grass per acre on residential lawns to provide an estimate of total grass generation for comparison with Inventory estimates.

Finally, available data will be reviewed to ensure all types of yard trimmings and food scraps are being included in Inventory estimates, such as debris from road construction.

6.11 Land Converted to Settlements (CRF Category 4E2)

Land Converted to Settlements includes all settlements in an Inventory year that had been in another land use(s) during the previous 20 years (USDA-NRCS 2015).[70] For example, cropland, grassland or forest land converted to settlements during the past 20 years would be reported in this category. Recently-converted lands are retained in this category for 20 years as recommended by IPCC (2006). This Inventory includes all settlements in the conterminous United States and Hawaii, but does not include settlements in Alaska. Areas of drained organic soils on settlements in federal lands are also not included in this Inventory. Consequently, there is a discrepancy between the total amount of managed area for *Land Converted to Settlements* (see Section 6.1—Representation of the U.S. Land Base) and the settlements area included in the inventory analysis.

Land use change can lead to large losses of carbon (C) to the atmosphere, particularly conversions from forest land (Houghton et al. 1983). Moreover, conversion of forest to another land use (i.e., deforestation) is one of the largest anthropogenic sources of emissions to the atmosphere globally (Schimel 1995), although this source may be declining globally according to a recent assessment (Tubiello et al. 2015).

IPCC (2006) recommends reporting changes in biomass, dead organic matter, and soil organic C (SOC) stocks due to land use change. All soil C stock changes are estimated and reported for *Land Converted to Settlements*, but there

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[70] NRI survey locations are classified according to land-use histories starting in 1979, and consequently the classifications are based on less than 20 years from 1990 to 2001. This may have led to an underestimation of *Land Converted to Settlements* in the early part of the time series to the extent that some areas are converted to settlements from 1971 to 1978.

is limited reporting of other pools in this Inventory. Loss of aboveground and belowground biomass, dead wood and litter C are reported for *Forest Land Converted to Settlements*, but not for other land use conversions to settlements.

Forest Land Converted to Settlements is the largest source of emissions from 1990 to 2016, accounting for approximately 66 percent of the average total loss of C among all of the land use conversions in *Land Converted to Settlements.* Losses of aboveground and belowground biomass, dead wood and litter C losses in 2016 are 32.7, 6.6, 2.2, and 2.0 MMT CO_2 Eq. (8.9, 1.8, 0.6, and 0.5 MMT C). Mineral and organic soils also lost 22.6 and 1.9 MMT CO_2 Eq. in 2016 (6.2 and 0.5 MMT C). The total net flux is 68.0 MMT CO_2 Eq. in 2016 (18.5 MMT C), which is an 83 percent increase in CO_2 emissions compared to the emissions in the initial reporting year of 1990. The main driver of net emissions for this source category is the conversion of forest land to settlements, with large losses of biomass C.

Table 6-84: Net CO_2 Flux from Soil, Dead Organic Matter and Biomass C Stock Changes for *Land Converted to Settlements* (MMT CO_2 Eq.)

	1990	2005	2012	2013	2014	2015	2016
Cropland Converted to Settlements	**4.1**	**11.9**	**10.3**	**10.3**	**10.2**	**10.2**	**10.1**
Mineral Soils	3.5	10.7	9.4	9.4	9.4	9.3	9.3
Organic Soils	0.6	1.2	0.9	0.9	0.9	0.8	0.9
Forest Land Converted to Settlements	**29.0**	**42.3**	**44.8**	**44.9**	**44.8**	**44.8**	**44.8**
Aboveground Live Biomass	19.9	29.9	32.7	32.7	32.7	32.7	32.7
Belowground Live Biomass	4.0	6.0	6.6	6.6	6.6	6.6	6.6
Dead Wood	2.2	2.7	2.2	2.2	2.2	2.2	2.2
Litter	2.0	2.3	2.0	2.0	2.0	2.0	2.0
Mineral Soils	0.9	1.3	1.3	1.3	1.3	1.3	1.3
Organic Soils	+	+	+	0.1	+	+	+
Grassland Converted Settlements	**4.0**	**13.5**	**12.4**	**12.4**	**12.4**	**12.4**	**12.3**
Mineral Soils	3.5	12.3	11.5	11.5	11.5	11.4	11.4
Organic Soils	0.5	1.2	0.8	0.9	0.9	0.9	0.9
Other Lands Converted to Settlements	0.2	**0.7**	**0.7**	**0.7**	**0.7**	**0.7**	**0.7**
Mineral Soils	0.2	0.6	0.6	0.6	0.6	0.6	0.6
Organic Soils	+	0.1	0.1	0.1	0.1	0.1	0.1
Wetlands Converted to Settlements	+	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Mineral Soils	+	0.1	0.1	0.1	0.1	0.1	0.1
Organic Soils	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total Aboveground Biomass Flux	**19.9**	**29.9**	**32.7**	**32.7**	**32.7**	**32.7**	**32.7**
Total Belowground Biomass Flux	**4.0**	**6.0**	**6.6**	**6.6**	**6.6**	**6.6**	**6.6**
Total Dead Wood Flux	**2.2**	**2.7**	**2.2**	**2.2**	**2.2**	**2.2**	**2.2**
Total Litter Flux	**2.0**	**2.3**	**2.0**	**2.0**	**2.0**	**2.0**	**2.0**
Total Mineral Soil Flux	**8.0**	**24.9**	**22.9**	**22.9**	**22.8**	**22.7**	**22.6**
Total Organic Soil Flux	**1.1**	**2.5**	**1.9**	**2.0**	**1.9**	**1.9**	**1.9**
Total Net Flux	**37.2**	**68.4**	**68.3**	**68.3**	**68.2**	**68.1**	**68.0**

+ Does not exceed 0.05 MMT CO_2 Eq.

Notes: Estimates after 2012 are based on a data splicing method (see Methodology section). Totals may not sum due to independent rounding.

Table 6-85: Net CO_2 Flux from Soil, Dead Organic Matter and Biomass C Stock Changes for *Land Converted to Settlements* (MMT C)

	1990	2005	2012	2013	2014	2015	2016
Cropland Converted to Settlements	**1.1**	**3.2**	**2.8**	**2.8**	**2.8**	**2.8**	**2.8**
Mineral Soils	0.9	2.9	2.6	2.6	2.6	2.5	25

Organic Soils	0.2	0.3	0.2	0.2	0.2	0.2	0.2
Forest Land Converted to Settlements	**7.9**	**11.5**	**12.2**	**12.2**	**12.2**	**12.2**	**12.2**
Aboveground Live Biomass	5.4	8.2	8.9	8.9	8.9	8.9	8.9
Belowground Live Biomass	1.1	1.6	1.8	1.8	1.8	1.8	1.8
Dead Wood	0.6	0.7	0.6	0.6	0.6	0.6	0.6
Litter	0.5	0.6	0.5	0.5	0.5	0.5	0.5
Mineral Soils	0.3	0.4	0.4	0.3	0.3	0.3	0.3
Organic Soils	+	+	+	+	+	+	+
Grassland Converted Settlements	**1.1**	**3.7**	**3.4**	**3.4**	**3.4**	**3.4**	**3.4**
Mineral Soils	0.9	3.4	3.1	3.1	3.1	3.1	3.1
Organic Soils	0.1	0.3	0.2	0.2	0.2	0.2	0.2
Other Lands Converted to Settlements	**+**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**
Mineral Soils	+	0.2	0.2	0.2	0.2	0.2	0.2
Organic Soils	+	+	+	+	+	+	+
Wetlands Converted to Settlements	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Mineral Soils	+	+	+	+	+	+	+
Organic Soils	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total Aboveground Biomass Flux	**5.4**	**8.2**	**8.9**	**8.9**	**8.9**	**8.9**	**8.9**
Total Belowground Biomass Flux	**1.1**	**1.6**	**1.8**	**1.8**	**1.8**	**1.8**	**1.8**
Total Dead Wood Flux	**0.6**	**0.7**	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**
Total Litter Flux	**0.5**	**0.6**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**
Total Mineral Soil Flux	**2.2**	**6.8**	**6.2**	**6.2**	**6.2**	**6.2**	**6.2**
Total Organic Soil Flux	**0.3**	**0.7**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**
Total Net Flux	**10.2**	**18.7**	**18.6**	**18.6**	**18.6**	**18.6**	**18.5**

+ Does not exceed 0.05 MMT C

Notes: Estimates after 2012 are based on a data splicing method (see Methodology section). Totals may not sum due to independent rounding.

Methodology

The following section includes a description of the methodology used to estimate C stock changes for *Land Converted to Settlements*, including (1) loss of aboveground and belowground biomass, dead wood and litter C with conversion of forest lands to settlements, as well as (2) the impact from all land use conversions to settlements on mineral and organic soil C stocks.

Biomass, Dead Wood, and Litter Carbon Stock Changes

A combination of Tier 1 and 2 methods is applied to estimate aboveground and belowground biomass, dead wood, and litter C stock changes for *Forest Land Converted to Settlements.* For this method, all annual plots and portions of plots (i.e., conditions; hereafter referred to as plots) from the Forest Inventory and Analysis (FIA) program are evaluated for land use change in the 48 conterminous United States (i.e., all states except Alaska and Hawaii) (USDA Forest Service 2015). Specifically, all annual re-measured FIA plots that are classified as *Forest Land Converted to Settlements* are identified in each state, and C density estimates before conversion are compiled for aboveground biomass, belowground biomass, dead wood, and litter. However, there are exceptions for the Intermountain Region of the Western United States (Arizona, Colorado, Idaho, Montana, New Mexico, Nevada, and Utah), in which there are a small number of plots that are converted from Forest Land to other Land Uses. In this region, all plots identified as a conversion from forest land to another land use are grouped and used to estimate the C densities before conversion, rather than subdividing the plots into specific land use change categories. Furthermore, there are no re-measured annual plots in Wyoming, and so the C densities before conversion are based on data from Colorado, Idaho, Montana, and Utah.

The C density before conversion is estimated for aboveground biomass, belowground biomass, dead wood, and litter C pools. Soil C stock changes are also addressed, but are based on methods discussed in the next section. Individual tree aboveground and belowground C density estimates are based on Woodall et al. (2011). The estimates of aboveground and belowground biomass includes live understory species (i.e., undergrowth plants in a forest) comprised of woody shrubs and trees less than 2.54 cm in diameter at breast height. It is assumed that 10 percent of total understory C mass is belowground (Smith et al. 2006). Estimates of C density are derived from information in Birdsey (1996) and Jenkins et al. (2003). The C density before conversion for standing dead trees is estimated following the basic method applied to live trees (Woodall et al. 2011) with additional modifications to account for decay and structural loss (Domke et al. 2011; Harmon et al. 2011). Downed dead wood is defined as pieces of dead wood greater than 7.5 cm diameter at transect intersections that are not attached to live or standing dead trees, and includes stumps and roots of harvested trees. The C density before conversion for downed dead wood is estimated based on measurements of downed dead wood of a subset of FIA plots (Domke et al. 2013; Woodall and Monleon 2008), and models specific to regions and forest types within each region are used to estimate dead wood C densities. Litter C is the pool of decaying leaves and woody fragments with diameters of up to 7.5 cm that are above the mineral soil (also known as duff, humus, and fine woody debris). A subset of FIA plots are measured for litter C, and a modeling approach is used to estimate litter C density based on the measurements (Domke et al. 2016). See Annex 3.13 for more information about initial C density estimates for Forest Land.

In all states, the initial C in the forest land before conversion to settlements is assumed to be lost to the atmosphere in the year of the conversion (i.e., 0 tonnes dry matter ha^{-1} immediately after conversion), which is consistent with the Tier 1 method in the IPCC guidelines (IPCC 2006). It is also assumed that the accumulation of new biomass, dead wood and litter is negligible in the new settlement area.[71] Therefore, total emissions and removals are estimated based solely on the loss of all C existing on the forest land before conversion.

Soil Carbon Stock Changes

Soil C stock changes are estimated for *Land Converted to Settlements* according to land-use histories recorded in the 2012 USDA NRI survey for non-federal lands (USDA-NRCS 2015). Land use and some management information were originally collected for each NRI survey locations on a 5-year cycle beginning in 1982. In 1998, the NRI program began collecting annual data, and the annual data are currently available through 2012 (USDA-NRCS 2015). However, this Inventory only uses NRI data through 2012 because newer data were not available.

NRI survey locations are classified as *Land Converted to Settlements* in a given year between 1990 and 2012 if the land use is settlements but had been classified as another use during the previous 20 years. NRI survey locations are classified according to land-use histories starting in 1979, and consequently the classifications are based on less than 20 years from 1990 to 1998. This may have led to an underestimation of *Land Converted to Settlements* in the early part of the time series to the extent that some areas are converted to grassland between 1971 and 1978. For federal lands, the land use history is derived from land cover changes in the National Land Cover Dataset (Homer et al. 2007; Fry et al. 2011; Homer et al. 2015).

Mineral Soil Carbon Stock Changes

An IPCC Tier 2 method (Ogle et al. 2003) is applied to estimate C stock changes for *Land Converted to Settlements* on mineral soils from 1990 to 2012. Data on climate, soil types, land-use, and land management activity are used to classify land area and apply appropriate stock change factors (Ogle et al. 2003, 2006). Reference C stocks are estimated using the National Soil Survey Characterization Database (NRCS 1997) with cultivated cropland as the reference condition, rather than native vegetation as used in IPCC (2006). Soil measurements under agricultural management are much more common and easily identified in the National Soil Survey Characterization Database (NRCS 1997) than are soils under a native condition, and therefore cultivated cropland provide a more robust sample for estimating the reference condition. U.S.-specific C stock change factors are derived from published literature to determine the impact of management practices on SOC storage (Ogle et al. 2003, Ogle et al. 2006). However, there are insufficient data to estimate a set of land use, management, and input factors for settlements. Moreover, the 2012 NRI survey data (USDA-NRCS 2015) do not provide the information needed to assign different land use subcategories to settlements, such as turf grass and impervious surfaces, which is needed to apply the Tier 1 factors from the IPCC guidelines (2006). Therefore, the United States has adopted a land use factor of 0.7 to

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[71] C accumulation in woody biomass following conversion of lands to settlements is included in Section 6.10 *Settlements Remaining Settlements: Changes in Carbon Stocks in Urban Trees.*

represent the loss of soil C with conversion to settlements, which is similar to the estimated losses with conversion to cropland. More specific factor values can be derived in future inventories as data become available. See Annex 3.12 for additional discussion of the Tier 2 methodology for mineral soils.

A linear extrapolation of the trend in the time series is applied to estimate soil C stock changes from 2013 to 2016 because NRI activity data are not available for these years. Specifically, a linear regression model with autoregressive moving-average (ARMA) errors (Brockwell and Davis 2016) is used to estimate the trend in stock changes over time from 1990 to 2012, and in turn, the trend is used to approximate stock changes from 2013 to 2016. The Tier 2 method described previously will be applied to recalculate the 2013 to 2016 emissions in a future Inventory.

Organic Soil Carbon Stock Changes

Annual C emissions from drained organic soils in *Land Converted to Settlements* are estimated using the Tier 2 method provided in IPCC (2006). The Tier 2 method assumes that organic soils are losing C at a rate similar to croplands, and therefore uses the country-specific values for cropland (Ogle et al. 2003). To estimate CO_2 emissions from 1990 to 2012, the total area of organic soils in *Land Converted to Settlements* is multiplied by the Tier 2 emission factor, which is 11.2 MT C per ha in cool temperate regions, 14.0 MT C per ha in warm temperate regions and 14.3 MT C per ha in subtropical regions (See Annex 3.12 for more information). Similar to the mineral soil C stocks changes, a linear extrapolation of the trend in the time series is applied to estimate the emissions from 2013 to 2016 because NRI activity data are not available for these years to determine the area of *Land Converted to Settlements*.

Uncertainty and Time-Series Consistency

The uncertainty analysis for C losses with *Forest Land Converted to Settlements* is conducted in the same way as the uncertainty assessment for forest ecosystem C flux in the *Forest Land Remaining Forest Land* category. Sample and model-based error are combined using simple error propagation methods provided by the IPCC (2006), i.e., by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities. For additional details see the Uncertainty Analysis in Annex 3.13. The uncertainty analysis for mineral soil C stock changes and annual C emission estimates from drained organic soils in *Land Converted to Settlements* is estimated using a Monte Carlo approach, which is also described in the *Cropland Remaining Cropland* section.

Uncertainty estimates are presented in Table 6-86 for each subsource (i.e., biomass C stocks, mineral soil C stocks and organic soil C stocks) and the method applied in the inventory analysis (i.e., Tier 2 and Tier 3). Uncertainty estimates from the Tier 2 and 3 approaches are combined using the simple error propagation methods provided by the IPCC (2006), i.e., as described in the previous paragraph. There are also additional uncertainties propagated through the analysis associated with the data splicing methods applied to estimate soil C stock changes from 2013 to 2016. The combined uncertainty for total C stocks in *Land Converted to Settlements* ranges from 29 percent below to 29 percent above the 2016 stock change estimate of 68.0 MMT CO_2 Eq.

Table 6-86: Approach 2 Quantitative Uncertainty Estimates for Soil, Dead Organic Matter and Biomass C Stock Changes occurring within *Land Converted to Settlements* (MMT CO_2 Eq. and Percent)

Source	2016 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate[a] (MMT CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Cropland Converted to Settlements	**10.1**	**8.1**	**12.2**	**-20%**	**20%**
Mineral Soil C Stocks	9.3	7.2	11.3	-22%	22%
Organic Soil C Stocks	0.9	0.6	1.1	-32%	32%
Forest Land Converted to Settlements	**44.8**	**25.3**	**64.2**	**-43%**	**43%**
Aboveground Biomass C Stocks	32.7	13.7	51.8	-58%	58%
Belowground Biomass C Stocks	6.6	2.8	10.5	-58%	58%
Dead Wood	2.2	0.9	3.5	-58%	58%
Litter	2.0	1.5	2.4	-22%	22%
Mineral Soil C Stocks	1.3	1.0	1.5	-18%	18%

Organic Soil C Stocks	+	+	+	-35%	35%
Grassland Converted to Settlements	**12.3**	**10.0**	**14.6**	**-18%**	**18%**
Mineral Soil C Stocks	11.4	9.1	13.6	-20%	20%
Organic Soil C Stocks	0.9	0.6	1.2	-36%	36%
Other Lands Converted to Settlements	**0.7**	**0.6**	**0.9**	**-21%**	**21%**
Mineral Soil C Stocks	0.6	0.5	0.7	-22%	22%
Organic Soil C Stocks	0.1	+	0.2	-71%	71%
Wetlands Converted to Settlements	**0.1**	**0.0**	**0.1**	**-37%**	**37%**
Mineral Soil C Stocks	0.1	0.0	0.1	-37%	37%
Organic Soil C Stocks	0.0	0.0	0.0	0%	0%
Total: Land Converted to Settlements	**68.0**	**48.3**	**87.7**	**-29%**	**29%**
Aboveground Biomass C Stocks	**32.7**	**13.7**	**51.8**	**-58%**	**58%**
Belowground Biomass C Stocks	**6.6**	**2.8**	**10.5**	**-58%**	**58%**
Dead Wood	**2.2**	**0.9**	**3.5**	**-58%**	**58%**
Litter	**2.0**	**1.5**	**2.4**	**-22%**	**22%**
Mineral Soil C Stocks	**22.6**	**19.5**	**25.6**	**-13%**	**13%**
Organic Soil C Stocks	**1.9**	**1.2**	**2.5**	**-34%**	**33%**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Range of C stock change estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological recalculations are applied to the latter part of the time series (2013 to 2015) using the linear time series model described above. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

Quality control measures included checking input data, model scripts, and results to ensure data are properly handled throughout the inventory process. Inventory reporting forms and text are reviewed and revised as needed to correct transcription errors.

Recalculations Discussion

Methodological recalculations are associated with extending the time series from 2013 through 2016 using a linear time series model. The recalculation had a minor effect on the time series overall with C stock changes declining by less than 1 percent on average.

Planned Improvements

A planned improvement for the *Land Converted to Settlements* category is to develop an inventory of C stock changes in Alaska. This includes C stock changes for biomass, dead organic matter and soils. There are also plans to extend the Inventory to included C losses associated with drained organic soils in settlements occurring on federal lands. New land representation data will also be compiled, and the time series recalculated for the latter years in the time series that are estimated using data splicing methods in this Inventory.

6.12 Other Land Remaining Other Land (CRF Category 4F1)

Land use is constantly occurring, and areas under a number of differing land-use types remain in their respective land-use type each year, just as other land can remain as other land. While the magnitude of *Other Land Remaining Other Land* is known (see Table 6-7), research is ongoing to track C pools in this land use. Until such time that reliable and comprehensive estimates of C for *Other Land Remaining Other Land* can be produced, it is not possible to estimate CO_2, CH_4 or N_2O fluxes on *Other Land Remaining Other Land* at this time.

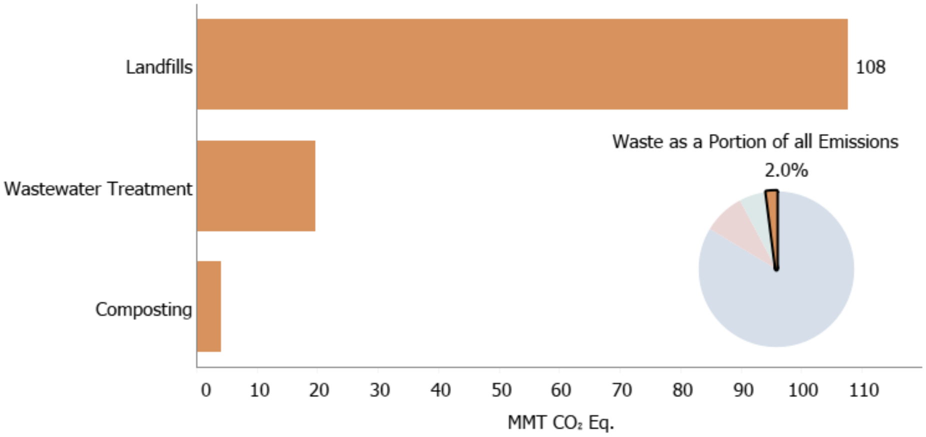
6.13 Land Converted to Other Land (CRF Category 4F2)

Land-use change is constantly occurring, and areas under a number of differing land-use types are converted to other land each year, just as other land is converted to other uses. While the magnitude of these area changes is known (see Table 6-7), research is ongoing to track C across *Other Land Remaining Other Land* and *Land Converted to Other Land*. Until such time that reliable and comprehensive estimates of C across these land-use and land-use change categories can be produced, it is not possible to separate CO_2, CH_4 or N_2O fluxes on *Land Converted to Other Land* from fluxes on *Other Land Remaining Other Land* at this time.

7. Waste

Waste management and treatment activities are sources of greenhouse gas emissions (see Figure 7-1). Landfills accounted for approximately 16.4 percent of total U.S. anthropogenic methane (CH_4) emissions in 2016, the third largest contribution of any CH_4 source in the United States. Additionally, wastewater treatment and composting of organic waste accounted for approximately 2.3 percent and 0.3 percent of U.S. CH_4 emissions, respectively. Nitrous oxide (N_2O) emissions from the discharge of wastewater treatment effluents into aquatic environments were estimated, as were N_2O emissions from the treatment process itself. Nitrous oxide emissions from composting were also estimated. Together, these waste activities account for 1.9 percent of total U.S. N_2O emissions. Nitrogen oxides (NO_x), carbon monoxide (CO), and non-CH_4 volatile organic compounds (NMVOCs) are emitted by waste activities, and are addressed separately at the end of this chapter. A summary of greenhouse gas emissions from the Waste chapter is presented in Table 7-1 and Table 7-2.

Figure 7-1: 2016 Waste Chapter Greenhouse Gas Sources (MMT CO_2 Eq.)



Overall, in 2016, waste activities generated emissions of 131.5 MMT CO_2 Eq., or 2.0 percent of total U.S. greenhouse gas emissions.[1]

Table 7-1: Emissions from Waste (MMT CO_2 Eq.)

Gas/Source	1990	2005	2012	2013	2014	2015	2016
CH_4	**195.6**	**150.4**	**134.0**	**130.2**	**129.8**	**128.9**	**124.6**
Landfills	179.6	132.7	117.0	113.3	112.7	111.7	107.7

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[1] Emissions reported in the Waste chapter for landfills and wastewater treatment include those from all 50 states, including Hawaii and Alaska, as well as from U.S. Territories to the extent those waste management activities are occurring. Emissions for composting include all 50 states, including Hawaii and Alaska, but not U.S. Territories. Composting emissions from U.S. Territories are assumed to be small.

Wastewater Treatment	15.7	15.8	15.1	14.9	15.0	15.1	14.8
Composting	0.4	1.9	1.9	2.0	2.1	2.1	2.1
N_2O	**3.7**	**6.1**	**6.4**	**6.5**	**6.7**	**6.7**	**6.8**
Wastewater Treatment	3.4	4.4	4.6	4.7	4.8	4.8	5.0
Composting	0.3	1.7	1.7	1.8	1.9	1.9	1.9
Total	**199.3**	**156.4**	**140.4**	**136.7**	**136.5**	**135.6**	**131.5**

Note: Totals may not sum due to independent rounding.

Table 7-2: Emissions from Waste (kt)

Gas/Source	1990	2005	2012	2013	2014	2015	2016
CH_4	**7,825**	**6,016**	**5,361**	**5,208**	**5,190**	**5,155**	**4,984**
Landfills	7,182	5,310	4,680	4,531	4,509	4,467	4,306
Wastewater Treatment	627	631	604	596	598	605	593
Composting	15	75	77	81	84	84	85
N_2O	**12**	**20**	**21**	**22**	**23**	**23**	**23**
Wastewater Treatment	11	15	16	16	16	16	17
Composting	1	6	6	6	6	6	6

Note: Totals may not sum due to independent rounding.

Carbon dioxide (CO_2), CH_4, and N_2O emissions from the incineration of waste are accounted for in the Energy sector rather than in the Waste sector because almost all incineration of municipal solid waste (MSW) in the United States occurs at waste-to-energy facilities where useful energy is recovered. Similarly, the Energy sector also includes an estimate of emissions from burning waste tires and hazardous industrial waste, because virtually all of the combustion occurs in industrial and utility boilers that recover energy. The incineration of waste in the United States in 2016 resulted in 11.0 MMT CO_2 Eq. emissions, more than half of which is attributable to the combustion of plastics. For more details on emissions from the incineration of waste, see Section 7.4.

Box 7-1: Methodological Approach for Estimating and Reporting U.S. Emissions and Removals

In following the United Nations Framework Convention on Climate Change (UNFCCC) requirement under Article 4.1 to develop and submit national greenhouse gas emission inventories, the emissions and removals presented in this report and this chapter, are organized by source and sink categories and calculated using internationally-accepted methods provided by the Intergovernmental Panel on Climate Change (IPCC) in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories (2006 IPCC Guidelines)*. Additionally, the calculated emissions and removals in a given year for the United States are presented in a common manner in line with the UNFCCC reporting guidelines for the reporting of inventories under this international agreement. The use of consistent methods to calculate emissions and removals by all nations providing their inventories to the UNFCCC ensures that these reports are comparable. The presentation of emissions and sinks provided in this Inventory do not preclude alternative examinations, but rather, this Inventory presents emissions and removals in a common format consistent with how countries are to report Inventories under the UNFCCC. The report itself, and this chapter, follows this standardized format, and provides an explanation of the application of methods used to calculate emissions and removals.

Box 7-2: Waste Data from EPA's Greenhouse Gas Reporting Program

On October 30, 2009, the U.S. Environmental Protection Agency (EPA) published a rule requiring annual reporting of greenhouse gas data from large greenhouse gas emission sources in the United States. Implementation of the rule, codified at 40 CFR Part 98, is referred to as EPA's Greenhouse Gas Reporting Program (GHGRP). The rule applies to direct greenhouse gas emitters, fossil fuel suppliers, industrial gas suppliers, and facilities that inject CO_2 underground for sequestration or other reasons and requires reporting by sources or suppliers in 41 industrial categories. Annual reporting is at the facility level, except for certain suppliers of fossil fuels and industrial greenhouse gases. Data reporting by affected facilities includes the reporting of emissions from fuel combustion at that affected facility. In general, the threshold for reporting is 25,000 metric tons or more of CO_2 Eq. per year.

EPA presents the data collected by its GHGRP through a data publication tool that allows data to be viewed in several formats including maps, tables, charts and graphs for individual facilities or groups of facilities.[2]

EPA's GHGRP dataset and the data presented in this Inventory are complementary. The GHGRP dataset continues to be an important resource for the Inventory, providing not only annual emissions information, but also other annual information, such as activity data and emission factors that can improve and refine national emission estimates and trends over time. GHGRP data also allow EPA to disaggregate national inventory estimates in new ways that can highlight differences across regions and sub-categories of emissions, along with enhancing application of QA/QC procedures and assessment of uncertainties.

EPA uses annual GHGRP data in a number of categories to improve the national estimates presented in this Inventory consistent with IPCC guidelines. Within the Waste Chapter, EPA uses directly reported GHGRP data for net CH_4 emissions from MSW landfills for the years 2010 to 2016 of the Inventory. This data is also used to back-cast emissions from MSW landfills for the years 2005 to 2009.

7.1 Landfills (CRF Source Category 5A1)

In the United States, solid waste is managed by landfilling, recovery through recycling or composting, and combustion through waste-to-energy facilities. Disposing of solid waste in modern, managed landfills is the most commonly used waste management technique in the United States. More information on how solid waste data are collected and managed in the United States is provided in Box 7-3. The municipal solid waste (MSW) and industrial waste landfills referred to in this section are all modern landfills that must comply with a variety of regulations as discussed in Box 7-35. Disposing of waste in illegal dumping sites is not considered to have occurred in years later than 1980 and these sites are not considered to contribute to net emissions in this section for the timeframe of 1990 to the current Inventory year. MSW landfills, or sanitary landfills, are sites where MSW is managed to prevent or minimize health, safety, and environmental impacts. Waste is deposited in different cells and covered daily with soil; many have environmental monitoring systems to track performance, collect leachate, and collect landfill gas. Industrial waste landfills are constructed in a similar way as MSW landfills, but are used to dispose of industrial solid waste, such as RCRA Subtitle D wastes (e.g., non-hazardous industrial solid waste defined in Title 40 of the Code of Federal Regulations or CFR in section 257.2), commercial solid wastes, or conditionally exempt small-quantity generator wastes (EPA 2016a).

After being placed in a landfill, organic waste (such as paper, food scraps, and yard trimmings) is initially decomposed by aerobic bacteria. After the oxygen has been depleted, the remaining waste is available for consumption by anaerobic bacteria, which break down organic matter into substances such as cellulose, amino acids, and sugars. These substances are further broken down through fermentation into gases and short-chain organic compounds that form the substrates for the growth of methanogenic bacteria. These methane (CH_4) producing anaerobic bacteria convert the fermentation products into stabilized organic materials and biogas consisting of approximately 50 percent biogenic carbon dioxide (CO_2) and 50 percent CH_4, by volume. Landfill biogas also contains trace amounts of non-methane organic compounds (NMOC) and volatile organic compounds (VOC) that either result from decomposition byproducts or volatilization of biodegradable wastes (EPA 2008).

Methane and CO_2 are the primary constituents of landfill gas generation and emissions. However, the *2006 IPCC Guidelines* set an international convention to not report biogenic CO_2 from activities in the Waste sector (IPCC 2006). Net carbon dioxide flux from carbon stock changes in landfills are estimated and reported under the Land Use, Land-Use Change, and Forestry (LULUCF) sector (see Chapter 6 of this Inventory). Additionally, emissions of NMOC and VOC are not estimated because they are emitted in trace amounts. Nitrous oxide (N_2O) emissions from

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[2] See <http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf>.

the disposal and application of sewage sludge on landfills are also not explicitly modeled as part of greenhouse gas emissions from landfills. Nitrous oxide emissions from sewage sludge applied to landfills as a daily cover or for disposal are expected to be relatively small because the microbial environment in an anaerobic landfill is not very conducive to the nitrification and denitrification processes that result in N_2O emissions. Furthermore, the *2006 IPCC Guidelines* did not include a methodology for estimating N_2O emissions from solid waste disposal sites "because they are not significant." Therefore, only CH_4 generation and emissions are estimated for landfills under the Waste sector.

Methane generation and emissions from landfills are a function of several factors, including: (1) the total amount and composition of waste-in-place, which is the total waste landfilled annually over the operational lifetime of a landfill; (2) the characteristics of the landfill receiving waste (e.g., size, climate, cover material); (3) the amount of CH_4 that is recovered and either flared or used for energy purposes; and (4) the amount of CH_4 oxidized as the landfill gas – that is not collected by a gas collection system – passes through the cover material into the atmosphere. Each landfill has unique characteristics, but all managed landfills employ similar operating practices, including the application of a daily and intermediate cover material over the waste being disposed of in the landfill to prevent odor and reduce risks to public health. Based on recent literature, the specific type of cover material used can affect the rate of oxidation of landfill gas (RTI 2011). The most commonly used cover materials are soil, clay, and sand. Some states also permit the use of green waste, tarps, waste derived materials, sewage sludge or biosolids, and contaminated soil as a daily cover. Methane production typically begins within the first year after the waste is disposed of in a landfill and will continue for 10 to 60 years or longer as the degradable waste decomposes over time.

In 2016, landfill CH_4 emissions were approximately 107.7 MMT CO_2 Eq. (4,306 kt), representing the third largest source of CH_4 emissions in the United States, behind natural gas systems and enteric fermentation. Emissions from MSW landfills accounted for approximately 95 percent of total landfill emissions, while industrial waste landfills accounted for the remainder. Estimates of operational MSW landfills in the United States have ranged from 1,900 to 2,000 facilities (EPA 2017a; EPA 2017b; Waste Business Journal (WBJ) 2016; WBJ 2010). More recently, the Environment Research & Education Foundation (EREF) conducted a nationwide analysis of MSW management, and counted 1,540 operational MSW landfills in 2013 (EREF 2016). Conversely, there are approximately 3,200 MSW landfills in the United States that have been closed since 1980 (for which a closure date is known, [EPA 2017a; WBJ 2010]). While the number of active MSW landfills has decreased significantly over the past 20 years, from approximately 6,326 in 1990 to 1,540 in the 2013, the average landfill size has increased (EREF 2016; EPA 2017b; BioCycle 2010). With regard to industrial waste landfills, the WBJ database (WBJ 2016) includes approximately 1,200 landfills accepting industrial and/or construction and demolition debris for 2016 (WBJ 2016). Only 172 facilities with industrial waste landfills met the reporting threshold under Subpart TT (Industrial Waste Landfills) of EPA's Greenhouse Gas Reporting Program (GHGRP), indicating that there may be several hundred industrial waste landfills that are not required to report under EPA's GHGRP.

The annual amount of MSW generated and subsequently disposed in MSW landfills varies annually and depends on several factors (e.g., the economy, consumer patterns, recycling and composting programs, inclusion in a garbage collection service). The estimated annual quantity of waste placed in MSW landfills increased 10 percent from approximately 205 MMT in 1990 to 226 MMT in 2000 and then decreased by 11 percent to 205 MMT in 2016 (see Annex 3.14, Table A-251). The total amount of MSW generated is expected to increase as the U.S. population continues to grow, but the percentage of waste landfilled may decline due to increased recycling and composting practices. The estimated quantity of waste placed in industrial waste landfills (from the pulp and paper and food processing sectors) has remained relatively steady since 1990, ranging from 9.7 MMT in 1990 to 10.3 MMT in 2016 (see Annex 3.14, Table A-251). Net CH_4 emissions from MSW landfills have decreased since 1990 (see Table 7-3 and Table 7-4).

In 2016, the Landfill Methane Outreach Program (LMOP) identified 32 new landfill gas-to-energy (LFGE) projects (EPA 2017a) that began operation. While the amount of landfill gas collected and combusted continues to increase, the rate of increase in collection and combustion no longer exceeds the rate of additional CH_4 generation from the amount of organic MSW landfilled as the U.S. population grows.

Landfill gas collection and control is not accounted for at industrial waste landfills in this chapter (see the Methodology discussion for more information).

Table 7-3: CH_4 Emissions from Landfills (MMT CO_2 Eq.)

Activity	**1990**		**2005**		**2012**	**2013**	**2014**	**2015**	**2016**
MSW CH_4 Generation	205.3		-		-	-	-	-	-
Industrial CH_4 Generation	12.1		15.9		16.5	16.5	16.6	16.6	16.6
MSW CH_4 Recovered	(17.9)		-		-	-	-	-	-
MSW CH_4 Oxidized	(18.7)		-		-	-	-	-	-
Industrial CH_4 Oxidized	(1.2)		(1.6)		(1.6)	(1.7)	(1.7)	(1.7)	(1.7)
MSW net CH_4 Emissions (GHGRP)	-		118.4		102.2	98.4	97.8	96.7	92.7
Total	**179.6**		**132.7**		**117.0**	**113.3**	**112.7**	**111.7**	**107.7**

"-" Not applicable due to methodology change.

Note: Totals may not sum due to independent rounding. Parentheses indicate negative values. For years 1990 to 2004, the Inventory methodology uses the first order decay methodology. A methodological change occurs in year 2005. For years 2005 to 2016, directly reported net CH_4 emissions from the GHGRP data are used plus a scale-up factor to account for emissions from landfill facilities that are not subject to the GHGRP. These data incorporate CH_4 recovered and oxidized. As such, CH_4 generation, CH_4 recovery, and CH_4 oxidized are not calculated separately for 2005 to 2016. See the Time-Series Consistency section of this chapter for more information.

Table 7-4: CH_4 Emissions from Landfills (kt)

Activity	**1990**		**2005**		**2012**	**2013**	**2014**	**2015**	**2016**
MSW CH_4 Generation	8,214		-		-	-	-	-	-
Industrial CH_4 Generation	484		636		659	661	662	663	664
MSW CH_4 Recovered	(718)		-		-	-	-	-	-
MSW CH_4 Oxidized	(750)		-		-	-	-	-	-
Industrial CH_4 Oxidized	(48)		(64)		(66)	(66)	(66)	(66)	(66)
MSW net CH_4 Emissions (GHGRP)	-		4,737		4,087	3,936	3,913	3,870	3,708
Total	**7,182**		**5,310**		**4,680**	**4,531**	**4,509**	**4,467**	**4,306**

"-" Not applicable due to methodology change.

Note: Totals may not sum due to independent rounding. Parentheses indicate negative values. For years 1990 to 2004, the Inventory methodology uses the first order decay methodology. A methodological change occurs in year 2005. For years 2005 to 2016, directly reported net CH_4 emissions from the GHGRP data are used plus a scale-up factor to account for emissions from landfill facilities that are not subject to the GHGRP. These data incorporate CH_4 recovered and oxidized. As such, CH_4 generation and CH_4 recovery are not calculated separately. See the Time-Series Consistency section of this chapter for more information.

Methodology

Methodology Applied for MSW Landfills

Methane emissions from landfills can be estimated using two primary methods. The first method uses the first order decay (FOD) model as described by the *2006 IPCC Guidelines* to estimate CH_4 generation. The amount of CH_4 recovered and combusted from MSW landfills is subtracted from the CH_4 generation, and is then adjusted with an oxidation factor. The oxidation factor represents the amount of CH_4 in a landfill that is oxidized to CO_2 as it passes through the landfill cover (e.g., soil, clay, geomembrane). This method is presented below, and is similar to Equation HH-5 in CFR Part 98.343 for MSW landfills, and Equation TT-6 in CFR Part 98.463 for industrial waste landfills.

$$CH_{4,\text{Solid Waste}} = [CH_{4,\text{MSW}} + CH_{4,\text{Ind}} - R] - Ox$$

where,

$CH_{4,\text{Solid Waste}}$ = Net CH_4 emissions from solid waste
$CH_{4,\text{MSW}}$ = CH_4 generation from MSW landfills
$CH_{4,\text{Ind}}$ = CH_4 generation from industrial waste landfills
R = CH_4 recovered and combusted (only for MSW landfills)

Ox = CH_4 oxidized from MSW and industrial waste landfills before release to the atmosphere

The second method used to calculate CH_4 emissions from landfills, also called the back-calculation method, is based on directly measured amounts of recovered CH_4 from the landfill gas and is expressed below and by Equation HH-8 in CFR Part 98.343. The two parts of the equation consider the portion of CH_4 in the landfill gas that is not collected by the landfill gas collection system, and the portion that is collected. First, the recovered CH_4 is adjusted with the collection efficiency of the gas collection and control system and the fraction of hours the recovery system operated in the calendar year. This quantity represents the amount of CH_4 in the landfill gas that is not captured by the collection system; this amount is then adjusted for oxidation. The second portion of the equation adjusts the portion of CH_4 in the collected landfill gas with the efficiency of the destruction device(s), and the fraction of hours the destruction device(s) operated during the year.

$$CH_4\text{,Solid Waste} = [\left(\frac{R}{CE\ x\ f_{REC}} - R\right) x(1 - OX) + R\ x\ \left(1 - (DE\ x\ f_{Dest})\right)]$$

where,

R = Quantity of recovered CH_4 from Equation HH-4 of EPA's GHGRP
CE = Collection efficiency estimated at the landfill, considering system coverage, operation, and cover system materials from Table HH-3 of EPA's GHGRP. If area by soil cover type information is not available, the default value of 0.75 should be used. (percent)
f_{REC} = fraction of hours the recovery system was operating (percent)
OX = oxidation factor (percent)
DE = destruction efficiency (percent)
f_{Dest} = fraction of hours the destruction device was operating (fraction)

The current Inventory uses both methods to estimate CH_4 emissions across the time series. Prior to the previous (1990 through 2015) Inventory, only the FOD method was used. Methodological changes were made to the 1990 through 2015 Inventory to incorporate higher tier data (i.e., directly reported CH_4 emissions to EPA's GHGRP), which cannot be directly applied to earlier years in the time series without significant bias. The technique used to merge the directly reported GHGRP data with the previous methodology is described as the overlap technique in the Time-Series Consistency chapter of the *2006 IPCC Guidelines*. Additional details on the technique used is included in a technical memorandum (RTI 2017).

A summary of the methodology used to generate the current 1990 through 2016 Inventory estimates for MSW landfills is as follows and also illustrated in Annex Figure A-18:

- **1940 through 1989:** These years are included for historical waste disposal amounts. Estimates of the annual quantity of waste landfilled for 1960 through 1988 were obtained from EPA's *Anthropogenic Methane Emissions in the United States*, *Estimates for 1990: Report to Congress* (EPA 1993) and an extensive landfill survey by EPA's Office of Solid Waste in 1986 (EPA 1988). Although waste placed in landfills in the 1940s and 1950s contributes very little to current CH_4 generation, estimates for those years were included in the FOD model for completeness in accounting for CH_4 generation rates and are based on the population in those years and the per capita rate for land disposal for the 1960s. For the Inventory calculations, wastes landfilled prior to 1980 were broken into two groups: wastes disposed in managed, anaerobic landfills (Methane Conversion Factor, MCF, of 1) and those disposed in uncategorized solid waste disposal waste sites (MCF of 0.6). Uncategorized sites represent those sites for which limited information is known about the management practices. All calculations after 1980 assume waste is disposed in managed, anaerobic landfills. The FOD method was applied to estimate annual CH_4 generation. Methane recovery amounts were then subtracted and the result was then adjusted with a 10 percent oxidation factor to derive the net emissions estimates.
- **1990 through 2004:** The Inventory time series begins in 1990. The FOD method is exclusively used for this group of years. The national total of waste generated (based on state-specific landfill waste generation data) and a national average disposal factor for 1989 through 2008 were obtained from the State of Garbage (SOG) survey every two years (i.e., 2002, 2004, and 2006 as published in BioCycle 2006, and 2008 as published in BioCycle 2010). In-between years were interpolated based on population growth. For years 1989 to 2000, directly reported total MSW generation data were used; for other years, the estimated MSW

generation (excluding construction and demolition waste and inerts) were presented in the reports and used in the Inventory. The FOD method was applied to estimate annual CH_4 generation. Landfill-specific CH_4 recovery amounts were then subtracted from CH_4 generation and the result was then adjusted with a 10 percent oxidation factor to derive the net emissions estimates.

- **2005 through 2009:** Emissions for these years are estimated using net CH_4 emissions that are reported by landfill facilities under EPA's GHGRP. Because not all landfills in the United States are required to report to EPA's GHGRP, a 9 percent scale-up factor is applied to the GHGRP emissions for completeness. Supporting information, including details on the technique used to estimate emissions for 2005 to 2009 and to ensure time-series consistency by incorporating the directly reported GHGRP emissions is presented in Annex 3.14 and in RTI (2018). A single oxidation factor is not applied to the annual CH_4 generated as is done for 1990 to 2004 because the GHGRP emissions data are used, which already take oxidation into account. The GHGRP allows facilities to use varying oxidation factors depending on their facility-specific calculated CH_4 flux rate (i.e., 0, 10, 25, or 35 percent). The average oxidation factor from the GHGRP facilities is 19.5 percent.
- **2010 through 2016:** Directly reported net CH_4 emissions to the GHGRP are used with a 9 percent scale-up factor to account for landfills that are not required to report to the GHGRP. A combination of the FOD method and the back-calculated CH_4 emissions were used by the facilities reporting to the GHGRP. Landfills reporting to the GHGRP without gas collection and control apply the FOD method, while most landfills with landfill gas collection and control apply the back-calculation method. As noted above, GHGRP facilities use a variety of oxidation factors; therefore, the average oxidation factor from the GHGRP facilities is 19.5 percent.

A detailed discussion of the data sources and methodology used to calculate CH_4 generation and recovery is provided below. Supporting information, including details on the technique used to ensure time-series consistency by incorporating the directly-reported GHGRP emissions is presented in the Time-Series Consistency section of this chapter and in Annex 3.14.

Description of the Methodology for MSW Landfills as Applied for 1990-2004

National MSW Methane Generation and Disposal Estimates

States and local municipalities across the United States do not consistently track and report quantities of MSW generated or collected for management, nor do they report end-of-life disposal methods to a centralized system. Therefore, national MSW landfill waste generation and disposal data are obtained from secondary data, specifically the SOG surveys, published approximately every two years, with the most recent publication date of 2014. The SOG survey was the only continually updated nationwide survey of waste disposed in landfills in the United States and was the primary data source with which to estimate nationwide CH_4 generation from MSW landfills. Now, EPA's GHGRP waste disposal data and MSW management data published by EREF are available.

The SOG surveys collect data from the state agencies and then apply the principles of mass balance where all MSW generated is equal to the amount of MSW landfilled, combusted in waste-to-energy plants, composted, and/or recycled (BioCycle 2010; Shin 2014). This approach assumes that all waste management methods are tracked and reported to state agencies. Survey respondents are asked to provide a breakdown of MSW generated and managed by landfilling, recycling, composting, and combustion (in waste-to-energy facilities) in actual tonnages as opposed to reporting a percent generated under each waste disposal option. The data reported through the survey have typically been adjusted to exclude non-MSW materials (e.g., industrial and agricultural wastes, construction and demolition debris, automobile scrap, and sludge from wastewater treatment plants) that may be included in survey responses. While these wastes may be disposed of in MSW landfills, they are not the primary type of waste material disposed and are typically inert. In the most recent survey, state agencies were asked to provide already filtered, MSW-only data. Where this was not possible, they were asked to provide comments to better understand the data being reported. All state disposal data are adjusted for imports and exports across state lines where imported waste is included in a state's total while exported waste is not. Methodological changes have occurred over the time frame the SOG survey has been published, and this has affected the fluctuating trends observed in the data (RTI 2013).

State-specific landfill MSW generation data and a national average disposal factor for 1989 through 2008 were obtained from the SOG survey every two years (i.e., 2002, 2004, and 2006 as published in BioCycle 2006, and 2008 as published in BioCycle 2010). The landfill inventory calculations start with hard numbers (where available) as presented in the SOG documentation for the report years 2002, 2004, 2006, and 2008. In-between year waste generation is interpolated using the prior and next SOG report data. For example, waste generated in 2003 = (waste generation in 2002 + waste generation in 2004)/2. The quantities of waste generated across all states are summed and that value is then used as the nationwide quantity of waste generated in each year of the time series. The SOG survey is voluntary and not all states provide data in each survey year. To estimate waste generation for states that did not provide data in any given reporting year, one of the following methods was used (RTI 2013):

- For years when a state-specific waste generation rate was available from the previous SOG reporting year submission, the State-specific waste generation rate for that particular state was used.

  – or –

- For years where a state-specific waste generation rate was not available from the previous SOG reporting year submission, the waste amount is generated using the national average waste generation rate. In other words, Waste Generated = Reporting Year Population × the National Average Waste Generation Rate
  - The National Average Waste Generation Rate is determined by dividing the total reported waste generated across the reporting states by the total population for reporting states.
  - This waste generation rate may be above or below the waste generation rate for the non-reporting states and contributes to the overall uncertainty of the annual total waste generation amounts used in the model.

Use of these methods to estimate solid waste generated by states is a key aspect of how the SOG data was manipulated and why the results differ for total solid waste generated as estimated by SOG and in the Inventory. In the early years (2002 data in particular), SOG made no attempt to fill gaps for non-survey responses. For the 2004 data, the SOG team used proxy data (mainly from the WBJ) to fill gaps for non-reporting states and survey responses.

Another key aspect of the SOG survey is that it focuses on MSW-only data. The data states collect for solid waste typically are representative of total solid waste and not the MSW-only fraction. In the early years of the SOG survey, most states reported total solid waste rather than MSW-only waste. The SOG team, in response, "filtered" the state-reported data to reflect the MSW-only portion.

Also important to note about this data source is that the waste generation data reported by states to the SOG survey fluctuates from year to year. Although some fluctuation is expected, for some states, the year-to-year fluctuations are quite significant (>20 percent increase or decrease in some case) (RTI 2013). The SOG survey reports for these years do not provide additional explanation for these fluctuations and the source data are not available for further assessment. Although exact reasons for the large fluctuations are difficult to obtain without direct communication with states, staff from the SOG team that were contacted speculate that significant fluctuations are present because the particular state could not gather complete information for waste generation (i.e., they are missing part of recycled and composted waste data) during a given reporting year. In addition, SOG team staff speculated that some states may have included C&D and industrial wastes in their previous MSW generation submissions, but made efforts to exclude that (and other non-MSW categories) in more recent reports (RTI 2013).

The most recent SOG survey provides data for 2011 (Shin 2014). The EREF published a report, *MSW Management in the United States*, which includes state-specific landfill MSW generation and disposal data for 2010 and 2013 using a similar methodology as the SOG surveys (EREF 2016). State-specific landfill waste generation data for the years in between the SOG surveys and EREF report (e.g., 2001, 2003, 2005, 2007, and 2009) were either interpolated or extrapolated based on the SOG or EREF data and the U.S. Census population data (U.S. Census Bureau 2016). In the current Inventory methodology, the MSW generation and disposal data are no longer used to estimate CH_4 emissions for the years 2005 to 2016 because EPA's GHGRP emissions data are now used for those years. The MSW generation and disposal data for these years are still useful for examining general trends in MSW management in the United States.

Estimates of the quantity of waste landfilled from 1989 to 2004 are determined by applying an average national waste disposal factor to the total amount of waste generated (i.e., the SOG data). A national average waste disposal factor is determined for each year an SOG survey is published and equals the ratio of the total amount of waste landfilled in the United States to the total amount of waste generated in the United States. The waste disposal factor is interpolated or extrapolated for the years in-between the SOG surveys, as is done for the amount of waste generated for a given survey year.

The *2006 IPCC Guidelines* recommend at least 50 years of waste disposal data to estimate CH_4 emissions. Estimates of the annual quantity of waste landfilled for 1960 through 1988 were obtained from EPA's *Anthropogenic Methane Emissions in the United States, Estimates for 1990: Report to Congress* (EPA 1993) and an extensive landfill survey by EPA's Office of Solid Waste in 1986 (EPA 1988). Although waste placed in landfills in the 1940s and 1950s contributes very little to current CH_4 generation, estimates for those years were included in the FOD model for completeness in accounting for CH_4 generation rates and are based on the population in those years and the per capita rate for land disposal for the 1960s. For calculations in the current Inventory, wastes landfilled prior to 1980 were broken into two groups: wastes disposed in landfills (MCF of 1) and those disposed in uncategorized siteas (MCF of 0.6). All calculations after 1980 assume waste is disposed in managed, modern landfills. See Annex 3.14 for more details.

National Landfill Gas Recovery Estimates for MSW Landfills

The estimated landfill gas recovered per year (R) at MSW landfills for 1990 to 2004 was based on a combination of four databases and including recovery from flares and/or landfill gas-to-energy (LFGE) projects:

- EPA's GHGRP dataset for MSW landfills (EPA 2015a);[3]
- A database developed by the Energy Information Administration (EIA) for the voluntary reporting of greenhouse gases (EIA 2007);
- A database of LFGE projects that is primarily based on information compiled by the EPA LMOP (EPA 2016b);[4] and
- The flare vendor database (contains updated sales data collected from vendors of flaring equipment).

The same landfill may be included one or more times across these four databases. To avoid double or triplecounting CH_4 recovery, the landfills across each database were compared and duplicates identified. A hierarchy of recovery data is used based on the certainty of the data in each database. In summary, the GHGRP > EIA > LFGE > flare vendor database. The rationale for this hierarchy is described below.

EPA's GHGRP MSW landfills database was first introduced as a data source for landfill gas recovery in the 1990 to 2013 Inventory. EPA's GHGRP MSW landfills database contains facility-reported data that undergoes rigorous verification, thus it is considered to contain the least uncertain data of the four CH_4 recovery databases. However, as mentioned earlier, this database is unique in that it only contains a portion of the landfills in the United States (although, presumably the highest emitters since only those landfills that meet a certain CH_4 generation threshold must report) and only contains data for 2010 and later. In the current Inventory methodology, CH_4 recovery for 1990 to 2004 for facilities reporting to EPA's GHGRP has been estimated using the directly reported emissions for those facilities from 2010 to 2015, and an Excel forecasting function so that the GHGRP data source can be applied to earlier years in the time series. Prior to 2005, if a landfill in EPA's GHGRP was also in the LFGE or EIA databases, the landfill gas project information, specifically the project start year, from either the LFGE or EIA databases was used as the cutoff year for the estimated CH_4 recovery in the GHGRP database. For example, if a landfill reporting under EPA's GHGRP was also included in the LFGE database under a project that started in 2002 that is still operational, the CH_4 recovery data in the GHGRP database for that facility was back-calculated to the year 2002 only.

If a landfill in the GHGRP MSW landfills database was also in the EIA, LFGE, and/or flare vendor database, the avoided emissions were only based on EPA's GHGRP MSW landfills database to avoid double or triple counting the recovery amounts. In other words, the CH_4 recovery from the same landfill was not included in the total recovery from the EIA, LFGE, or flare vendor databases.

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[3] The 2015 GHGRP dataset is used to estimate landfill gas recovery from MSW landfills for the years 1990 to 2004 of the Inventory. This database is no longer updated because the methodology has changed such that the directly reported net methane emissions from the GHGRP are used and landfill gas recovery is not separately estimated.

[4] The LFGE database was not updated for the current (1990 to 2016) Inventory because the methodology does not use this database for years 2005 and later, thus the LMOP 2016 database is the most recent year reflected in the LFGE database for the Inventory.

If a landfill in the EIA database was also in the LFGE and/or the flare vendor database, the CH_4 recovery was based on the EIA data because landfill owners or operators directly reported the amount of CH_4 recovered using gas flow concentration and measurements, and because the reporting accounted for changes over time.

If both the flare data and LFGE recovery data were available for any of the remaining landfills (i.e., not in the EIA or GHGRP databases), then the avoided emissions were based on the LFGE data, which provides reported landfill-specific data on gas flow for direct use projects and project capacity (i.e., megawatts) for electricity projects. The LFGE database is based on the most recent EPA LMOP database (published annually). The remaining portion of avoided emissions is calculated by the flare vendor database, which estimates CH_4 combusted by flares using the midpoint of a flare's reported capacity. New flare vendor sales data have not been collected since 2015 because these data are not used for estimates beyond 2005 in the time series. Given that each LFGE project is likely to also have a flare, double counting reductions from flares and LFGE projects in the LFGE database was avoided by subtracting emission reductions associated with LFGE projects for which a flare had not been identified from the emission reductions associated with flares (referred to as the flare correction factor). A further explanation of the methodology used to estimate the landfill gas recovered can be found in Annex 3.14.

A destruction efficiency of 99 percent was applied to CH_4 recovered to estimate CH_4 emissions avoided due to the combusting of CH_4 in destruction devices (i.e., flares) in the EIA, LFGE, and flare vendor databases. The median value of the reported destruction efficiencies to the GHGRP was 99 percent for all reporting years (2010 through 2015). For the other three recovery databases, the 99 percent destruction efficiency value selected was based on the range of efficiencies (86 to greater than 99 percent) recommended for flares in EPA's *AP-42 Compilation of Air Pollutant Emission Factors,* Draft Section 2.4, Table 2.4-3 (EPA 2008). A typical value of 97.7 percent was presented for the non-CH_4 components (i.e., VOC and NMOC) in test results (EPA 2008). An arithmetic average of 98.3 percent and a median value of 99 percent are derived from the test results presented in EPA (2008). Thus, a value of 99 percent for the destruction efficiency of flares has been used in the Inventory methodology. Other data sources supporting a 99 percent destruction efficiency include those used to establish New Source Performance Standards (NSPS) for landfills and in recommendations for shutdown flares used by the EPA LMOP.

National MSW Landfill Methane Oxidation Estimates

The amount of CH_4 oxidized by the landfill cover at MSW landfills was assumed to be 10 percent of the CH_4 generated that is not recovered (IPCC 2006; Mancinelli and McKay 1985; Czepiel et al. 1996) for the years 1990 to 2004.

National MSW Net Emissions Estimates

Net CH_4 emissions are calculated by subtracting the CH_4 recovered and CH_4 oxidized from CH_4 generated at MSW landfills.

Description of the Methodology for MSW Landfills as Applied for 2005 to 2009

The Inventory methodology uses directly reported net CH_4 emissions for the 2010 to 2016 reporting years from the GHGRP to back-cast emissions for 2005 to 2009. The emissions for 2005 to 2009 are recalculated each year the Inventory is published to account for the additional year of reported data and any revisions that facilities make to past GHGRP reports. When EPA verifies the greenhouse gas reports, comparisons are made with data submitted in earlier reporting years and errors may be identified in these earlier year reports. Facility representatives may submit revised reports for any reporting year in order to correct these errors. Facilities reporting to the GHGRP that do not have landfill gas collection and control systems use the FOD method. Facilities with landfill gas collection and control must use both the FOD method and a back-calculation approach. The back-calculation approach starts with the amount of CH_4 recovered and works back through the system to account for gas not collected by the landfill gas collection and control system (i.e., the collection efficiency).

A scale-up factor to account for emissions from landfills that do not report to EPA's GHGRP is also applied annually. In theory, national MSW landfill emissions should equal the net CH_4 emissions reported to the GHGRP plus net CH_4 emissions from landfills that do not report to the GHGRP. EPA estimated a scale-up factor of 9 percent. The rationale behind the 9 percent scale-up factor is included in Annex 3.14 and in RTI (2018) .

The GHGRP data allow facilities to apply a range of oxidation factors (0.0, 0.10, 0.25, or 0.35) based on the calculated CH_4 flux at the landfill. Therefore, one oxidation factor is not applied for this time frame, as is done for 1990 to 2004. The average oxidation factor across the GHGRP data is 19.5 percent.

Description of the Methodology for MSW Landfills as Applied for 2010 to 2016

Directly reported CH_4 emissions to the GHGRP are used for 2010 to 2016 plus the 9 percent scale-up factor to account for emissions from landfills that do not report to the GHGRP. The average oxidation factor across the GHGRP data is 19.5 percent.

Description of the First Order Decay Methodology for Industrial Waste Landfills

Emissions from industrial waste landfills are estimated from industrial production data (ERG 2017), waste disposal factors, and the FOD method. There are currently no data sources that track and report the amount and type of waste disposed of in the universe of industrial waste landfills in the United States. EPA's GHGRP provides some insight into waste disposal in industrial waste landfills, but is not comprehensive. Data reported to the GHGRP on industrial waste landfills suggests that most of the organic waste which would result in methane emissions is disposed at pulp and paper and food processing facilities. Of the 172 facilities that report to subpart TT of the GHGRP, 93 (54 percent) are in the North American Industrial Classification System (NAICS) for Pulp, Paper, and Wood Products (NAICS 321 and 322) and 12 (7 percent) are in Food Manufacturing (NAICS 311) (EPA 2017b). Based on this limited information, the Inventory methodology assumes most of the organic waste placed in industrial waste landfills originates from the food processing (meat, vegetables, fruits) and pulp and paper sectors (EPA 1993a), thus estimates of industrial landfill emissions focused on these two sectors. The amount of waste landfilled is assumed to be a fraction of production that is held constant over the time series as explained in Annex 3.14. The composition of waste disposed of in industrial waste landfills is expected to be more consistent in terms of composition and quantity than that disposed of in MSW landfills.

Landfill CH_4 recovery is not accounted for in industrial waste landfills. Data collected through EPA's GHGRP for industrial waste landfills (Subpart TT) show that only two of the 176 facilities, or 1 percent of facilities, have active gas collection systems (EPA 2017b). However, because EPA's GHGRP is not a national database and comprehensive data regarding gas collection systems have not been published for industrial waste landfills, assumptions regarding a percentage of landfill gas collection systems, or a total annual amount of landfill gas collected for the non-reporting industrial waste landfills have not been made for the Inventory methodology.

The amount of CH_4 oxidized by the landfill cover at industrial waste landfills was assumed to be 10 percent of the CH_4 generated (IPCC 2006; Mancinelli and McKay 1985; Czepiel et al. 1996) for all years.

Uncertainty and Time-Series Consistency

Several types of uncertainty are associated with the estimates of CH_4 emissions from MSW and industrial waste landfills when the FOD method is applied directly for 1990 to 2004 in the Waste Model and, to some extent, in the GHGRP methodology. The approach used in the MSW emission estimates assumes that the CH_4 generation potential (L_o) and the rate of decay that produces CH_4 from MSW, as determined from several studies of CH_4 recovery at MSW landfills, are representative of conditions at U.S. MSW landfills. When this top-down approach is applied at the nationwide level, the uncertainties are assumed to be less than when applying this approach to individual landfills and then aggregating the results to the national level. In other words, the FOD method as applied in this Inventory is not facility-specific modeling and while this approach may over- or under-estimate CH_4 generation at some landfills if used at the facility-level, the result is expected to balance out because it is being applied nationwide. There is also a high degree of uncertainty and variability associated with the FOD model, particularly when a homogeneous waste composition and hypothetical decomposition rates are applied to heterogeneous landfills (IPCC 2006). There is less uncertainty in the GHGRP data because this methodology is facility-specific, uses directly measured CH_4 recovery data (when applicable), and allows for a variety of landfill gas collection efficiencies, destruction efficiencies, and/or oxidation factors to be used. An uncertainty factor of 8 percent is applied to the directly reported CH_4 emissions to EPA's GHGRP.

Uncertainty also exists in the scale-up factor applied for years 2005 to 2009 and in the back-casted emissions estimates for 2005 to 2009. As detailed in RTI (2018), limited information is available for landfills that do not report to the GHGRP. RTI developed an initial list of landfills that do not report to the GHGRP with the intent of quantifying the total waste-in-place for these landfills that would equal the scale-up factor. Input was provided by industry, LMOP, and additional EPA support. However, gaps still exist and assumptions were made for many landfills in order to estimate the scale-up factor. Additionally, a simple methodology was used to back-cast emissions for 2005 to 2009 using the GHGRP emissions from 2010 to 2016. This methodology does not factor in annual landfill to landfill changes in landfill CH_4 generation and recovery. Because of this, an uncertainty factor of 25 percent is applied to emissions for 2005 to 2009.

With regard to the time series and as stated in *2006 IPCC Guidelines Volume 1: Chapter 5 Time-Series Consistency* (IPCC 2006), "the time series is a central component of the greenhouse gas inventory because it provides information on historical emissions trends and tracks the effects of strategies to reduce emissions at the national level. All emissions in a time series should be estimated consistently, which means that as far as possible, the time series should be calculated using the same method and data sources in all years" (IPCC 2006). This chapter however, recommends against back-casting emissions back to 1990 with a limited set of data and instead provides guidance on techniques to splice, or join methodologies together. One of those techniques is referred to as the overlap technique. The overlap technique is recommended when new data become available for multiple years. This was the case with the GHGRP data, where directly reported CH_4 emissions data became available for more than 1,200 MSW landfills beginning in 2010. The GHGRP emissions data had to be merged with emissions from the FOD method to avoid a drastic change in emissions in 2010, when the datasets were combined. EPA also had to consider that according to IPCC's good practice, efforts should be made to reduce uncertainty in Inventory calculations and that, when compared to the GHGRP data, the FOD method presents greater uncertainty.

In evaluating the best way to combine the two datasets, EPA considered either using the FOD method from 1990 to 2009, or using the FOD method for a portion of that time and back-casting the GHGRP emissions data to a year where emissions from the two methodologies aligned. Plotting the back-casted GHGRP emissions against the emissions estimates from the FOD method showed an alignment of the data in 2004 and later years which facilitated the use of the overlap technique while also reducing uncertainty. Therefore, EPA decided to back-cast the GHGRP emissions from 2009 to 2005 only, in order to merge the datasets and adhere to the IPCC *Good Practice Guidance*.

Aside from the uncertainty in estimating landfill CH_4 generation, uncertainty also exists in the estimates of the landfill gas oxidized. Facilities directly reporting to the GHGRP can use oxidation factors ranging from 0 to 35 percent, depending on their facility-specific CH_4 flux. As recommended by the *2006 IPCC Guidelines* for managed landfills, a 10 percent default oxidation factor is applied in the Inventory for both MSW landfills (those not reporting to the GHGRP) and industrial waste landfills regardless of climate, the type of cover material, and/or presence of a gas collection system. The number of published field studies measuring the rate of oxidation has increased substantially since the *2006 IPCC Guidelines* were published and, as discussed in the Potential Improvements section, efforts are being made to review the literature and revise this value, as appropriate.

Another significant source of uncertainty lies with the estimates of CH_4 recovered by flaring and gas-to-energy projects at MSW landfills that are sourced from the Inventory's CH_4 recovery databases (used for years 1990 to 2004). Four CH_4 recovery databases are used to estimate nationwide CH_4 recovery for MSW landfills for 1990 to 2004; whereas directly reported CH_4 recovery is used for facilities reporting to the GHGRP for years 2005 to 2015. The GHGRP MSW landfills database was added as a fourth recovery database starting with the 1990 through 2013 Inventory report. Relying on multiple databases for a complete picture introduces uncertainty because the coverage and characteristics of each database differs, which increases the chance of double counting avoided emissions. Additionally, the methodology and assumptions that go into each database differ. For example, the flare database assumes the midpoint of each flare capacity at the time it is sold and installed at a landfill; the flare may be achieving a higher capacity, in which case the flare database would underestimate the amount of CH_4 recovered.

The LFGE database was updated annually until 2015. The flare database was populated annually until 2015 by the voluntary sharing of flare sales data by select vendors, which likely underestimated recovery for landfills not included in the three other recovery databases used by the Inventory. The EIA database has not been updated since 2006 and has, for the most part, been replaced by the GHGRP MSW landfills database. To avoid double counting and to use the most relevant estimate of CH_4 recovery for a given landfill, a hierarchical approach is used among the four databases. GHGRP data and the EIA data are given precedence because facility data were directly reported; the LFGE data are given second priority because CH_4 recovery is estimated from facility-reported LFGE system characteristics; and the flare data are given the lowest priority because this database contains minimal information about the flare, no site-specific operating characteristics, and includes smaller landfills not included in the other three databases (Bronstein et al. 2012). The coverage provided across the databases most likely represents the complete universe of landfill CH_4 gas recovery; however, the number of unique landfills between the four databases does differ.

The *2006 IPCC Guidelines* default value of 10 percent for uncertainty in recovery estimates was used for two of the four recovery databases in the uncertainty analysis where metering of landfill gas was in place (for about 64 percent of the CH_4 estimated to be recovered). This 10 percent uncertainty factor applies to the LFGE database; 12 percent to the EIA database; and 1 percent for the GHGRP MSW landfills dataset because of the supporting information provided and rigorous verification process. For flaring without metered recovery data (the flare database), a much higher uncertainty value of 50 percent is used. The compounding uncertainties associated with the four databases in addition to the uncertainties associated with the FOD method and annual waste disposal quantities leads to the large upper and lower bounds for MSW landfills presented in Table 7-5.

The lack of landfill-specific information regarding the number and type of industrial waste landfills in the United States is a primary source of uncertainty with respect to the industrial waste generation and emission estimates. The approach used here assumes that most of the organic waste disposed of in industrial waste landfills that would result in CH_4 emissions consists of waste from the pulp and paper and food processing sectors. However, because waste generation and disposal data are not available in an existing data source for all U.S. industrial waste landfills, a straight disposal factor is applied over the entire time series to the amount of waste generated to determine the amounts disposed. Industrial waste facilities reporting under EPA's GHGRP do report detailed waste stream information, and these data have been used to improve, for example, the DOC value used in the Inventory methodology for the pulp and paper sector. A 10 percent oxidation factor is also applied to CH_4 generation estimates for industrial waste landfills, and carries the same amount of uncertainty as with the factor applied to CH_4 generation for MSW landfills.

The results of the *2006 IPCC Guidelines* Approach 2 quantitative uncertainty analysis are summarized in Table 7-5. There is considerable uncertainty for the MSW landfills estimates due to the number of data sources used, each with its own uncertainty factor.

Table 7-5: Approach 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Landfills ($MMT CO_2$ Eq. and Percent)

Source	Gas	2016 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Total Landfills	**CH_4**	**107.7**	**82.6**	**131.9**	**-23%**	**23%**
MSW	CH_4	92.7	69.6	116.5	-25%	26%
Industrial	CH_4	14.9	10.3	18.7	-31%	25%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. QA/QC plan, which is in accordance with Vol. 1 Chapter 6 of *2006 IPCC Guidelines* (see Annex 8 for more details). QA/QC checks are performed for the transcription of the published data set (e.g., EPA's GHGRP dataset) used to populate the Inventory data set in terms of completeness and accuracy against the reference source. Additionally, all datasets used for this category have been checked to ensure they are of appropriate quality and are representative of U.S. conditions. The primary calculation spreadsheet is tailored from the *2006 IPCC Guidelines* waste model and has been verified previously using the original, peer-reviewed IPCC waste model. All model input values and calculations were verified by secondary QA/QC review. Stakeholder engagements sessions in 2016 and 2017 were used to gather input on methodological improvements and facilitate an external expert review on the methodology, activity data, and emission factors.

Category-specific checks include the following:

- Evaluation of the secondary data sources used as inputs to the Inventory dataset to ensure they are appropriately collected and are reliable;
- Cross-checking the data (activity data and emissions estimates) with previous years to ensure the data are reasonable, and that any significant variation can be explained through the activity data;
- Conducting literature reviews to evaluate the appropriateness of country-specific emission factors (e.g., DOC values, precipitation zones with respect to the application of the k values) given findings from recent peer-reviewed studies; and
- Reviewing secondary datasets to ensure they are nationally complete and supplementing where necessary (e.g., using a scale-up factor to account for emissions from landfills that do not report to EPA's GHGRP).

A primary focus of the QA/QC checks in past Inventories was to ensure that CH_4 recovery estimates were not double-counted and that all LFGE projects and flares were included in the respective project databases. QA/QC checks performed in the past for the recovery databases were not performed in this Inventory, because new data were not added to the recovery databases in this Inventory year. For the GHGRP data, EPA verifies annual facility-level reports through a multi-step process (e.g., combination of electronic checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent. Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred.[5]

Recalculations Discussion

Recalculations to the back-casted GHGRP emissions for 2005 to 2009 were performed, and the scale-up factor applied to years 2005 to the current year (2016) was revised. These recalculations decreased net emissions for MSW landfills from 2005 to 2015 when compared to the previous Inventory report.

First, the GHGRP data for all available years is used to back-cast emissions for 2005 to 2009. Revisions to the individual facility reports submitted to the GHGRP can be made at any time and a portion of facilities have revised their reports since 2010 for various reasons, resulting in changes to the total net CH_4 emissions for MSW landfills. Each Inventory year, the back-casted emissions for 2005 to 2009 will be recalculated using the most recently verified data from the GHGRP. Changes in these data result in changes to the back-casted emissions.

Second, the scale-up factor was revised from 12.5 percent to 9 percent. The scale-up factor to supplement directly reported emissions from the GHGRP was first applied in the 1990 to 2015 Inventory. The initial scale-up factor of 12.5 percent was developed as a rough estimate with the intent of it being refined after engaging with stakeholders and completing various data analyses. EPA has since investigated options to develop a more precise scale-up factor to apply to the GHGRP data and has refined the scale-up factor to 9 percent as detailed in RTI 2018. The revised scale-up factor was developed after extracting data on the first year of waste acceptance, annual waste disposal, and total waste-in-place from the LMOP database and WBJ Directory 2016 for landfills that are not reporting to the GHGRP. EPA created a database of non-reporting landfills and sought input from various stakeholders (industry and LMOP). Stakeholders were asked to review the database of non-reporting landfills and to provide input on the following: whether the landfill reported to the GHGRP (and reporting identification number), if the landfill was considered an MSW or other landfill, whether the landfill was open or closed, first year of waste acceptance, closure year (for closed landfills), estimated closure year (for active landfills), geographical coordinates (latitude and longitude), and annual waste acceptance data or total waste-in-place.

The revised scale-up factor of 9 percent is based on the total waste-in-place from readily available information for landfills that do not report to the GHGRP. It is the ratio of the "non-reporting landfills waste-in-place" to the sum total of the GHGRP waste-in-place and the non-reporting landfills waste-in-place.

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[5] See <https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf>.

Planned Improvements

EPA has engaged in stakeholder outreach through a series of webinars since December 2016 to increase the transparency in the Inventory methodology and to identify ideas and supplemental data sources that can lead to methodological improvements. The areas where EPA is actively working on improvements include the oxidation factor for 1990 to 2004, the DOC value for 1990 to 2004, the decay rate (k value) for 1990 to 2004, and the scale-up factor.

EPA is continuing to investigate options to adjust the oxidation factor from the 10 percent currently used for 1990 to 2004 to another value or approach such as the binned approach used in the GHGRP (e.g., 10 percent, 25 percent, or 35 percent based on methane flux). The oxidation factor currently applied in the later portion of the time series (2005 to 2016) averages at 19.5 percent due to the use of the GHGRP data while the earlier portion of the time series applies the default of 10 percent.

The Inventory currently uses one value of 0.20 for the DOC for years 1990 to 2004. With respect to improvements to the DOC value, EPA developed a database with MSW characterization data from individual studies across the United States. EPA will review this data against the Inventory time series to assess the validity of the current DOC value and how it is applied in the FOD method. Waste characterization studies vary greatly in terms of the granularity of waste types included and the spatial boundaries of each study (e.g., one landfill, a metro area, statewide). EPA also notes the longer term recommendation from industry stakeholders regarding the DOC values used in the GHGRP, in the context of new information on the composition of waste disposed in MSW landfills; these newer values could then be reflected in the 2005 and later years of the Inventory.

EPA will review the k values for the three climate types (dry, moderate, and wet) against new data and other landfill gas models, and how they are applied to the percentage of the population assigned to these climate types. EPA will also assess the uncertainty factor applied to these k values in the Waste Model. A 30 percent uncertainty factor is applied to each k value in the Monte Carlo analysis, which is consistent with that recommended by the IPCC (2006).

With respect to the scale-up factor, EPA will periodically assess the impact to the waste-in-place and emissions data from facilities that have resubmitted annual reports during any reporting years, are new reporting facilities, and from facilities that have stopped reporting to the GHGRP to ensure national estimates are as complete as possible. Facilities may stop reporting to the GHGRP when they meet the “off-ramp” provisions (reported less than 15,000 metric tons of CO_2 equivalent for 3 consecutive years or less than 25,000 metric tons of CO_2 equivalent for 5 consecutive years). If warranted, EPA will revise the scale-up factor to reflect newly acquired information to ensure completeness of the Inventory.

EPA also plans to investigate revisions to the destruction efficiencies for flares and the fluctuation in natural gas pricing and other potential factors that are impacting the development of new LFGTE projects for inclusion in a future Inventory report, as appropriate.

Box 7-3: Nationwide Municipal Solid Waste Data Sources

Municipal solid waste generated in the United States can be managed through landfilling, recycling, composting, and combustion with energy recovery. There are three main sources for nationwide solid waste management data in the United States:

- The *BioCycle* and Earth Engineering Center of Columbia University’s SOG in America surveys [no longer published];
- The EPA’s *Advancing Sustainable Materials Management* reports; and
- The EREF’s MSW Generation in the United States reports.

The SOG surveys and, now EREF, collect state-reported data on the amount of waste generated and the amount of waste managed via different management options: landfilling, recycling, composting, and combustion. The survey asks for actual tonnages instead of percentages in each waste category (e.g., residential, commercial, industrial, construction and demolition, organics, tires) for each waste management option. If such a breakdown is not available, the survey asks for total tons landfilled. The data are adjusted for imports and exports across state lines so that the principles of mass balance are adhered to, whereby the amount of waste managed does not exceed the amount of waste generated. The SOG and EREF reports present survey data aggregated to the state level.

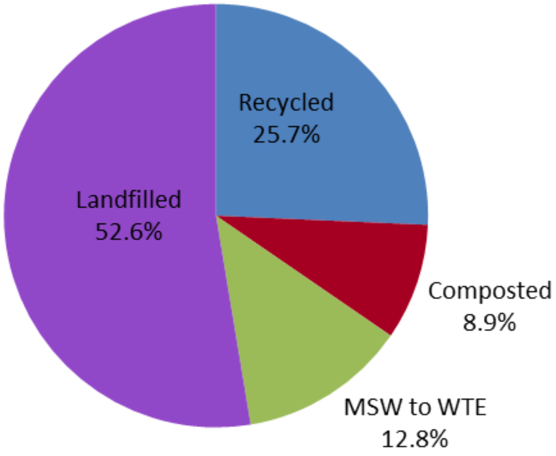
The EPA *Advancing Sustainable Materials Management* reports use a materials flow methodology, which relies heavily on a mass balance approach. Data are gathered from industry associations, key businesses, similar industry sources, and government agencies (e.g., the Department of Commerce and the U.S. Census Bureau) and are used to estimate tons of materials and products generated, recycled, combusted with energy recovery or landfilled nationwide. The amount of MSW generated is estimated by estimating production and then adjusting these values by addressing the imports and exports of produced materials to other countries. MSW that is not recycled, composted, or combusted is assumed to be landfilled. The data presented in the report are nationwide totals.

In this Inventory, emissions from solid waste management are presented separately by waste management option, except for recycling of waste materials. Emissions from recycling are attributed to the stationary combustion of fossil fuels that may be used to power on-site recycling machinery, and are presented in the stationary combustion chapter in the Energy sector, although the emissions estimates are not called out separately. Emissions from solid waste disposal in landfills and the composting of solid waste materials are presented in the Landfills and Composting sections in the Waste sector of this report. In the United States, almost all incineration of MSW occurs at waste-to-energy (WTE) facilities or industrial facilities where useful energy is recovered, and thus emissions from waste incineration are accounted for in the Incineration chapter of the Energy sector of this report.

Box 7-4: Overview of the Waste Sector

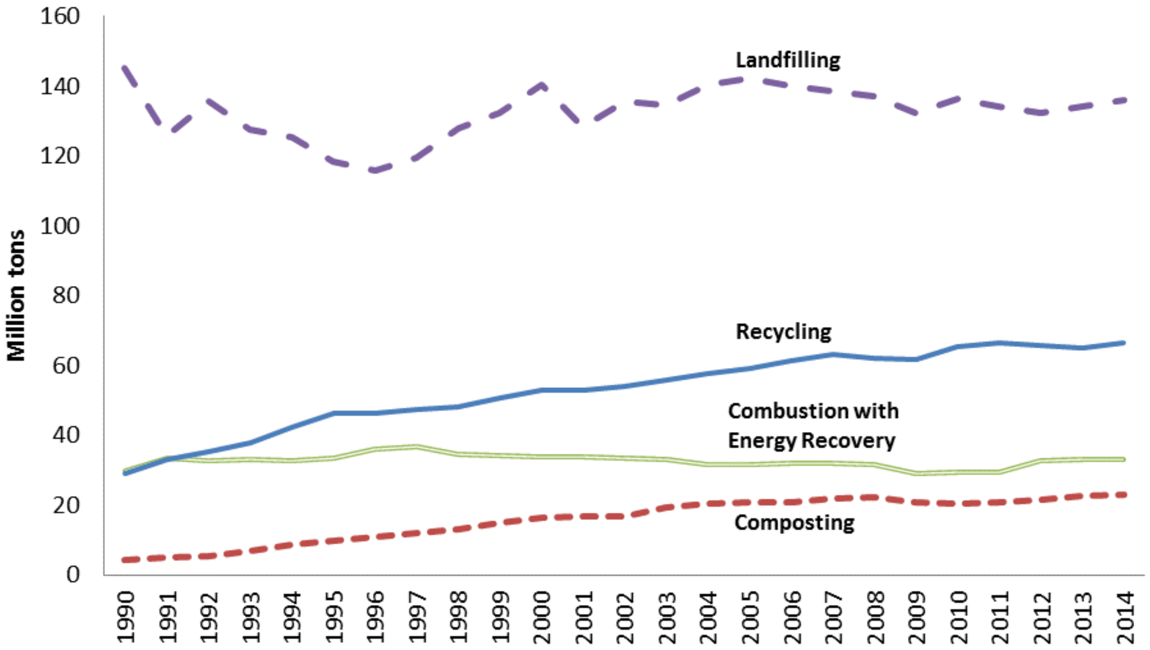
As shown in Figure 7-2 and Figure 7-3, landfilling of MSW is currently and has been the most common waste management practice. A large portion of materials in the waste stream are recovered for recycling and composting, which is becoming an increasingly prevalent trend throughout the country. Materials that are composted and recycled would have previously been disposed in a landfill.

Figure 7-2: Management of Municipal Solid Waste in the United States, 2014



Source: EPA (2016c)
Note: 2014 is the latest year of available data.

Figure 7-3: MSW Management Trends from 1990 to 2014



Source: EPA (2016c).
Note: 2014 is the latest year of available data.

Table 7-6 presents a typical composition of waste disposed of at a typical MSW landfill in the United States over time. It is important to note that the actual composition of waste entering each landfill will vary from that presented in Table 7-6. Understanding how the waste composition changes over time, specifically for the degradable waste types (i.e., those types known to generate CH_4 as they break down in a modern MSW landfill), is important for estimating greenhouse gas emissions. Increased diversion of degradable materials so that they are not disposed of in landfills reduces the CH_4 generation potential and CH_4 emissions from landfills. For certain degradable waste types (i.e., paper and paperboard), the amounts discarded have decreased over time due to an increase in waste diversion through recycling and composting (see Table 7-6 and Figure 7-4). As shown in Figure 7-4, the diversion of food scraps has been consistently low since 1990 because most cities and counties do not practice curbside collection of these materials. Neither Table 7-6 nor Figure 7-4 reflect the frequency of backyard composting of yard trimmings and food waste because this information is largely not collected nationwide and is hard to estimate.

Table 7-6: Materials Discarded[a] in the Municipal Waste Stream by Waste Type from 1990 to 2014 (Percent)[b]

Waste Type	1990		2005		2010	2011[c]	2012	2013	2014
Paper and Paperboard	30.0%		24.7%		16.1%	14.7%	14.7%	15.0%	14.3%
Glass	6.0%		5.8%		5.1%	5.1%	5.2%	5.2%	5.2%
Metals	7.2%		7.9%		9.0%	8.9%	9.2%	9.5%	9.4%
Plastics	9.5%		16.4%		17.9%	17.9%	18.2%	18.4%	18.5%
Rubber and Leather	3.2%		2.9%		3.2%	3.8%	3.2%	3.1%	3.1%
Textiles	2.9%		5.3%		6.5%	6.8%	7.1%	7.4%	7.7%
Wood	6.9%		7.5%		8.2%	8.2%	8.2%	8.0%	8.1%
Other[d]	1.4%		1.8%		2.1%	2.0%	2.0%	1.9%	1.9%
Food Scraps	13.6%		18.5%		21.0%	21.4%	21.0%	21.0%	21.6%
Yard Trimmings	17.6%		7.0%		8.6%	8.8%	8.7%	8.1%	7.9%
Miscellaneous Inorganic Wastes	1.7%		2.2%		2.3%	2.4%	2.4%	2.4%	2.3%

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[a] Discards after materials and compost recovery. In this table, discards include combustion with energy recovery. Does not include construction & demolition debris, industrial process wastes, or certain other wastes.

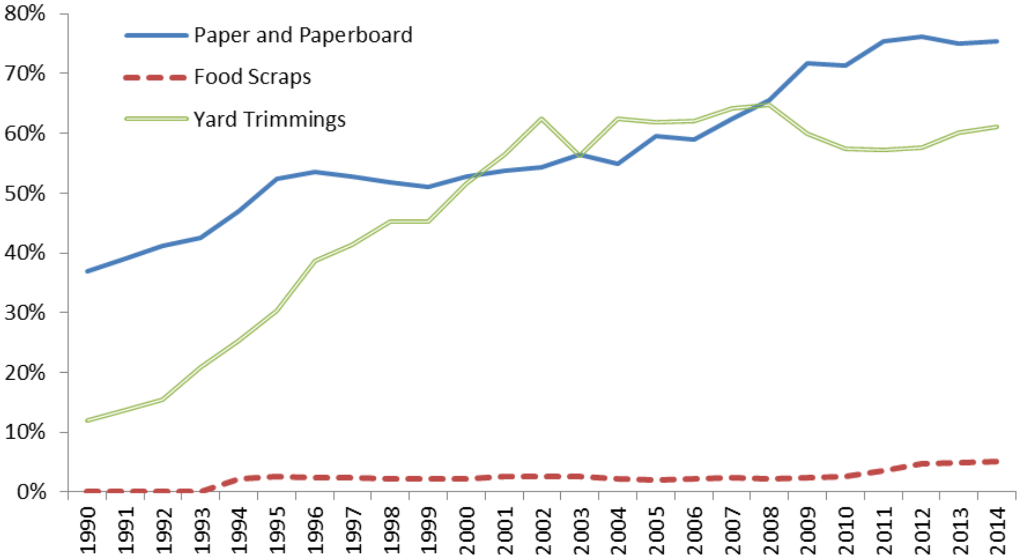
[b] Data for all years except 2011 are from the EPA's *Advancing Sustainable Materials Management: 2014 Tables and Figures* report (Table 4) published in December 2016 (EPA 2016c).

[c] 2011 data are not included in the most recent *Advancing Sustainable Materials Management* report (2014), thus data from the 2013 report (Table 3) was kept in place for 2011 (EPA 2015b).

[d] Includes electrolytes in batteries and fluff pulp, feces, and urine in disposable diapers. Details may not add to totals due to rounding.

Note: 2014 is the latest year of available data.

Figure 7-4: Percent of Degradable Materials Diverted from Landfills from 1990 to 2014 (Percent)



Source: (EPA 2016c).
Note: 2014 is the latest year of available data.

Box 7-5: Description of a Modern, Managed Landfill

Modern, managed landfills are well-engineered facilities that are located, designed, operated, and monitored to ensure compliance with federal, state, and tribal regulations. MSW landfills must be designed to protect the environment from contaminants which may be present in the solid waste stream. Additionally, many new landfills collect and destroy landfill gas through flares or landfill gas-to-energy projects. Requirements for affected MSW landfills may include:

- Siting requirements to protect sensitive areas (e.g., airports, floodplains, wetlands, fault areas, seismic impact zones, and unstable areas);
- Design requirements for new landfills to ensure that Maximum Contaminant Levels (MCLs) will not be exceeded in the uppermost aquifer (e.g., composite liners and leachate collection systems);
- Leachate collection and removal systems;
- Operating practices (e.g., daily and intermediate cover, receipt of regulated hazardous wastes, use of landfill cover material, access options to prevent illegal dumping, use of a collection system to prevent stormwater run-on/run-off, record-keeping);
- Air monitoring requirements (explosive gases);
- Groundwater monitoring requirements;
- Closure and post-closure care requirements (e.g., final cover construction); and
- Corrective action provisions.

Specific federal regulations that affected MSW landfills must comply with include the 40 CFR Part 258 (Subtitle D of RCRA), or equivalent state regulations and the NSPS 40 CFR Part 60 Subpart WWW. Additionally, state and tribal requirements may exist.[6]

7.2 Wastewater Treatment (CRF Source Category 5D)

Wastewater treatment processes can produce anthropogenic methane (CH_4) and nitrous oxide (N_2O) emissions. Wastewater from domestic and industrial sources is treated to remove soluble organic matter, suspended solids, pathogenic organisms, and chemical contaminants.[7] Treatment may either occur on site, most commonly through septic systems or package plants, or off site at centralized treatment systems. In the United States, approximately 19 percent of domestic wastewater is treated in septic systems or other on-site systems, while the rest is collected and treated centrally (U.S. Census Bureau 2015). Centralized wastewater treatment systems may include a variety of processes, ranging from lagooning to advanced tertiary treatment technology for removing nutrients. Some wastewater may also be treated through the use of constructed (or semi-natural) wetland systems, though it is much less common in the United States (ERG 2016). Constructed wetlands may be used as the primary method of wastewater treatment, or as a tertiary treatment step following settling and biological treatment. Constructed wetlands develop natural processes that involve vegetation, soil, and associated microbial assemblages to trap and treat incoming contaminants (IPCC 2014).

Soluble organic matter is generally removed using biological processes in which microorganisms consume the organic matter for maintenance and growth. The resulting biomass (sludge) is removed from the effluent prior to discharge to the receiving stream. Microorganisms can biodegrade soluble organic material in wastewater under aerobic or anaerobic conditions, where the latter condition produces CH_4. During collection and treatment, wastewater may be accidentally or deliberately managed under anaerobic conditions. In addition, the sludge may be further biodegraded under aerobic or anaerobic conditions. The generation of N_2O may also result from the treatment of domestic wastewater during both nitrification and denitrification of the nitrogen (N) present, usually in the form of urea, ammonia, and proteins. These compounds are converted to nitrate (NO_3) through the aerobic process of nitrification. Denitrification occurs under anoxic conditions (without free oxygen), and involves the biological conversion of nitrate into dinitrogen gas (N_2). Nitrous oxide can be an intermediate product of both processes, but has typically been associated with denitrification. Recent research suggests that higher emissions of N_2O may in fact originate from nitrification (Ahn et al. 2010). Other more recent research suggests that N_2O may also result from other types of wastewater treatment operations (Chandran 2012).

The principal factor in determining the CH_4 generation potential of wastewater is the amount of degradable organic material in the wastewater. Common parameters used to measure the organic component of the wastewater are the biochemical oxygen demand (BOD) and chemical oxygen demand (COD). Under the same conditions, wastewater with higher COD (or BOD) concentrations will generally yield more CH_4 than wastewater with lower COD (or BOD) concentrations. BOD represents the amount of oxygen that would be required to completely consume the organic matter contained in the wastewater through aerobic decomposition processes, while COD measures the total material available for chemical oxidation (both biodegradable and non-biodegradable). The BOD value is most commonly expressed in milligrams of oxygen consumed per liter of sample during 5 days of incubation at 20°C, or BOD_5. Because BOD is an aerobic parameter, it is preferable to use COD to estimate CH_4 production, since CH_4 is produced only in anaerobic conditions. The principal factor in determining the N_2O generation potential of

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[6] For more information regarding federal MSW landfill regulations, see <http://www.epa.gov/osw/nonhaz/municipal/landfill/msw_regs.htm>.

[7] Throughout the Inventory, emissions from domestic wastewater also include any commercial and industrial wastewater collected and co-treated with domestic wastewater.

wastewater is the amount of N in the wastewater. The variability of N in the influent to the treatment system, as well as the operating conditions of the treatment system itself, also impact the N_2O generation potential.

In 2016, CH_4 emissions from domestic wastewater treatment were 8.9 MMT CO_2 Eq. (357 kt CH_4). Emissions remained fairly steady from 1990 through 1999, but have decreased since that time due to decreasing percentages of wastewater being treated in anaerobic systems, generally including reduced use of on-site septic systems and central anaerobic treatment systems (EPA 1992, 1996, 2000, and 2004; U.S. Census Bureau 2015). In 2016, CH_4 emissions from industrial wastewater treatment were estimated to be 5.9 MMT CO_2 Eq. (236 kt CH_4). Industrial emission sources have generally increased across the time series through 1999 and then fluctuated up and down with production changes associated with the treatment of wastewater from the pulp and paper manufacturing, meat and poultry processing, fruit and vegetable processing, starch-based ethanol production, and petroleum refining industries. Table 7-7 and Table 7-8 provide CH_4 emission estimates from domestic and industrial wastewater treatment.

With respect to N_2O, the United States identifies two distinct sources for N_2O emissions from domestic wastewater: emissions from centralized wastewater treatment processes, and emissions from effluent from centralized treatment systems that has been discharged into aquatic environments. The 2016 emissions of N_2O from centralized wastewater treatment processes and from effluent were estimated to be 0.4 MMT CO_2 Eq. (1.2 kt N_2O) and 4.6 MMT CO_2 Eq. (15.4 kt N_2O), respectively. Total N_2O emissions from domestic wastewater were estimated to be 5.0 MMT CO_2 Eq. (16.6 kt N_2O). Nitrous oxide emissions from wastewater treatment processes gradually increased across the time series as a result of increasing U.S. population and protein consumption. Nitrous oxide emissions are not estimated from industrial wastewater treatment because there is no IPCC methodology provided or industrial wastewater emission factors available. Table 7-7 and Table 7-8 provide N_2O emission estimates from domestic wastewater treatment.

Table 7-7: CH_4 and N_2O Emissions from Domestic and Industrial Wastewater Treatment (MMT CO_2 Eq.)

Activity	1990	2005	2012	2013	2014	2015	2016
CH_4	**15.7**	**15.8**	**15.1**	**14.9**	**15.0**	**15.1**	**14.8**
Domestic	10.5	10.1	9.3	9.1	9.2	9.3	8.9
Industrial[a]	5.1	5.7	5.8	5.8	5.7	5.8	5.9
N_2O	**3.4**	**4.4**	**4.6**	**4.7**	**4.8**	**4.8**	**5.0**
Centralized WWTP	0.2	0.3	0.3	0.3	0.3	0.3	0.4
Domestic Effluent	3.2	4.1	4.3	4.3	4.5	4.5	4.6
Total	**19.1**	**20.2**	**19.7**	**19.6**	**19.8**	**20.0**	**19.8**

[a] Industrial activity includes the pulp and paper manufacturing, meat and poultry processing, fruit and vegetable processing, starch-based ethanol production, and petroleum refining industries.

Note: Totals may not sum due to independent rounding.

Table 7-8: CH_4 and N_2O Emissions from Domestic and Industrial Wastewater Treatment (kt)

Activity	1990	2005	2012	2013	2014	2015	2016
CH_4	**627**	**631**	**604**	**596**	**598**	**605**	**593**
Domestic	422	404	372	365	369	374	357
Industrial[a]	205	227	232	231	229	231	236
N_2O	**11**	**15**	**16**	**16**	**16**	**16**	**17**
Centralized WWTP	1	1	1	1	1	1	1
Domestic Effluent	11	14	14	15	15	15	15

[a] Industrial activity includes the pulp and paper manufacturing, meat and poultry processing, fruit and vegetable processing, starch-based ethanol production, and petroleum refining industries.

Note: Totals may not sum due to independent rounding.

Methodology

Domestic Wastewater CH_4 Emission Estimates

Domestic wastewater CH_4 emissions originate from both septic systems and from centralized treatment systems, such as publicly owned treatment works (POTWs). Within these centralized systems, CH_4 emissions can arise from aerobic systems that are not well managed or that are designed to have periods of anaerobic activity (e.g., constructed wetlands and facultative lagoons), anaerobic systems (anaerobic lagoons and anaerobic reactors), and from anaerobic digesters when the captured biogas is not completely combusted. The methodological equations are:

$$\textit{Emissions from Septic Systems} = \text{A}$$
$$= \text{US}_{\text{POP}} \times (\text{\% onsite}) \times (\text{EF}_{\text{SEPTIC}}) \times 1/10^9 \times 365.25$$

$$\textit{Emissions from Centrally Treated Aerobic Systems (other than Constructed Wetlands)} + \textit{Emissions from Centrally Treated Aerobic Systems (Constructed Wetlands Only)} + \textit{Emissions from Centrally Treated Aerobic Systems (Constructed Wetlands used as Tertiary Treatment)} = \text{B}$$

where,

$$\textit{Emissions from Centrally Treated Aerobic Systems (other than Constructed Wetlands)}$$
$$= [(\text{\% collected}) \times (\text{total BOD}_5\text{ produced}) \times (\text{\% aerobic}_{\text{OTCW}}) \times (\text{\% aerobic w/out primary}) + (\text{\% collected}) \times (\text{total BOD}_5\text{ produced}) \times (\text{\% aerobic}_{\text{OTCW}}) \times (\text{\% aerobic w/primary}) \times (\text{1-\% BOD removed in prim. treat.})] \times (\text{\% operations not well managed}) \times (\text{B}_\text{o}) \times (\text{MCF-aerobic\_not\_well\_man})$$

$$\textit{Emissions from Centrally Treated Aerobic Systems (Constructed Wetlands Only)}$$
$$= [(\text{\% collected}) \times (\text{total BOD}_5\text{ produced}) \times (\text{\%aerobic}_{\text{CW}})] \times (\text{B}_\text{o}) \times (\text{MCF-constructed wetlands})$$

$$\textit{Emissions from Centrally Treated Aerobic Systems (Constructed Wetlands used as Tertiary Treatment)}$$
$$= [(\text{POTW\_flow\_CW}) \times (\text{BOD}_{\text{CW,INF}}) \times 3.79] \times 1/10^6 \times 365.25$$

$$\textit{Emissions from Centrally Treated Anaerobic Systems} = \text{C}$$
$$= \{[(\text{\% collected}) \times (\text{total BOD}_5\text{ produced}) \times (\text{\% anaerobic}) \times (\text{\% anaerobic w/out primary})] + [(\text{\% collected}) \times (\text{total BOD}_5\text{ produced}) \times (\text{\% anaerobic}) \times (\text{\% anaerobic w/primary}) \times (\text{1-\% BOD removed in prim. treat.})]\} \times (\text{B}_\text{o}) \times (\text{MCF-anaerobic})$$

$$\textit{Emissions from Anaerobic Digesters} = \text{D}$$
$$= [(\text{POTW\_flow\_AD}) \times (\text{digester gas})/(100)] \times 0.0283 \times (\text{FRAC\_CH}_4) \times 365.25 \times (\text{density of CH}_4) \times (\text{1-DE}) \times 1/10^9$$

$$\text{Total Domestic CH}_4\text{ Emissions from Wastewater (kt)} = \text{A} + \text{B} + \text{C} + \text{D}$$

where,

US_{POP} = U.S. population
% onsite = Flow to septic systems / total flow
% collected = Flow to POTWs / total flow
% $\text{aerobic}_{\text{OTCW}}$ = Flow to aerobic systems, other than wetlands only / total flow to POTWs
% $\text{aerobic}_{\text{CW}}$ = Flow to aerobic systems, constructed wetlands used as sole treatment / total flow to POTWs
% anaerobic = Flow to anaerobic systems / total flow to POTWs
% aerobic w/out primary = Percent of aerobic systems that do not employ primary treatment
% aerobic w/primary = Percent of aerobic systems that employ primary treatment
% BOD removed in prim. treat. = Percent of BOD removed in primary treatment
% operations not well managed = Percent of aerobic systems that are not well managed and in which some anaerobic degradation occurs
% anaerobic w/out primary = Percent of anaerobic systems that do not employ primary treatment

% anaerobic w/primary = Percent of anaerobic systems that employ primary treatment
EF_{SEPTIC} = Methane emission factor – septic systems
Total BOD_5 produced = kg BOD/capita/day × U.S. population × 365.25 days/yr
$BOD_{CW,INF}$ = BOD concentration in wastewater entering the constructed wetland
B_o = Maximum CH_4-producing capacity for domestic wastewater
$1/10^6$ = Conversion factor, kg to kt
365.25 = Days in a year
3.79 = Conversion factor, liters to gallons
MCF-aerobic_not_well_man. = CH_4 correction factor for aerobic systems that are not well managed
MCF-anaerobic = CH_4 correction factor for anaerobic systems
MCF-constructed wetlands = CH_4 correction factor for surface flow constructed wetlands
DE = CH_4 destruction efficiency from flaring or burning in engine
POTW_flow_CW = Wastewater flow to POTWs that use constructed wetlands as tertiary treatment (MGD)
POTW_flow_AD = Wastewater influent flow to POTWs that have anaerobic digesters (MGD)
digester gas = Cubic feet of digester gas produced per person per day
100 = Wastewater flow to POTW (gallons/person/day)
0.0283 = Conversion factor, ft^3 to m^3
FRAC_CH_4 = Proportion of CH_4 in biogas
662 = Density of CH_4 (g CH_4/m^3 CH_4)
$1/10^9$ = Conversion factor, g to kt

Emissions from Septic Systems:

Methane emissions from septic systems were estimated by multiplying the U.S. population by the percent of wastewater treated in septic systems (about 19 percent) and an emission factor (10.7 g CH_4/capita/day) (Leverenz et al. 2010), and then converting the result to kt/year. U.S. population data were taken from the U.S. Census Bureau International Database (U.S. Census Bureau 2017) and include the populations of the United States, American Samoa, Guam, Northern Mariana Islands, Puerto Rico, and the U.S. Virgin Islands. Table 7-9 presents U.S. population for 1990 through 2016.

Emissions from Centrally Treated Aerobic and Anaerobic Systems:

Methane emissions from POTWs were estimated by multiplying the total BOD_5 produced in the United States by the percent of wastewater treated centrally (about 81 percent) (U.S. Census Bureau 2015), the relative percentage of wastewater treated by aerobic and anaerobic systems (other than constructed wetlands), the relative percentage of wastewater facilities with primary treatment (EPA 1992, 1996, 2000, and 2004), the percentage of BOD_5 treated after primary treatment (67.5 percent, 32.5 percent removed in primary treatment) (Metcalf & Eddy 2003), the maximum CH_4-producing capacity of domestic wastewater (B_o, 0.6 kg CH_4/kg BOD) (IPCC 2006), and the relative methane conversion factors (MCF) not well managed aerobic (0.3) (IPCC 2006), and anaerobic (0.8) (IPCC 2006) systems.

Table 7-9 presents total BOD_5 produced for 1990 through 2016. The proportions of domestic wastewater treated onsite versus at centralized treatment plants were based on data from the 1989, 1991, 1993, 1995, 1997, 1999, 2001, 2003, 2005, 2007, 2009, 2011, 2013, and 2015 *American Housing Surveys* conducted by the U.S. Census Bureau (U.S. Census Bureau 2015), with data for intervening years obtained by linear interpolation and 2016 forecasted using 1990 to 2015 data. The percent of wastewater flow to aerobic and anaerobic systems, the percent of aerobic and anaerobic systems that do and do not employ primary treatment, and the wastewater flow to POTWs that have anaerobic digesters were obtained from the 1992, 1996, 2000, and 2004 Clean Watersheds Needs Survey (EPA 1992, 1996, 2000, and 2004). Data for intervening years were obtained by linear interpolation and the years 2005 through 2016 were forecasted from the rest of the time series. The percent of wastewater flow to aerobic systems that use only constructed wetlands and wastewater flow to POTWs that use constructed wetlands as tertiary treatment were obtained from the 1992, 1996, 2000, 2004, 2008, and 2012 Clean Watersheds Needs Survey (EPA 1992, 1996, 2000, 2004, 2008b, and 2012). Data for intervening years were obtained by linear interpolation and the years 2013 through 2016 were forecasted from the rest of the time series. The BOD_5 production rate (0.09 kg/capita/day) and the percent BOD_5 removed by primary treatment for domestic wastewater were obtained from Metcalf & Eddy (2003).

Table 7-9: U.S. Population (Millions) and Domestic Wastewater BOD_5 Produced (kt)

Year	Population	BOD_5
1990	253	8,333
2005	300	9,853
2012	318	10,458
2013	320	10,534
2014	323	10,615
2015	325	10,696
2016	328	10,780

Sources: U.S. Census Bureau (2017); Metcalf & Eddy (2003).

For constructed wetlands, an MCF of 0.4 was used, which is the IPCC suggested MCF for surface flow wetlands. This is the most conservative factor for constructed wetlands and was recommended by IPCC (2014) when the type of constructed wetland is not known. A BOD_5 concentration of 30 mg/L was used for wastewater entering constructed wetlands used as tertiary treatment based on U.S. secondary treatment standards for POTWs. These standards are based on plants generally utilizing simple settling and biological treatment (EPA 2013).

All aerobic systems are assumed to be well-managed as there are currently no data available to quantify the number of systems that are not well-managed. In addition, methane emissions were calculated for systems that treat wastewater with constructed wetlands and systems that use constructed wetlands as tertiary treatment; however, constructed wetlands are a relatively small portion of wastewater treated centrally (<0.1 percent).

Emissions from Anaerobic Digesters:

Total CH_4 emissions from anaerobic digesters were estimated by multiplying the wastewater influent flow to POTWs with anaerobic digesters, the cubic feet of digester gas generated per person per day divided by the flow to POTWs, the fraction of CH_4 in biogas (0.65), the density of CH_4 (662 g CH_4/m^3 CH_4) (EPA 1993a), one minus the destruction efficiency from burning the biogas in an energy/thermal device (0.99 for enclosed flares) and then converting the results to kt/year.

The CH_4 destruction efficiency for CH_4 recovered from sludge digestion operations, 99 percent, was selected based on the range of efficiencies (98 to 100 percent) recommended for flares in *AP-42 Compilation of Air Pollutant Emission Factors*, Chapter 2.4 (EPA 1998), efficiencies used to establish New Source Performance Standards (NSPS) for landfills, along with data from CAR (2011), Sullivan (2007), Sullivan (2010), and UNFCCC (2012). The cubic feet of digester gas produced per person per day (1.0 ft^3/person/day) and the proportion of CH_4 in biogas (0.65) come from Metcalf & Eddy (2014). The wastewater flow to a POTW (100 gal/person/day) was taken from the Great Lakes-Upper Mississippi River Board of State and Provincial Public Health and Environmental Managers, "*Recommended Standards for Wastewater Facilities (Ten-State Standards)*" (2004).

Table 7-10 presents domestic wastewater CH_4 emissions for both septic and centralized systems, including anaerobic digesters, in 2016.

Table 7-10: Domestic Wastewater CH_4 Emissions from Septic and Centralized Systems (2016, MMT CO_2 Eq. and Percent)

	CH_4 Emissions (MMT CO_2 Eq.)	% of Domestic Wastewater CH_4
Septic Systems	6.0	66.7%
Centrally-Treated Aerobic Systems	0.1	1.1%
Centrally-Treated Anaerobic Systems	2.7	29.8%
Anaerobic Digesters	0.2	2.3%
Total	**8.9**	**100%**

Note: Totals may not sum due to independent rounding.

Industrial Wastewater CH_4 Emission Estimates

Methane emission estimates from industrial wastewater were developed according to the methodology described in the *2006 IPCC Guidelines*. Industry categories that are likely to produce significant CH_4 emissions from wastewater treatment were identified and included in the Inventory. The main criteria used to identify these industries are whether they generate high volumes of wastewater, whether there is a high organic wastewater load, and whether the wastewater is treated using methods that result in CH_4 emissions. The top five industries that meet these criteria are pulp and paper manufacturing; meat and poultry processing; vegetables, fruits, and juices processing; starch-based ethanol production; and petroleum refining. Wastewater treatment emissions for these sectors for 2016 are displayed in Table 7-11 below. Table 7-12 contains production data for these industries.

Table 7-11: Industrial Wastewater CH_4 Emissions by Sector (2016, MMT CO_2 Eq. and Percent)

	CH_4 Emissions (MMT CO_2 Eq.)	% of Industrial Wastewater CH_4
Meat & Poultry	4.5	76.8%
Pulp & Paper	0.9	15.8%
Fruit & Vegetables	0.1	2.4%
Petroleum Refineries	0.1	2.5%
Ethanol Refineries	0.1	2.5%
Total	**5.9**	**100%**

Note: Totals may not sum due to independent rounding.

Table 7-12: U.S. Pulp and Paper, Meat, Poultry, Vegetables, Fruits and Juices, Ethanol, and Petroleum Refining Production (MMT)

Year	Pulp and Paper[a]	Meat (Live Weight Killed)	Poultry (Live Weight Killed)	Vegetables, Fruits and Juices	Ethanol	Petroleum Refining
1990	128.9	27.3	14.6	38.7	2.5	702.4
2005	138.5	31.4	25.1	42.9	11.7	818.6
2012	124.7	33.8	26.1	45.6	39.5	856.1
2013	120.8	33.6	26.5	45.1	39.7	878.7
2014	123.2	32.2	26.9	45.3	42.8	903.9
2015	121.8	32.8	27.7	44.6	44.2	914.5
2016	121.4	34.2	28.3	43.3	45.8	925.3

[a] Pulp and paper production is the sum of woodpulp production plus paper and paperboard production.

Sources: Lockwood-Post (2002); FAO (2017a); USDA (2017a); Cooper (2017); EIA (2017).

Methane emissions from these categories were estimated by multiplying the annual product output by the average outflow, the organics loading (in COD) in the outflow, the maximum CH_4 producing potential of industrial wastewater (B_o), and the percentage of organic loading assumed to degrade anaerobically in a given treatment system (MCF). Ratios of BOD:COD in various industrial wastewaters were obtained from EPA (1997a) and used to estimate COD loadings. The B_o value used for all industries is the IPCC default value of 0.25 kg CH_4/kg COD (IPCC 2006).

For each industry, the percent of plants in the industry that treat wastewater on site, the percent of plants that have a primary treatment step prior to biological treatment, and the percent of plants that treat wastewater anaerobically were defined. The percent of wastewater treated anaerobically onsite (TA) was estimated for both primary treatment ($\%TA_p$) and secondary treatment ($\%TA_s$). For plants that have primary treatment in place, an estimate of COD that is removed prior to wastewater treatment in the anaerobic treatment units was incorporated. The values used in the %TA calculations are presented in Table 7-13 below.

The methodological equations are:

$$\mathrm{CH_4\ (industrial\ wastewater)} = [\mathrm{P} \times \mathrm{W} \times \mathrm{COD} \times \%\mathrm{TA_p} \times \mathrm{B_o} \times \mathrm{MCF}] + [\mathrm{P} \times \mathrm{W} \times \mathrm{COD} \times \%\mathrm{TA_s} \times \mathrm{B_o} \times \mathrm{MCF}]$$

$$\%TA_p = [\%Plants_o \times \%WW_{a,p} \times \%COD_p]$$

$$\%TA_s = [\%Plants_a \times \%WW_{a,s} \times \%COD_s] + [\%Plants_t \times \%WW_{a,t} \times \%COD_s]$$

where,

CH_4 (industrial wastewater) = Total CH_4 emissions from industrial wastewater (kg/year)
P = Industry output (metric tons/year)
W = Wastewater generated (m^3/metric ton of product)
COD = Organics loading in wastewater (kg/m^3)
$\%TA_p$ = Percent of wastewater treated anaerobically on site in primary treatment
$\%TA_s$ = Percent of wastewater treated anaerobically on site in secondary treatment
$\%Plants_o$ = Percent of plants with onsite treatment
$\%WW_{a,p}$ = Percent of wastewater treated anaerobically in primary treatment
$\%COD_p$ = Percent of COD entering primary treatment
$\%Plants_a$ = Percent of plants with anaerobic secondary treatment
$\%Plants_t$ = Percent of plants with other secondary treatment
$\%WW_{a,s}$ = Percent of wastewater treated anaerobically in anaerobic secondary treatment
$\%WW_{a,t}$ = Percent of wastewater treated anaerobically in other secondary treatment
$\%COD_s$ = Percent of COD entering secondary treatment
B_o = Maximum CH_4 producing potential of industrial wastewater (kg CH_4/kg COD)
MCF = CH_4 correction factor, indicating the extent to which the organic content (measured as COD) degrades anaerobically

Alternate methodological equations for calculating %TA were used for secondary treatment in the pulp and paper industry to account for aerobic systems with anaerobic portions. These equations are:

$$\%TA_a = [\%Plants_a \times \%WW_{a,s} \times \%COD_s]+[\%Plant_{s,t} \times \%WW_{a,t} \times COD_s]$$

$$\%TA_{a,t} = [\%Plants_{a,t} \times \%WW_{a,s} \times \%COD_s]$$

where,

$\%TA_a$ = Percent of wastewater treated anaerobically on site in secondary treatment
$\%TA_{a,t}$ = Percent of wastewater treated in aerobic systems with anaerobic portions on site in secondary treatment
$\%Plants_a$ = Percent of plants with anaerobic secondary treatment
$\%Plants_{a,t}$ = Percent of plants with partially anaerobic secondary treatment
$\%WW_{a,s}$ = Percent of wastewater treated anaerobically in anaerobic secondary treatment
$\%WW_{a,t}$ = Percent of wastewater treated anaerobically in other secondary treatment
$\%COD_s$ = Percent of COD entering secondary treatment

As described below, the values presented in Table 7-13 were used in the emission calculations and are described in detail in ERG (2008), ERG (2013a), and ERG (2013b).

Table 7-13: Variables Used to Calculate Percent Wastewater Treated Anaerobically by Industry (Percent)

Variable	Industry						
	Pulp and Paper	Meat Processing	Poultry Processing	Fruit/ Vegetable Processing	Ethanol Production – Wet Mill	Ethanol Production – Dry Mill	Petroleum Refining
$\%TA_p$	0	0	0	0	0	0	0
$\%TA_s$	0	33	25	4.2	33.3	75	23.6
$\%TA_a$	2.2	0	0	0	0	0	0
$\%TA_{a,t}$	11.8	0	0	0	0	0	0
$\%Plants_o$	0	100	100	11	100	100	100
$\%Plants_a$	5	33	25	5.5	33.3	75	23.6
$\%Plants_{a,t}$	28	0	0	0	0	0	0
$\%Plants_t$	35	67	75	5.5	66.7	25	0

$\%WW_{a,p}$	0	0	0	0	0	0	0
$\%WW_{a,s}$	100	100	100	100	100	100	100
$\%WW_{a,t}$	0	0	0	0	0	0	0
$\%COD_p$	100	100	100	100	100	100	100
$\%COD_s$	42	100	100	77	100	100	100

Note: Due to differences in data availability and methodology, zero values in the table are for calculation purposes only and may indicate unavailable data.

Sources: ERG (2008); ERG (2013a); and ERG (2013b).

Pulp and Paper. Wastewater treatment for the pulp and paper industry typically includes neutralization, screening, sedimentation, and flotation/hydrocycloning to remove solids (World Bank 1999; Nemerow and Dasgupta 1991). Secondary treatment (storage, settling, and biological treatment) mainly consists of lagooning. In determining the percent that degrades anaerobically, both primary and secondary treatment were considered. In the United States, primary treatment is focused on solids removal, equalization, neutralization, and color reduction (EPA 1993b). The vast majority of pulp and paper mills with on-site treatment systems use mechanical clarifiers to remove suspended solids from the wastewater. About 10 percent of pulp and paper mills with treatment systems use settling ponds for primary treatment and these are more likely to be located at mills that do not perform secondary treatment (EPA 1993b). However, because the vast majority of primary treatment operations at U.S. pulp and paper mills use mechanical clarifiers, and less than 10 percent of pulp and paper wastewater is managed in primary settling ponds that are not expected to have anaerobic conditions, negligible emissions are assumed to occur during primary treatment.

Approximately 42 percent of the BOD passes on to secondary treatment, which consists of activated sludge, aerated stabilization basins, or non-aerated stabilization basins. Based on EPA's *OAQPS Pulp and Paper Sector Survey*, 5.3 percent of pulp and paper mills reported using anaerobic secondary treatment for wastewater and/or pulp condensates (ERG 2013a). Twenty-eight percent of mills also reported the use of quiescent settling ponds. Using engineering judgment, these systems were determined to be aerobic with possible anaerobic portions. For the truly anaerobic systems, an MCF of 0.8 is used, as these are typically deep stabilization basins. For the partially anaerobic systems, an MCF of 0.2 is used, which is the *2006 IPCC Guidelines*-suggested MCF for shallow lagoons.

A time series of CH_4 emissions for 1990 through 2001 was developed based on production figures reported in the Lockwood-Post Directory (Lockwood-Post 2002). Data from the Food and Agricultural Organization of the United Nations (FAO) database FAOSTAT were used for 2002 through 2015 (FAO 2017a). A time series of the overall wastewater outflow for 1990 through 1994 varies based on data outlined in ERG (2013a) to reflect historical wastewater flow. Wastewater generation rates for 1995, 2000, and 2002 were estimated from the 2014 *American Forest and Paper Association* (AF&PA) *Sustainability Report* (AF&PA 2014). Wastewater generation rates for 2004, 2006, 2008, 2010, 2012, and 2014 were estimated from the 2016 AF&PA Sustainability Report (AF&PA 2016). Data for intervening years were obtained by linear interpolation, while 2015 and 2016 were forecasted using 1990 to 2014 and 1990 to 2015 data, respectively. The average BOD concentrations in raw wastewater was estimated to be 0.4 grams BOD/liter (EPA 1997b; EPA 1993b; World Bank 1999). The COD:BOD ratio used to convert the organic loading to COD for pulp and paper mills was 2 (EPA 1997a).

Meat and Poultry Processing. The meat and poultry processing industry makes extensive use of anaerobic lagoons in sequence with screening, fat traps, and dissolved air flotation when treating wastewater on site. About 33 percent of meat processing operations (EPA 2002) and 25 percent of poultry processing operations (U.S. Poultry 2006) perform on-site treatment in anaerobic lagoons. The IPCC default B_o of 0.25 kg CH_4/kg COD and default MCF of 0.8 for anaerobic lagoons were used to estimate the CH_4 produced from these on-site treatment systems. Production data, in carcass weight and live weight killed for the meat and poultry industry, were obtained from the USDA *Agricultural Statistics Database and the Agricultural Statistics Annual Reports* (USDA 2017a). Data collected by EPA's Office of Water provided estimates for wastewater flows into anaerobic lagoons: 5.3 and 12.5 m^3/metric ton for meat and poultry production (live weight killed), respectively (EPA 2002). The loadings are 2.8 and 1.5 g BOD/liter for meat and poultry, respectively. The COD:BOD ratio used to convert the organic loading to COD for both meat and poultry facilities was 3 (EPA 1997a).

Vegetables, Fruits, and Juices Processing. Treatment of wastewater from fruits, vegetables, and juices processing includes screening, coagulation/settling, and biological treatment (lagooning). The flows are frequently seasonal, and robust treatment systems are preferred for on-site treatment. Effluent is suitable for discharge to POTWs. This industry is likely to use lagoons intended for aerobic operation, but the large seasonal loadings may develop limited anaerobic zones. In addition, some anaerobic lagoons may also be used (Nemerow and Dasgupta 1991). Consequently, 4.2 percent of these wastewater organics are assumed to degrade anaerobically. The IPCC default B_o of 0.25 kg CH_4/kg COD and default MCF of 0.8 for anaerobic treatment were used to estimate the CH_4 produced from these on-site treatment systems. The USDA National Agricultural Statistics Service (USDA 2017a, 2017c) provided production data for potatoes, other vegetables, citrus fruit, non-citrus fruit, and grapes processed for wine. Outflow and BOD data, presented in Table 7-14, were obtained from EPA (1974) for potato, citrus fruit, and apple processing, and from EPA (1975) for all other commodities. The COD:BOD ratio used to convert the organic loading to COD for all fruit, vegetable, and juice facilities was 1.5 (EPA 1997a).

Table 7-14: Wastewater Flow (m^3/ton) and BOD Production (g/L) for U.S. Vegetables, Fruits, and Juices Production

Commodity	Wastewater Outflow (m^3/ton)	BOD (g/L)
Vegetables		
Potatoes	10.27	1.765
Other Vegetables	8.55	0.776
Fruit		
Apples	3.66	1.371
Citrus Fruits	10.11	0.317
Non-citrus Fruits	12.42	1.204
Grapes (for wine)	2.78	1.831

Sources: EPA (1974); EPA (1975).

Ethanol Production. Ethanol, or ethyl alcohol, is produced primarily for use as a fuel component, but is also used in industrial applications and in the manufacture of beverage alcohol. Ethanol can be produced from the fermentation of sugar-based feedstocks (e.g., molasses and beets), starch- or grain-based feedstocks (e.g., corn, sorghum, and beverage waste), and cellulosic biomass feedstocks (e.g., agricultural wastes, wood, and bagasse). Ethanol can also be produced synthetically from ethylene or hydrogen and carbon monoxide. However, synthetic ethanol comprises only about 2 percent of ethanol production, and although the U.S. Department of Energy (DOE) predicts cellulosic ethanol to greatly increase in the coming years, currently it is only in an experimental stage in the United States. Currently, ethanol is mostly made from sugar and starch crops, but with advances in technology, cellulosic biomass is increasingly used as ethanol feedstock (DOE 2013).

Ethanol is produced from corn (or other starch-based feedstocks) primarily by two methods: wet milling and dry milling. Historically, the majority of ethanol was produced by the wet milling process, but now the majority is produced by the dry milling process. The dry milling process is cheaper to implement, and has become more efficient in recent years (Rendleman and Shapouri 2007). The wastewater generated at ethanol production facilities is handled in a variety of ways. Dry milling facilities often combine the resulting evaporator condensate with other process wastewaters, such as equipment wash water, scrubber water, and boiler blowdown and anaerobically treat this wastewater using various types of digesters. Wet milling facilities often treat their steepwater condensate in anaerobic systems followed by aerobic polishing systems. Wet milling facilities may treat the stillage (or processed stillage) from the ethanol fermentation/distillation process separately or together with steepwater and/or wash water. Methane generated in anaerobic digesters is commonly collected and either flared or used as fuel in the ethanol production process (ERG 2006).

Available information was compiled from the industry on wastewater generation rates, which ranged from 1.25 gallons per gallon ethanol produced (for dry milling) to 10 gallons per gallon ethanol produced (for wet milling) (Ruocco 2006a; Ruocco 2006b; Merrick 1998; Donovan 1996; NRBP 2001). COD concentrations were found to be about 3 g/L (Ruocco 2006a; Merrick 1998; White and Johnson 2003). One hundred percent of plants were estimated to have onsite wastewater treatment, and the variables used to calculate percent wastewater treated anaerobically are presented in Table 7-13. A default MCF of 0.8 for anaerobic treatment was used to estimate the CH_4 produced from these on-site treatment systems. The amount of CH_4 recovered through the use of biomethanators was estimated, and a 99 percent destruction efficiency was used. Biomethanators are anaerobic reactors that use microorganisms under anaerobic conditions to reduce COD and organic acids and recover biogas from wastewater (ERG 2006). Methane emissions were then estimated as follows:

$$\text{Methane} = [\text{Production} \times \text{Flow} \times \text{COD} \times 3.785 \times ([\%\text{Plants}_o \times \%\text{WW}_{a,p} \times \%\text{COD}_p] + [\%\text{Plants}_a \times \%\text{WW}_{a,s} \times \%\text{COD}_s] + [\%\text{Plants}_t \times \%\text{WW}_{a,t} \times \%\text{COD}_s]) \times \text{B}_o \times \text{MCF} \times \%\text{ Not Recovered}] + [\text{Production} \times \text{Flow} \times 3.785 \times \text{COD} \times ([\%\text{Plants}_o \times \%\text{WW}_{a,p} \times \%\text{COD}_p] + [\%\text{Plants}_a \times \%\text{WW}_{a,s} \times \%\text{COD}_s] + [\%\text{Plants}_t \times \%\text{WW}_{a,t} \times \%\text{COD}_s]) \times \text{B}_o \times \text{MCF} \times (\%\text{ Recovered}) \times (1\text{-DE})] \times 1/10^9$$

where,

Production = Gallons ethanol produced (wet milling or dry milling)
Flow = Gallons wastewater generated per gallon ethanol produced
COD = COD concentration in influent (g/l)
3.785 = Conversion factor, gallons to liters
$\%\text{Plants}_o$ = Percent of plants with onsite treatment
$\%\text{WW}_{a,p}$ = Percent of wastewater treated anaerobically in primary treatment
$\%\text{COD}_p$ = Percent of COD entering primary treatment
$\%\text{Plants}_a$ = Percent of plants with anaerobic secondary treatment
$\%\text{Plants}_t$ = Percent of plants with other secondary treatment
$\%\text{WW}_{a,s}$ = Percent of wastewater treated anaerobically in anaerobic secondary treatment
$\%\text{WW}_{a,t}$ = Percent of wastewater treated anaerobically in other secondary treatment
$\%\text{COD}_s$ = Percent of COD entering secondary treatment
B_o = Maximum methane producing capacity (g CH_4/g COD)
MCF = Methane conversion factor
% Recovered = Percent of wastewater treated in system with emission recovery
% Not Recovered = 1 - percent of wastewater treated in system with emission recovery
DE = Destruction efficiency of recovery system
$1/10^9$ = Conversion factor, g to kt

A time series of CH_4 emissions for 1990 through 2016 was developed based on production data from the Renewable Fuels Association (Cooper 2017).

Petroleum Refining. Petroleum refining wastewater treatment operations have the potential to produce CH_4 emissions from anaerobic wastewater treatment. EPA's Office of Air and Radiation performed an Information Collection Request (ICR) for petroleum refineries in 2011.[8] Of the responding facilities, 23.6 percent reported using non-aerated surface impoundments or other biological treatment units, both of which have the potential to lead to anaerobic conditions (ERG 2013b). In addition, the wastewater generation rate was determined to be 26.4 gallons per barrel of finished product (ERG 2013b). An average COD value in the wastewater was estimated at 0.45 kg/m^3 (Benyahia et al. 2006). A default MCF of 0.3 was used for partially aerobic systems.

The equation used to calculate CH_4 generation at petroleum refining wastewater treatment systems is presented below:

$$\text{Methane} = \text{Flow} \times \text{COD} \times \%\text{TA} \times \text{B}_o \times \text{MCF}$$

where,

Flow = Annual flow treated through anaerobic treatment system (m^3/year)
COD = COD loading in wastewater entering anaerobic treatment system (kg/m^3)
%TA = Percent of wastewater treated anaerobically on site
B_o = Maximum methane producing potential of industrial wastewater (kg CH_4/kg COD)
MCF = Methane conversion factor

A time series of CH_4 emissions for 1990 through 2016 was developed based on production data from the EIA 2017.

Domestic Wastewater N_2O Emission Estimates

Nitrous oxide emissions from domestic wastewater (wastewater treatment) were estimated using the IPCC (2006) methodology and supplemented with IPCC (2014) methodology to include constructed wetland emissions, including

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[8] Available online at <https://www.epa.gov/stationary-sources-air-pollution/comprehensive-data-collected-petroleum-refining-sector>

calculations that take into account N removal with biosolids, non-consumption and industrial/commercial wastewater N, and emissions from advanced and constructed wetlands at centralized wastewater treatment plants:

- In the United States, a certain amount of N is removed with biosolids, which is applied to land, incinerated, or landfilled (N_{SLUDGE}). The value for N discharged into aquatic environments as effluent is reduced to account for the biosolids application.
- The *2006 IPCC Guidelines* use annual, per capita protein consumption (kg protein/person-year). For this Inventory, the amount of protein available to be consumed is estimated based on per capita annual food availability data and its protein content, and then that data is adjusted using a factor to account for the fraction of protein actually consumed.
- Small amounts of gaseous nitrogen oxides are formed as byproducts in the conversion of nitrate to N gas in anoxic biological treatment systems. Approximately 7 g N_2O is generated per capita per year if wastewater treatment includes intentional nitrification and denitrification (Scheehle and Doorn 2001). Analysis of the use of treatment systems in the United States that include denitrification has shown a significant increase in the time period between 2004 and 2012, from serving populations totaling 2.4 million people to 21.3 million people (EPA 2004 and EPA 2012). This is consistent with efforts throughout the United States to improve nutrient removal at centralized treatment systems in response to specific water quality concerns. Based on an emission factor of 7 g per capita per year, and data from CWNS 2004, 2008, and 2012, approximately 21.2 metric tons of additional N_2O may have been emitted via denitrification in 2004, while about 186 metric tons may have been emitted via denitrification in both 2008 and 2012. Similar analyses were completed for each year in the Inventory using data from CWNS on the amount of wastewater in centralized systems treated in denitrification units. Plants without intentional nitrification or denitrification are assumed to generate 3.2 g N_2O per capita per year.
- Constructed wetlands may be used as the sole treatment unit at a centralized wastewater treatment plant or may serve as tertiary treatment after simple settling and biological treatment. Emissions from all constructed wetland systems were included in the estimates of emissions from centralized wastewater treatment plant processes and effluent from these plants. The emission factor of 0.0013 kg N_2O-N/kg N produced for constructed wetlands is from IPCC (2014).
- N_2O emissions from wastewater treatment plants are estimated, and as such, the N associated with these emissions is subtracted from the amount of N estimated to be discharged into aquatic environments as effluent, consistent with the *2006 IPCC Guidelines*.

Nitrous oxide emissions from domestic wastewater were estimated using the following methodology:

$$N_2O_{\text{TOTAL}} = N_2O_{\text{PLANT}} + N_2O_{\text{EFFLUENT}}$$

$$N_2O_{\text{PLANT}} = N_2O_{\text{NIT/DENIT}} + N_2O_{\text{WOUT NIT/DENIT}} + N_2O_{\text{CW ONLY}} + N_2O_{\text{CW TERTIARY}}$$

$$N_2O_{\text{NIT/DENIT}} = [(US_{\text{POPND}}) \times EF_2 \times F_{\text{IND-COM}}] \times 1/10^9$$

$$N_2O_{\text{WOUT NIT/DENIT}} = \{[(US_{\text{POP}} \times \text{WWTP}) - US_{\text{POPND}} - US_{\text{POPCW}}] \times 10^6 \times F_{\text{IND-COM}} \times EF_1\} \times 1/10^9$$

$$N_2O_{\text{CW ONLY}} = \{[(US_{\text{POPCW}} \times 10^6 \times \text{Protein} \times F_{\text{NPR}} \times F_{\text{NON-CON}} \times F_{\text{IND-COM}}) \times EF_4] \times 44/28\} \times 1/10^6$$

$$N_2O_{\text{CW TERTIARY}} = \{[(N_{\text{CW,INF}} \times \text{POTW\_flow\_CW} \times 3.79 \times 365.25) \times EF_4] \times 44/28\} \times 1/10^6$$

$$N_2O_{\text{EFFLUENT}} = [(US_{\text{POP}} \times \text{WWTP} \times \text{Protein} \times F_{\text{NPR}} \times F_{\text{NON-CON}} \times F_{\text{IND-COM}}) - N_{\text{SLUDGE}} - (N_2O_{\text{PLANT}} \times 10^6 \times 28/44)] \times EF_3 \times 44/28 \times 1/10^6$$

where,

N_2O_{TOTAL} = Annual emissions of N_2O (kt)
N_2O_{PLANT} = N_2O emissions from centralized wastewater treatment plants (kt)
$N_2O_{\text{NIT/DENIT}}$ = N_2O emissions from centralized wastewater treatment plants with nitrification/denitrification (kt)
$N_2O_{\text{WOUT NIT/DENIT}}$ = N_2O emissions from centralized wastewater treatment plants without nitrification/denitrification (kt)
$N_2O_{\text{CW ONLY}}$ = N_2O emissions from centralized wastewater treatment plants with constructed wetlands only (kt)

$N_2O_{CW\ TERTIARY}$ = N_2O emissions from centralized wastewater treatment plants with constructed wetlands used as tertiary treatment (kt)
$N_2O_{EFFLUENT}$ = N_2O emissions from wastewater effluent discharged to aquatic environments (kt)
US_{POP} = U.S. population
US_{POPND} = U.S. population that is served by biological denitrification
US_{POPCW} = U.S. population that is served by only constructed wetland systems
WWTP = Fraction of population using WWTP (as opposed to septic systems)
POTW_flow_CW = Wastewater flow to POTWs that use constructed wetlands as tertiary treatment (MGD)
EF_1 = Emission factor – plants without intentional denitrification
EF_2 = Emission factor – plant with intentional nitrification or denitrification
Protein = Annual per capita protein consumption (kg/person/year)
$N_{CW,INF}$ = Influent nitrogen concentration to constructed wetlands used as tertiary treatment (mg/L)
F_{NPR} = Fraction of N in protein (kg N/kg protein)
$F_{NON\text{-}CON}$ = Factor for non-consumed protein added to wastewater
$F_{IND\text{-}COM}$ = Factor for industrial and commercial co-discharged protein into the sewer
N_{SLUDGE} = N removed with sludge, kg N/year
EF_3 = Emission factor (kg N_2O -N/kg sewage-N produced) – from effluent
EF_4 = Emission factor (kg N_2O -N/kg N produced) – constructed wetlands
3.79 = Conversion factor, liters to gallons
44/28 = Molecular weight ratio of N_2O to N_2
$1/10^6$ = Conversion factor, kg to Gg
$1/10^9$ = Conversion factor, g to Gg

U.S. population data were taken from the U.S. Census Bureau International Database (U.S. Census Bureau 2017) and include the populations of the United States, American Samoa, Guam, Northern Mariana Islands, Puerto Rico, and the U.S. Virgin Islands. The fraction of the U.S. population using wastewater treatment plants is based on data from the 1989, 1991, 1993, 1995, 1997, 1999, 2001, 2003, 2005, 2007, 2009, 2011, 2013, and 2015 *American Housing Survey* (U.S. Census Bureau 2015). Data for intervening years were obtained by linear interpolation and 2016 was forecasted using 1990 to 2015 data. The emission factor (EF_1) used to estimate emissions from wastewater treatment for plants without intentional nitrification or denitrification was taken from IPCC (2006), while the emission factor (EF_2) used to estimate emissions from wastewater treatment for plants with intentional nitrification or denitrification was taken from Scheehle and Doorn (2001). The emission factor (EF_4) used to estimate emissions from surface flow constructed wetlands (0.0013 kg N_2O -N/kg N produced) was taken from IPCC (2014). Data on annual per capita protein intake were provided by the U.S. Department of Agriculture Economic Research Service (USDA 2017b) and FAO (2017b). Protein consumption data was used directly from USDA for 1990 to 2010 and 2011 through 2013 was calculated using FAO data and a scaling factor. 2014 through 2016 were extrapolated from data for 1990 through 2013. An emission factor to estimate emissions from effluent (EF_3) has not been specifically estimated for the United States, thus the default IPCC value (0.005 kg N_2O-N/kg sewage-N produced) was applied (IPCC 2006). The fraction of N in protein (0.16 kg N/kg protein) was also obtained from IPCC (2006). The factor for non-consumed protein (1.2) and the factor for industrial and commercial co-discharged protein (1.25) were obtained from IPCC (2006). The amount of nitrogen removed by denitrification systems was taken from EPA (2008a), while the population served by denitrification systems was estimated from Clean Watersheds Needs Survey (EPA 1992, 1996, 2000, 2004, 2008b, and 2012). Sludge generation was obtained from EPA (1999) for 1988, 1996, and 1998 and from Beecher et al. (2007) for 2004. Intervening years were interpolated, and estimates for 2005 through 2016 were forecasted from the rest of the time series. The influent nitrogen concentration to constructed wetlands used as tertiary treatment (25 mg/L) was obtained from Metcalf & Eddy (2014). An estimate for the N removed as sludge (N_{SLUDGE}) was obtained by determining the amount of sludge disposed by incineration, by land application (agriculture or other), through surface disposal, in landfills, or through ocean dumping (EPA 1993b; Beecher et al. 2007; McFarland 2001; EPA 1999). In 2016, 295 kt N was removed with sludge. Table 7-15 presents the data for U.S. population, population served by biological denitrification, population served by wastewater treatment plants, available protein, protein consumed, and nitrogen removed with sludge.

Table 7-15: U.S. Population (Millions), Population Served by Biological Denitrification (Millions), Fraction of Population Served by Wastewater Treatment (percent), Available Protein (kg/person-year), Protein Consumed (kg/person-year), and Nitrogen Removed with Sludge (kt-N/year)

Year	Population	$Population_{ND}$	WWTP Population	Available Protein	Protein Consumed	N Removed with Sludge
1990	253	2.0	75.6	43.1	33.2	214.2
2005	300	7.1	78.8	44.9	34.7	261.1
2012	318	21.3	81.0	43.3	33.4	282.6
2013	320	19.8	81.4	43.3	33.4	285.6
2014	323	20.8	80.8	44.8	34.6	288.7
2015	325	21.8	80.2	44.8	34.5	291.8
2016	328	22.8	81.4	44.7	34.5	294.8

Sources: Population: U.S. Census Bureau (2017); $Population_{ND}$: EPA (1992), EPA (1996), EPA (2000), EPA (2004), EPA (2008b), EPA (2012); WWTP Population: U.S. Census Bureau (2015); Available Protein: USDA (2017b); N Removed with sludge: Beecher et al. (2007), McFarland (2001), EPA (1999), EPA (1993c).

Uncertainty and Time-Series Consistency

The overall uncertainty associated with both the 2016 CH_4 and N_2O emission estimates from wastewater treatment and discharge was calculated using the *2006 IPCC Guidelines* Approach 2 methodology (IPCC 2006). Uncertainty associated with the parameters used to estimate CH_4 emissions include that of numerous input variables used to model emissions from domestic wastewater, and wastewater from pulp and paper manufacturing, meat and poultry processing, fruits and vegetable processing, ethanol production, and petroleum refining. Uncertainty associated with the parameters used to estimate N_2O emissions include that of biosolids disposal, total U.S. population, average protein consumed per person, fraction of N in protein, non-consumption nitrogen factor, emission factors per capita and per mass of sewage-N, and for the percentage of total population using centralized wastewater treatment plants. Uncertainty associated with constructed wetlands parameters including U.S. population served by constructed wetlands, and emission and conversion factors are from IPCC (2014), whereas uncertainty associated with POTW flow to constructed wetlands and influent BOD and nitrogen concentrations were based on expert judgment.

The results of this Approach 2 quantitative uncertainty analysis are summarized in Table 7-16. Methane emissions from wastewater treatment were estimated to be between 11.0 and 18.0 MMT CO_2 Eq. at the 95 percent confidence level (or in 19 out of 20 Monte Carlo Stochastic Simulations). This indicates a range of approximately 26 percent below to 22 percent above the 2016 emissions estimate of 14.8 MMT CO_2 Eq. Nitrous oxide emissions from wastewater treatment were estimated to be between 1.3 and 10.5 MMT CO_2 Eq., which indicates a range of approximately 75 percent below to 112 percent above the 2016 emissions estimate of 5.0 MMT CO_2 Eq.

Table 7-16: Approach 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Wastewater Treatment (MMT CO_2 Eq. and Percent)

Source	Gas	2016 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Wastewater Treatment	**CH_4**	**14.8**	**11.0**	**18.0**	**-26%**	**+22%**
Domestic	CH_4	8.9	6.6	11.2	-26%	+26%
Industrial	CH_4	5.9	3.1	8.6	-48%	+45%
Wastewater Treatment	**N_2O**	**5.0**	**1.3**	**10.5**	**-75%**	**+112%**

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

QA/QC and Verification

General QA/QC procedures were applied to activity data, documentation, and emission calculations consistent with the U.S. QA/QC plan, which is in accordance with Vol. 1 Chapter 6 of *2006 IPCC Guidelines* (see Annex 8 for more details). This effort included a general or Tier 1 analysis, including the following checks:

- Checked for transcription errors in data input;
- Ensured references were specified for all activity data used in the calculations;
- Checked a sample of each emission calculation used for the source category;
- Checked that parameter and emission units were correctly recorded and that appropriate conversion factors were used;
- Checked for temporal consistency in time series input data for each portion of the source category;
- Confirmed that estimates were calculated and reported for all portions of the source category and for all years;
- Investigated data gaps that affected trends of emissions estimates; and
- Compared estimates to previous estimates to identify significant changes.

All transcription errors identified were corrected and documented. The QA/QC analysis did not reveal any systemic inaccuracies or incorrect input values.

Recalculations Discussion

Population data were updated to reflect revised U.S. Census Bureau datasets which resulted in changes to 2010 through 2015 values (U.S. Census Bureau 2017). In addition, the 2015 *American Housing Survey* became available which resulted in updated values for the percent of wastewater treatment collected versus treatment onsite for both 2014 and 2015 (U.S. Census Bureau 2015).

EPA evaluated pulp and paper wastewater generation rates in the *2016 American Forest & Paper Association Sustainability Report* based on the National Council of Air and Stream Improvement's (NCASI) recommendation, and determined updates to current Inventory data were appropriate. EPA updated values for 2004, 2006, 2008, 2010, 2012, and 2014 with data provided in the 2016 report. EPA also used the *2014 AF&PA Sustainability Report* to update the 1995, 2000, and 2002 values to more accurately reflect industry data. Data for intervening years were obtained by linear interpolation and the years 2015 and 2016 were forecasted from the rest of the time series. This change resulted in updated values for pulp and paper wastewater generation rates (m^3/ton) for 1995 through 2015.

Planned Improvements

EPA will continue to investigate the following improvements to the wastewater emissions estimates in the Inventory*:*

- Continue working with the NCASI to determine if there are sufficient data available to update the estimates of organic loading in pulp and paper wastewaters treated on-site;
- Investigate updated sources of activity data for wastewater treatment system type to distinguish between aerobic, anaerobic, and other systems with the potential to generate CH_4. This includes re-evaluating a methodology that was developed so that the 2008 and 2012 CWNS data could be used in estimating emissions from constructed wetlands to determine if it could be extended to all types of systems; and
- Continue reviewing other industrial wastewater treatment sources for those industries believed to discharge significant loads of BOD or COD, including dairy processing and brewery wastewater.

In addition, EPA will continue to monitor potential sources for updating Inventory data, including:

- WEF biosolid data as a potential source of digester, sludge, and biogas data from POTWs;
- Reports based on international research and other countries' inventory submissions to inform potential updates to the Inventory's emission factors, methodologies, or included industries;
- Research by groups such as the Water Environment Research Federation (WERF) on emissions from various types of municipal treatment systems, country-specific N_2O emission factors, and flare efficiencies;

- Data collected by WERF that indicate septic soil systems are a source of N_2O for the potential development of appropriate emission factors for septic system N_2O emissions;
- Sources of data for development of a country-specific methodology for N_2O emissions associated with on-site industrial wastewater treatment operations, including the appropriateness of using IPCC's default factor for domestic wastewater (0.005 kg N_2O-N/kg N);
- Sources of data for updating the factor for industrial and commercial co-discharged protein to determine if the IPCC factor currently used (1.25) is underestimating the contribution of industrial wastewater to N_2O emissions;
- Additional data sources for improving the uncertainty of the estimate of N entering municipal treatment systems; and
- Data to update the value used for N content of sludge, the amount of sludge produced, and sludge disposal practices, along with increasing the transparency of the fate of sludge produced in wastewater treatment.

A refinement of the *2006 IPCC Guidelines* is currently underway to incorporate abundant new scientific and empirical knowledge published since 2006 which the IPCC should take into account, particularly with respect to data for emission factor development. For wastewater treatment, this refinement includes a review of methane and nitrous oxide emission factors, and an assessment of adding methodologies to account for nitrous oxide emissions from both domestic and industrial wastewater. EPA will continue to monitor the status of this refinement for potential updates to the wastewater inventory methodology.

These planned improvements were described in greater detail in the previous Inventory report; please see Section 7.2 of the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2015*.

7.3 Composting (CRF Source Category 5B1)

Composting of organic waste, such as food waste, garden (yard) and park waste, and wastewater treatment sludge and/or biosolids, is common in the United States. Advantages of composting include reduced volume of the waste, stabilization of the waste, and destruction of pathogens in the waste. The end products of composting, depending on its quality, can be recycled as a fertilizer and soil amendment, or be disposed of in a landfill.

Composting is an aerobic process and a large fraction of the degradable organic carbon in the waste material is converted into carbon dioxide (CO_2). Methane (CH_4) is formed in anaerobic sections of the compost, which are created when there is excessive moisture or inadequate aeration (or mixing) of the compost pile. This CH_4 is then oxidized to a large extent in the aerobic sections of the compost. The estimated CH_4 released into the atmosphere ranges from less than 1 percent to a few percent of the initial C content in the material (IPCC 2006). Depending on how well the compost pile is managed, nitrous oxide (N_2O) emissions can be produced. The formation of N_2O depends on the initial nitrogen content of the material and is mostly due to nitrogen oxide (NO_x) denitrification during the later composting stages. Emissions vary and range from less than 0.5 percent to 5 percent of the initial nitrogen content of the material (IPCC 2006). Animal manures are typically expected to generate more N_2O than, for example, yard waste, however data are limited.

From 1990 to 2016, the amount of waste composted in the United States increased from 3,810 kt to 21,163 kt. There was some fluctuation in the amount of waste composted between 2006 to 2009. Since then, the annual quantity has increased and is now at an all-time high for the Inventory time series (see Table 7-19). A peak of 20,049 kt composted was observed in 2008, followed by a steep drop the following year to 18,824 kt composted, presumably driven by the economic crisis. Since then, the amount of waste composted has gradually increased, and when comparing 2010 to 2016, a 16 percent increase in waste composted is observed. Emissions of CH_4 and N_2O from composting from 2010 to 2015 have increased by the same percentage. In 2016, CH_4 emissions from composting (see Table 7-17 and Table 7-18) were 2.1 MMT CO_2 Eq. (85 kt), and N_2O emissions from composting were 1.9 MMT CO_2 Eq. (6 kt). The wastes composted primarily include yard trimmings (grass, leaves, and tree and brush trimmings) and food scraps from the residential and commercial sectors (such as grocery stores; restaurants; and school, business, and factory cafeterias). The composted waste quantities reported here do not include backyard composting or agricultural composting.

The growth in composting since the 1990s and specifically over the past decade is attributable primarily to the following factors: (1) the enactment of legislation by state and local governments that discouraged the disposal of yard trimmings in landfills, (2) yard trimming collection and yard trimming drop off sites provided by local solid waste management districts/divisions, (3) an increased awareness of the environmental benefits of composting, and (4) loans or grant programs to establish or expand composting infrastructure. Most bans or diversion laws on the disposal of yard trimmings were initiated in the early 1990s by state or local governments (U.S. Composting Council 2010). California, for example, enacted a waste diversion law for organics including yard trimmings and food scraps in 1999 (AB939) that required jurisdictions to divert 50 percent of the waste stream by 2000, or be subjected to fines. By 2010, 25 states, representing about 50 percent of the nation's population, had enacted such legislation (ILSR 2014; BioCycle 2010). There are many more initiatives at the metro and municipal level across the United States. More than 3,280 composting facilities exist in the United States with most (71 percent) composting yard trimmings only (ISLR 2014).

Table 7-17: CH_4 and N_2O Emissions from Composting (MMT CO_2 Eq.)

Activity	1990	2005	2012	2013	2014	2015	2016
CH_4	0.4	1.9	1.9	2.0	2.1	2.1	2.1
N_2O	0.3	1.7	1.7	1.8	1.9	1.9	1.9
Total	**0.7**	**3.5**	**3.7**	**3.9**	**4.0**	**4.0**	**4.0**

Table 7-18: CH_4 and N_2O Emissions from Composting (kt)

Activity	1990	2005	2012	2013	2014	2015	2016
CH_4	15.2	74.6	77.4	81.4	83.5	84.2	84.7
N_2O	1.1	5.6	5.8	6.1	6.3	6.3	6.3

Methodology

Methane and N_2O emissions from composting depend on factors such as the type of waste composted, the amount and type of supporting material (such as wood chips and peat) used, temperature, moisture content (e.g., wet and fluid versus dry and crumbly), and aeration during the composting process.

The emissions shown in Table 7-17 and Table 7-18 were estimated using the IPCC default (Tier 1) methodology (IPCC 2006), which is the product of an emission factor and the mass of organic waste composted (note: no CH_4 recovery is expected to occur at composting operations in the emission estimates presented):

$$E_i = M \times EF_i$$

where,

E_i = CH_4 or N_2O emissions from composting, kt CH_4 or N_2O,
M = mass of organic waste composted in kt,
EF_i = emission factor for composting, 4 t CH_4/kt of waste treated (wet basis) and 0.3 t N_2O/kt of waste treated (wet basis) (IPCC 2006), and
i = designates either CH_4 or N_2O.

Estimates of the quantity of waste composted (M) are presented in Table 7-19 for select years. Estimates of the quantity composted for 1990, 2005, 2010, and 2012 to 2014 were taken from EPA's *Advancing Sustainable Materials Management: Facts and Figures* 2014 (EPA 2016); the estimate of the quantity composted for 2011 was taken from EPA's *Municipal Solid Waste In The United States: 2012 Facts and Figures* (EPA 2014); estimates of the quantity composted for 2015 and 2016 were extrapolated using the 2014 quantity composted and a ratio of the U.S. population growth between 2014 and 2015, and 2015 to 2016 (U.S. Census Bureau 2016 and 2017).

Table 7-19: U.S. Waste Composted (kt)

Activity	1990	2005	2012	2013	2014	2015	2016
Waste Composted	3,810	18,643	19,351	20,358	20,884	21,052	21,163

Uncertainty and Time-Series Consistency

The estimated uncertainty from the *2006 IPCC Guidelines* is ±50 percent for the Approach 1 methodology. Emissions from composting in 2015 were estimated to be between 2.0 and 6.0 MMT CO_2 Eq., which indicates a range of 50 percent below to 50 percent above the actual 2016 emission estimate of 4.0 MMT CO_2 Eq. (see Table 7-20).

Table 7-20: Approach 1 Quantitative Uncertainty Estimates for Emissions from Composting (MMT CO_2 Eq. and Percent)

Source	Gas	2016 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate (MMT CO_2 Eq.)		Uncertainty Range Relative to Emission Estimate (%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Composting	CH_4, N_2O	4.0	2.0	6.0	-50%	+50%

QA/QC and Verification

General QA/QC procedures were applied to data gathering and input, documentation, and calculations consistent with the U.S. QA/QC plan, which is in accordance with Vol. 1 Chapter 6 of *2006 IPCC Guidelines* (see Annex 8 for more details).

Recalculations Discussion

No recalculations were made in this Inventory year. The composting estimates will be updated pending the release of a new EPA *Advancing Sustainable Materials Management: Facts and Figures* report.

Planned Improvements

For future Inventories, additional efforts will be made to improve the estimates of CH_4 and N_2O emissions from composting. For example, a literature search on emission factors and composting systems and management techniques has been completed and will be documented in a technical memorandum for the 1990 through 2017 Inventory. The purpose of this literature review was to compile all published emission factors specific to various composting systems and composted materials. This information will be used to determine whether the emission factors used in the current methodology should be revised, or expanded to account for geographical differences and/or differences in composting systems used. For example, outdoor composting processes in arid regions typically require the addition of moisture compared to similar composting processes in wetter climates. Additionally, composting systems that primarily compost food waste may generate CH_4 at different rates than those that compost yard trimmings because the food waste may have a higher moisture content and more readily degradable material. Further cooperation with estimating emissions in cooperation with the LULUCF Settlements section will also be investigated.

7.4 Waste Incineration (CRF Source Category 5C1)

As stated earlier in this chapter, carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) emissions from the incineration of waste are accounted for in the Energy sector rather than in the Waste sector because almost all incineration of municipal solid waste (MSW) in the United States occurs at waste-to-energy facilities where useful energy is recovered. Similarly, the Energy sector also includes an estimate of emissions from burning waste tires and hazardous industrial waste, because virtually all of the combustion occurs in industrial and utility boilers that recover energy. The incineration of waste in the United States in 2016 resulted in 11.0 MMT CO_2 Eq., over half of which (5.9 MMT CO_2 Eq.) is attributable to the combustion of plastics. For more details on emissions from the incineration of waste, see Section 3.3 of the Energy chapter.

Additional sources of emissions from waste incineration include non-hazardous industrial waste incineration and medical waste incineration. As described in Annex 5 of this report, data are not readily available for these sources and emission estimates are not provided. An analysis of the likely level of emissions was conducted based on a 2009 study of hospital/ medical/ infectious waste incinerator (HMIWI) facilities in the United States (RTI 2009). Based on that study's information of waste throughput and an analysis of the fossil-based composition of the waste, it was determined that annual greenhouse gas emissions for medical waste incineration would be below 500 kt CO_2 Eq. per year and considered insignificant for the purposes of Inventory reporting under the UNFCCC. More information on this analysis is provided in Annex 5.

7.5 Waste Sources of Indirect Greenhouse Gases

In addition to the main greenhouse gases addressed above, waste generating and handling processes are also sources of indirect greenhouse gas emissions. Total emissions of nitrogen oxides (NO_x), carbon monoxide (CO), and non-CH_4 volatile organic compounds (NMVOCs) from waste sources for the years 1990 through 2016 are provided in Table 7-21.

Table 7-21: Emissions of NO_x, CO, and NMVOC from Waste (kt)

Gas/Source	1990		2005		2012	2013	2014	2015	2016
NO_x	**+**		**2**		**2**	**2**	**2**	**2**	**2**
Landfills	+		2		2	2	2	2	2
Wastewater Treatment	+		0		0	0	0	0	0
Miscellaneous[a]	+		0		0	0	0	0	0
CO	**1**		**7**		**6**	**8**	**9**	**9**	**9**
Landfills	1		6		6	7	8	8	8
Wastewater Treatment	+		+		+	1	1	1	1
Miscellaneous[a]	+		0		0	0	0	0	0
NMVOCs	**673**		**114**		**45**	**51**	**57**	**57**	**57**
Wastewater Treatment	57		49		19	22	25	25	25
Miscellaneous[a]	557		43		17	19	22	22	22
Landfills	58		22		8	10	11	11	11

+ Does not exceed 0.5 kt.

[a] Miscellaneous includes TSDFs (Treatment, Storage, and Disposal Facilities under the Resource Conservation and Recovery Act [42 U.S.C. § 6924, SWDA § 3004]) and other waste categories.

Note: Totals may not sum due to independent rounding.

Methodology

Emission estimates for 1990 through 2016 were obtained from data published on the National Emission Inventory (NEI) Air Pollutant Emission Trends web site (EPA 2016), and disaggregated based on EPA (2003). Emission estimates for 2012 and 2013 for non-electric generating units (EGU) were updated to the most recent available data in EPA (2016). Emission estimates for 2012 and 2013 for non-mobile sources are recalculated emissions by interpolation from 2016 in EPA (2016). Emission estimates of these gases were provided by sector, using a "top down" estimating procedure—emissions were calculated either for individual sources or for many sources combined, using basic activity data (e.g., the amount of raw material processed) as an indicator of emissions.

National activity data were collected for individual categories from various agencies. Depending on the category, these basic activity data may include data on production, fuel deliveries, raw material processed, etc.

Uncertainty and Time-Series Consistency

No quantitative estimates of uncertainty were calculated for this source category. Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2016. Details on the emission trends through time are described in more detail in the Methodology section, above.

8. Other

The United States does not report any greenhouse gas emissions under the Intergovernmental Panel on Climate Change (IPCC) “Other” sector.

9. Recalculations and Improvements

Each year, many emission and sink estimates in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks* are recalculated and revised, as efforts are made to improve the estimates through the use of better methods and/or data with the goal of improving inventory quality, including the transparency, completeness, consistency and overall usefulness of the report. In this effort, the United States follows the *2006 IPCC Guidelines* (IPCC 2006), which states, "Both methodological changes and refinements over time are an essential part of improving inventory quality. It is *good practice* to change or refine methods when available data have changed; the previously used method is not consistent with the IPCC guidelines for that category; a category has become key; the previously used method is insufficient to reflect mitigation activities in a transparent manner; the capacity for inventory preparation has increased; improved inventory methods become available; and/or for correction of errors."

The results of all methodological changes and historical data updates made in the current Inventory are presented in Table 9-1 and Table 9-2. To understand the details of any specific recalculation or methodological improvement, see the *Recalculations Discussion* within each source/sink categories' section found in Chapters 3 through 7 of this report and a discussion of Inventory improvements in Annex 8. Table 9-1 summarizes the quantitative effect of all changes on U.S. greenhouse gas emissions in the Energy, IPPU, Agriculture, and Waste sectors, while Table 9-2 summarizes the quantitative effect of changes on annual net fluxes from LULUCF. Both tables present results relative to the previously published Inventory (i.e., the 1990 to 2015 report) in units of million metric tons of carbon dioxide equivalent (MMT CO_2 Eq.).

In general, when methodological changes have been implemented, the previous Inventory's time series (i.e., 1990 to 2015) will be recalculated to reflect the change, per guidance in IPCC (2006). Changes in historical data are generally the result of changes in statistical data supplied by other agencies, and do not necessarily impact the entire time series.

The following source and sink categories underwent the most significant methodological and historical data changes. A brief summary of the recalculations and/or improvements undertaken are provided for these categories.

- *Petroleum Systems (CH_4).* Updates were made to exploration and production segment methodologies for the Inventory, including revising activity and CH_4 emissions data for associated gas venting and flaring, miscellaneous production flaring, and well testing. The combined impact of revisions to 2015 petroleum systems CH_4 emissions, compared to the previous Inventory, is a decrease from 39.9 to 38.1 MMT CO_2 Eq. (1.8 MMT CO_2 Eq., or 4.5 percent). The CH_4 emissions estimate decrease was primarily due to recalculations related to associated gas venting and flaring which were updated to use a basin-level approach, and has the largest impact on years prior to 2013. The recalculations resulted in an average annual decrease in CH_4 emissions of 13.4 MMT CO_2 Eq. (28 percent), across the 1990 through 2015 time series, relative to the previous Inventory.
- *Natural Gas Systems (CO_2).* Updates were made to exploration through transmission and storage segments, including to calculate activity and emission factors for well testing and non-hydraulically fractured completions from EPA's GHGRP data, recalculate production segment major equipment activity factors using updated GHGRP data, and calculate new CO_2 emission factors for several sources throughout segments using GHGRP data. The combined impact of revisions to 2015 natural gas sector CO_2 emissions, compared to the previous Inventory, is a decrease from 42.4 to 24.9 MMT CO_2 (17.5 MMT CO_2, or 41 percent). The decreased estimate results primarily from recalculations related to the reallocation of CO_2 from flaring to petroleum systems from natural gas systems. Previously, data were not available to

disaggregate flared emissions between natural gas and petroleum. The recalculations resulted in an average annual decrease in CO_2 emissions of 10.5 MMT CO_2 Eq. (29.5) percent relative to the previous Inventory.

- *Petroleum Systems (CO_2).* Updates were made to exploration and production segment methodologies for the Inventory, including revising activity and CO_2 emissions data for associated gas venting and flaring, miscellaneous production flaring, and well testing. Production segment CO_2 emissions data were also revised for oil tanks, pneumatic controllers, and chemical injection pumps. The combined impact of revisions to 2015 petroleum systems CO_2 emissions, compared to the previous Inventory, is an increase from 3.6 to 28.8 MMT CO_2 (25.2 MMT CO_2, or by a factor of 7). The CO_2 emissions estimate increase was primarily due to recalculations related to the reallocation of CO_2 from flaring to petroleum systems from natural gas systems. Previously, data were not available to disaggregate flared emissions between natural gas systems and petroleum systems. The largest sources of CO_2 from flaring are associated gas flaring, tanks with flares, and miscellaneous production flaring. The recalculations resulted in an average annual increase in CO_2 emissions of 9.1 MMT CO_2 Eq. (240 percent) relative to the previous Inventory.
- *Mobile Combustion (CH_4).* Updates were made to the on-road, non-road and alternative fuel CH_4 emissions calculations for the current Inventory, resulting in both increases and decreases to different source categories. Decreases in on-road gasoline CH_4 emissions were offset by large increases in alternative fuel and non-road CH_4 emissions. New onroad CH_4 emission factors were calculated based on the ratio of non-methane organic gas (NMOG) emission standards for newer vehicles. In addition, new non-road emission factors were developed from the updated 2006 IPCC Tier 3 guidance and EPA's MOVES2014a model. New emission factors for alternative fuel vehicles were estimated using the newest version of GREET (2016). In addition, changes were made to the historic allocation of gasoline to on-road and non-road applications. These changes collectively resulted in an average annual increase in CH_4 emissions of 5.8 MMT CO_2 Eq. (166.8 percent) relative to the previous Inventory.
- *Natural Gas Systems (CH_4)* Updates were made to exploration through transmission and storage segments, including to calculate activity and emission factors for well testing and non-hydraulically fractured completions from EPA's GHGRP data, recalculate production segment major equipment activity factors using updated GHGRP data, and calculate new CO_2 emission factors for several sources throughout segments using GHGRP data. The combined impact of revisions to 2015 natural gas sector CH_4 emissions, compared to the previous Inventory, is an increase from 162.4 to 166.3 MMT CO_2 Eq. (3.9 MMT CO_2 Eq., or 2.4 percent). These changes resulted in an average annual increase in CH_4 emissions of 5.1 MMT CO_2 Eq. (3.1 percent) relative to the previous Inventory.
- *Information Item: Wood Biomass, Ethanol, and Biodiesel Consumption (CO_2).* EIA updated wood biomass and biofuels consumption statistics across the time series relative to the previous Inventory (EIA 2018a). EIA revised 2010 through 2015 wood energy consumption in the industrial sector, and 2014 through 2015 wood energy consumption in the residential and commercial sectors. Additionally, EIA revised sector allocations of ethanol in 2015, resulting in a shift of ethanol consumption from the industrial and commercial sectors to the transportation sector. These revisions to wood energy consumption resulted in an average annual increase in CO_2 emissions of 3.4 MMT CO_2 Eq. (1.2 percent) relative to the previous Inventory. Note, as indicated in Table 9-1, these emissions are not included in totals. CO_2 emissions from wood biomass and biofuel consumption are not included specifically in summing energy sector totals and are instead included in net carbon fluxes from changes in biogenic carbon reservoirs in the estimates for Land Use, Land-Use Change, and Forestry.
- *Mobile Combustion (N_2O).* Updates were made to the on-road, non-road and alternative fuel N_2O emissions calculations for the current Inventory resulting in both increases and decreases to different source categories. Decreases in on-road gasoline N_2O emissions were offset by large increases in alternative fuel and non-road N_2O emissions. New emission factors for N_2O emissions were developed for on-road vehicles based on an EPA regression analysis of the relationship between NO_x and N_2O. In addition, new non-road emissions factors were developed from the updated 2006 IPCC Tier 3 guidance and EPA's MOVES2014a model. N_2O emission factors were calculated using NONROAD activity and emission factors by fuel type from the European Environment Agency. New emission factors for alternative fuel vehicles were estimated using the newest version of GREET (2016). In addition, changes were made to the historic allocation of gasoline to on-road and non-road applications. These changes resulted in an average annual increase in N_2O emissions of 2.5 MMT CO_2 Eq. (9.2 percent) relative to the previous Inventory.

- *Fossil Fuel Combustion-Transportation (CO_2)*. Changes were made to the historic allocation of gasoline to on-road and non-road applications. In 2016, the Federal Highway Administration (FHWA) changed its methods for estimating the share of gasoline used in on-road and non-road applications. Among other updates, FHWA included lawn and garden equipment as well as off-road recreational equipment in its estimates of non-road gasoline consumption for the first time. This change created a time-series inconsistency between the data reported for years 2015 and 2016 and previous years. To create a more consistent time series of motor gasoline consumption and emissions data for the current Inventory, the historical time series was modified. Specifically, the lawn, garden, and recreational vehicle gasoline consumption from EPA's NONROAD model is subtracted from the highway motor gasoline consumption from FHWA Table MF-21 when determining the total highway motor gasoline consumption for years 1990 through 2014. This resulted in a decrease of gasoline use and emissions in the transportation sector and an increase in the commercial and industrial sectors. These changes resulted in an average annual shift in CO_2 emissions of 27.3 MMT CO_2 Eq. (1.6 percent) relative to the previous Inventory.

Finally, in addition to the more significant methodological updates noted above, the Inventory includes new categories not included in the previous Inventory that improve completeness of the national estimates. Specifically, the inclusion of CO_2 and CH_4 emissions from Abandoned Oil and Gas Wells and N_2O emissions from Caprolactam Production, etc.

Table 9-1: Revisions to U.S. Greenhouse Gas Emissions (MMT CO_2 Eq.)

Gas/Source	1990	2005	2012	2013	2014	2015	Average Annual Change
CO_2	**(1.8)**	**0.2**	**4.6**	**5.6**	**3.3**	**9.4**	**(1.2)**
Fossil Fuel Combustion	+	+	(0.3)	0.4	(2.0)	(0.5)	(0.1)
Electric Power Sector	*NC*	*NC*	*NC*	*NC*	*NC*	*+*	*+*
Transportation	*(26.2)*	*(31.3)*	*(34.9)*	*(35.4)*	*(25.7)*	*(0.9)*	*(27.3)*
Industrial	*16.4*	*27.7*	*30.0*	*31.0*	*18.9*	*4.0*	*22.9*
Residential	*NC*	*NC*	*+*	*0.1*	*(0.1)*	*(2.8)*	*(0.1)*
Commercial	*9.8*	*3.6*	*4.6*	*4.7*	*4.9*	*(0.8)*	*4.4*
U.S. Territories	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*
Non-Energy Use of Fuels	2.0	+	1.2	(0.2)	(0.1)	0.1	0.2
Natural Gas Systems	(7.9)	(7.6)	(11.9)	(13.6)	(17.0)	(17.5)	(10.5)
Cement Production	NC	NC	NC	NC	NC	NC	NC
Lime Production	NC	NC	NC	NC	NC	NC	NC
Other Process Uses of Carbonates	1.4	1.3	1.1	1.1	1.1	1.1	1.3
Glass Production	NC	NC	NC	NC	NC	NC	NC
Soda Ash Production	(1.4)	(1.3)	(1.1)	(1.1)	(1.1)	(1.1)	(1.3)
Carbon Dioxide Consumption	NC	NC	NC	NC	NC	0.2	+
Incineration of Waste	NC	NC	+	+	+	+	+
Titanium Dioxide Production	NC	NC	NC	NC	NC	NC	NC
Aluminum Production	NC	NC	NC	NC	NC	NC	NC
Iron and Steel Production & Metallurgical Coke Production	0.1	0.2	0.2	0.1	(0.3)	(1.1)	0.1
Ferroalloy Production	NC	NC	NC	NC	NC	NC	NC
Ammonia Production	NC	NC	NC	NC	NC	0.1	+
Urea Consumption for Non-Agricultural Purposes	NC	NC	+	0.1	0.2	3.0	0.1
Phosphoric Acid Production	NC	NC	NC	NC	NC	NC	NC
Petrochemical Production	(0.1)	(0.2)	NC	NC	NC	NC	(0.1)
Silicon Carbide Production and Consumption	NC	NC	NC	NC	NC	NC	NC
Lead Production	NC	NC	NC	NC	NC	NC	NC
Zinc Production	NC	NC	NC	NC	NC	+	+
Petroleum Systems	4.1	7.8	15.4	18.9	22.8	25.2	9.1
Abandoned Oil and Gas Wells	NC*	NC*	NC*	NC*	NC*	NC*	NC*
Magnesium Production and Processing	NC	NC	NC	NC	NC	NC	NC
Liming	NC	NC	NC	NC	NC	+	+
Urea Fertilization	NC	NC	+	(0.1)	(0.2)	(0.1)	+
International Bunker Fuels[b]	*NC*	*NC*	*NC*	*NC*	*0.2*	*0.1*	*+*
Wood Biomass, Ethanol, and Biodiesel Consumption[a]	*NC*	*NC*	*11.5*	*16.6*	*17.2*	*18.7*	*3.4*

CH_4	**(0.9)**	**7.7**	**(3.6)**	**3.8**	**4.8**	**9.7**	**3.6**
Stationary Combustion	0.1	0.4	0.8	0.8	0.8	0.9	0.4
Mobile Combustion	7.1	6.5	2.9	2.6	2.2	1.8	5.8
Coal Mining	NC	NC	NC	NC	(0.3)	0.3	+
Abandoned Underground Coal Mines	NC	NC	NC	NC	NC	NC	NC
Natural Gas Systems	1.1	9.4	3.4	4.6	1.8	3.9	5.1
Petroleum Systems	(15.7)	(13.9)	(13.8)	(7.9)	(4.5)	(1.8)	(13.4)
Abandoned Oil and Gas Wells	NC*	NC*	NC*	NC*	NC*	NC*	NC*
Petrochemical Production	NC	NC	NC	NC	NC	NC	NC
Silicon Carbide Production and Consumption	NC	NC	NC	NC	NC	NC	NC
Iron and Steel Production & Metallurgical Coke Production	NC	NC	NC	NC	NC	NC	NC
Ferroalloy Production	NC	NC	NC	NC	NC	NC	NC
Enteric Fermentation	NC	NC	NC	NC	NC	NC	NC
Manure Management	NC	NC	NC	NC	+	NC	+
Rice Cultivation	NC	NC	NC	0.2	1.4	1.1	0.1
Field Burning of Agricultural Residues	NC	NC	NC	NC	NC	NC	NC
Landfills	NC	(1.6)	(3.8)	(3.5)	(3.8)	(4.0)	(1.2)
Wastewater Treatment	+	(0.2)	+	+	0.2	0.3	(0.1)
Composting	NC	NC	NC	NC	NC	NC	NC
Incineration of Waste	NC	NC	NC	NC	NC	NC	NC
International Bunker Fuels[b]	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*
N_2O	**(4.8)**	**(3.9)**	**(5.0)**	**27.7**	**25.7**	**44.8**	**0.1**
Stationary Combustion	(0.8)	(2.8)	(4.5)	(4.2)	(4.3)	(5.0)	(2.3)
Mobile Combustion	0.5	3.1	3.9	4.0	4.0	4.2	2.5
Adipic Acid Production	NC	NC	NC	NC	NC	+	+
Nitric Acid Production	NC	NC	+	NC	NC	+	+
Manure Management	NC	NC	NC	NC	NC	NC	NC
Agricultural Soil Management	(6.1)	(6.3)	(6.2)	26.1	24.0	43.7	(2.0)
Field Burning of Agricultural Residues	NC	NC	NC	NC	NC	NC	NC
Wastewater Treatment	NC	NC	(0.2)	(0.2)	(0.1)	(0.1)	+
N_2O from Product Uses	NC	NC	NC	NC	NC	NC	NC
Caprolactam, Glyoxal, and Glyoxylic Acid Production	NC*	NC*	NC*	NC*	NC*	NC*	NC*
Incineration of Waste	NC	NC	NC	NC	NC	NC	NC
Composting	NC	NC	NC	NC	NC	NC	NC
Semiconductor Manufacture	NC	NC	+	+	+	+	+
International Bunker Fuels[b]	NC	NC	NC	NC	+	+	+
HFCs	**NC**	**3.0**	**(5.4)**	**(7.9)**	**(10.0)**	**(12.4)**	**(0.5)**
Substitution of Ozone Depleting Substances[d]	NC	3.0	(5.4)	(7.9)	(10.0)	(12.4)	(0.5)
HCFC-22 Production	NC	NC	NC	NC	NC	NC	NC
Semiconductor Manufacture	NC	+	+	+	+	+	+
Magnesium Production and Processing	NC	NC	NC	NC	NC	NC	NC
PFCs	**NC**	**0.1**	**(0.1)**	**+**	**(0.1)**	**(0.1)**	**+**
Aluminum Production	NC	NC	NC	NC	NC	NC	NC
Semiconductor Manufacture	NC	0.1	(0.1)	+	(0.1)	(0.1)	+
Substitution of Ozone Depleting Substances[d]	NC	NC	NC	NC	NC	NC	NC
SF_6	**+**	**0.1**	**(0.2)**	**(0.1)**	**(0.2)**	**0.1**	**+**
Electrical Transmission and Distribution	+	0.1	(0.1)	(0.1)	(0.2)	0.1	+
Semiconductor Manufacture	NC	+	+	+	+	+	+
Magnesium Production and Processing	NC	NC	NC	NC	+	+	+
NF_3	**NC**	**+**	**+**	**+**	**+**	**+**	**+**
Semiconductor Manufacture	NC	+	+	+	+	+	+
Net Emissions (Sources and Sinks)	(7.4)	7.0	(9.5)	29.1	23.5	51.5	
Percent Change	-0.1%	0.1%	-0.1%	0.4%	0.3%	0.8%	

Note: Net change in total emissions presented without LULUCF.

NC (No Change)

+ Absolute value does not exceed 0.05 MMT CO_2 Eq. or 0.05 percent.

* Indicates a new source for the current Inventory year.

[a] Not included in emissions total.

[b] Sinks are only included in net emissions total.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values.

Table 9-2: Revisions to U.S. Greenhouse Gas Emissions and Removals (Net Flux) from Land Use, Land-Use Change, and Forestry (MMT CO_2 Eq.)

Land Use Category	1990	2005	2012	2013	2014	2015	Average Annual Change
Forest Land Remaining Forest Land	**+**	**+**	**+**	**+**	**(0.1)**	**18.6**	**0.7**
Changes in Forest Carbon Stocks[a]	+	0.1	+	+	+	+	+
Non-CO_2 Emissions from Forest Fires	+	+	+	+	(0.1)	18.6	0.7
N_2O Emissions from Forest Soils[b]	NC	NC	NC	NC	NC	NC	NC
Non-CO_2 Emissions from Drained Organic Soils	+	+	+	+	+	+	+
Land Converted to Forest Land	**NC**	**(0.2)**	**0.3**	**0.3**	**0.2**	**0.2**	**+**
Changes in Forest Carbon Stocks[c]	NC	(0.2)	0.3	0.3	0.2	0.2	+
Cropland Remaining Cropland	**NC**	**NC**	**NC**	**8.2**	**6.7**	**11.7**	**1.0**
Changes in Mineral and Organic Soil Carbon Stocks	NC	NC	NC	8.2	6.7	11.7	1.0
Land Converted to Cropland	**NC**	**NC**	**NC**	**0.6**	**0.5**	**0.4**	**0.1**
Changes in all Ecosystem Carbon Stocks[d]	NC	NC	NC	0.6	0.5	0.4	0.1
Grassland Remaining Grassland	NC	NC	NC	16.7	12.8	30.3	2.3
Changes in Mineral and Organic Soil Carbon Stocks	NC	NC	NC	16.7	12.8	30.5	2.3
Non-CO_2 Emissions from Grassland Fires	NC	NC	NC	NC	NC	(0.2)	+
Land Converted to Grassland	**NC**	**NC**	**NC**	**1.4**	**1.0**	**2.9**	**0.2**
Changes in all Ecosystem Carbon Stocks[d]	NC	NC	NC	1.4	1.0	2.9	0.2
Wetlands Remaining Wetlands	**NC**	**NC**	**NC**	**NC**	**NC**	**NC**	**NC**
Changes in Organic Soil Carbon Stocks in Peatlands	NC*	NC*	NC*	NC*	NC*	NC*	NC*
Changes in Mineral and Organic Soil Carbon Stocks in Coastal Wetlands	(1.1)	(1.1)	(0.8)	(0.8)	(0.8)	(0.8)	(1.0)
CH_4 Emissions from Coastal Wetlands Remaining Coastal Wetlands	NC	NC	NC	NC	NC	NC	NC
N_2O Emissions from Coastal Wetlands Remaining Coastal Wetlands	NC	NC	NC	NC	NC	NC	NC
Non-CO_2 Emissions from Peatlands Remaining Peatlands	NC	NC	NC	NC	NC	NC	NC
Land Converted to Wetlands	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Changes in Mineral and Organic Soil Carbon Stocks[e]	+	+	+	+	+	+	+
CH_4 Emissions from Land Converted to Coastal Wetlands	NC	NC	NC	NC	NC	NC	NC
Settlements Remaining Settlements	**NC**	**NC**	**NC**	**0.1**	**0.1**	**+**	**+**
Changes in Organic Soil Carbon Stocks	NC	NC	NC	+	+	+	+
Changes in Urban Tree Carbon Stocks	NC	NC	NC	NC	NC	NC	NC
Changes in Yard Trimming and Food Scrap Carbon Stocks in Landfills	NC	NC	NC	NC	NC	NC	NC
N_2O Emissions from Settlement Soils[f]	NC	NC	NC	+	0.1	+	+
Land Converted to Settlements	**NC**	**NC**	**NC**	**0.1**	**(0.1)**	**(0.2)**	**+**
Changes in all Ecosystem Carbon Stocks[d]	NC	NC	NC	0.1	(0.1)	(0.2)	+
LULUCF Emissions[g]	**+**	**+**	**+**	**+**	**(0.1)**	**18.4**	
LULUCF Total Net Flux[h]	**+**	**(0.2)**	**0.3**	**27.2**	**21.1**	**45.3**	
LULUCF Sector Total[i]	**+**	**(0.2)**	**0.3**	**27.2**	**21.0**	**63.7**	
Percent Change	**0.0%**	**0.0%**	**0.0%**	**3.6%**	**2.8%**	**8.4%**	

NC (No Change)

+ Absolute value does not exceed 0.05 MMT CO_2 Eq. or 0.05 percent.

* Indicates a new source for the current Inventory year.

[a] Includes the net changes to carbon stocks stored in all forest ecosystem pools (including drained and undrained organic soils) and harvested wood products.

[b] Estimates include emissions from N fertilizer additions on both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.

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[c] Includes the net changes to carbon stocks stored in all forest ecosystem pools (excludes drained organic soils which are included in the flux from *Forest Land Remaining Forest Land* because it is not possible to separate the activity data at this time).

[d] Includes changes in mineral and organic soil carbon stocks for all land use conversions to cropland, grassland, and settlements, respectively. Also includes aboveground/belowground biomass, dead wood, and litter carbon stock changes for conversion of forest land to cropland, grassland, and settlements, respectively.

[e] Includes carbon stock changes for land converted to vegetated coastal wetlands.

[f] Estimates include emissions from N fertilizer additions on both *Settlements Remaining Settlements* and *Land Converted to Settlements*.

[g] LULUCF emissions include the CH_4 and N_2O emissions reported for *Peatlands Remaining Peatlands*, Forest Fires, Drained Organic Soils, Grassland Fires, and *Coastal Wetlands Remaining Coastal Wetlands*; CH_4 emissions from *Land Converted to Coastal Wetlands*; and N_2O emissions from Forest Soils and Settlement Soils.

[h] LULUCF Carbon Stock Change includes any C stock gains and losses from all land use and land use conversion categories.

[i] The LULUCF Sector Net Total is the net sum of all CH_4 and N_2O emissions to the atmosphere plus net carbon stock changes.

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

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