Carbon Sequestration in Colorado's Lands: An Integrated Spatial & Policy Analysis

Masters of the Environment
UNIVERSITY OF COLORADO **BOULDER**

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This report was prepared by the University of Colorado Boulder Masters of the Environment Program for the Colorado Chapter of The Nature Conservancy. The authors' recommendations are intended to inform TNC Colorado's current and future engagement on climate change.

Cover Photo

Dusk at Fox Ranch in Northeastern Colorado © *John Fielder*

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List of Acronyms

ACEP	Agricultural Conservation Easement Program
BLM	Bureau of Land Management
CBA	Cost Benefit Analysis
CDPHE	Colorado Department of Public Health and Environment
CNHP	Colorado Natural Heritage Program
CO_2	Carbon dioxide
CO_2eq	Carbon dioxide equivalent
CO DNR	Colorado Department of Natural Resources
COMaP	Colorado Ownership, Management and Protection Dataset
CREP	Conservation Reserve Easement Program
CRP	Conservation Reserve Program
CSP	Conservation Stewardship Program
CSU	Colorado State University
EPA	Environmental Protection Agency
EQIP	Environmental Quality Incentives Program
EVT	Existing Vegetation Type
GHG	Greenhouse gas
GIS	Geographic Information System
Ha	Hectare
INDC	Intended Nationally Determined Contribution
IQR	Interquartile range
LANDFIRE	Landscape Fire and Resource Management Planning Tools dataset
LCT	Land cover type
MAST	Mitigation Action Summary Table
MMT	Million metric tons
MT	Metric tons
MTBS	Monitoring Trends in Burn Severity dataset
NLCD	National Land Cover Dataset
NRCS	Natural Resource Conservation Service
NREL	Natural Resource Ecology Laboratory
PRISM	Parameter-elevation Regressions on Independent Slopes Model
TNC	The Nature Conservancy
USFS	United States Forest Service
USGS	United States Geological Service
WWA	Western Water Assessment

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Executive Summary

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It is clear that global climate change will continue to have major human and environmental impacts. Reducing greenhouse gas emissions is necessary to slow or mitigate the most catastrophic of these impacts. Lands around the world play a vital role in slowing the effects of climate change by storing and sequestering atmospheric carbon dioxide (CO_2). As federally-led efforts to curb climate change have been ineffective to date, sub-national efforts are becoming increasingly important. This report quantifies the carbon stored in Colorado's lands at the state level and examines policy opportunities to increase the amount of carbon stored through improved land management. We found that Colorado's lands currently hold **3,334 MMT CO_2eq**, compared to the US total of 48,382 MMT CO_2eq.[1] In addition, Colorado's lands can be managed to make a significant contribution toward Governor Hickenlooper's state climate goal of reducing statewide greenhouse gas emissions by more than 26% by the year 2025, compared to 2005 levels (or a cumulative decrease of roughly 39 MMT CO_2eq greenhouse gas emissions from the current level of 130 MMT CO_2eq).

[1] MMT CO_2eq refers to million metric tons of carbon dioxide equivalent

Key Findings

Carbon in Colorado's Lands

Over the next 40 years, statewide carbon stocks are expected to decline as Colorado's lands change. More frequent and intense forest fires are a major driver of this change, which are typically characterized by a dramatic loss in forest carbon. Another driver is increased urbanization, and in turn developed land, as Colorado's population continues to boom. These trends point to land management practices as important pathways to maintaining and increasing the ability of Colorado's lands to store carbon.

- Forests and woodlands together hold 68% of the carbon stored in Colorado's lands. Total reforestation of all existing major burn scars in the state would increase the amount of carbon stored in forests up to **160 MMT CO_2eq**. This represents **more than four times** the state's cumulative emissions reductions goal of 39 MMT CO_2eq by 2025. Whether or not this ceiling is fully achievable, it is clear that reforestation can have a meaningful impact on carbon stocks in Colorado.

- Avoiding all projected conversion of wetlands and grasslands in Colorado through 2051 would increase the carbon stored in those lands by **68 MMT CO_2eq**. By 2025, this avoided conversion could contribute to **31% of Colorado's climate goals**.

- While avoiding conversion of forests can be more impactful than avoiding conversion of wetlands or grasslands in a carbon context, much of the anticipated forest conversion through 2051 will be due to natural drivers like forest fires. The net carbon impact of preventative fire mitigation is still being debated in academic circles.

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Carbon Policy Recommendations for Colorado

To combat global climate change, policies should be put in place to incentivize practices that have been demonstrated to improve carbon storage, such as those detailed above. We recommend the immediate pursuit of the following four carbon policies and practices within the state of Colorado. They have been selected from a larger list of potential policies based upon their political feasibility and relative impact on carbon sequestration.

- **Carbon Task Force**: We recommend convening a government task force to study the role that land management can play in meeting the climate targets established by the Governor's recent Executive Order. This task force could be created through legislative or executive authority and should have the power to make formal recommendations to the Colorado General Assembly, as well as to federal land management and agricultural agencies.
- **Pursue Carbon Offsets:** Carbon offset projects produce verified carbon benefits and can yield financial returns from the sale of offset credits. Other chapters of The Nature Conservancy (TNC) and many other organizations currently pursue land use offset projects using tools such as conservation easements. Reforestation and improved forest management projects hold the greatest potential in Colorado. TNC Colorado could conduct offset projects and use the proceeds to protect more land from conversion, further increasing carbon stocks within the state.
- **Incentivize Reforestation of Private Lands:** We recommend the passage of a bill that establishes a Carbon Incentives Program to incentivize post-wildfire reforestation on private lands through direct financial aid, tax credits or technical assistance for reforestation projects. The bill could be modeled after the Maryland Forest Preservation Act of 2013, which includes a Reforestation Fund for private landowners. Stakeholder engagement will likely be required to ensure adequate levels of funding for the Carbon Incentives Program.
- **Pass a State Level Emissions Reductions Bill:** We recommend the passage of a bill that would mandate statewide emissions reductions and recognize the potential for improving the ability of Colorado's lands to store carbon. It could establish a price on carbon using a cap-and-trade program or a carbon tax. Although current political feasibility may be low, there is opportunity in Colorado's near future to pass a successful climate bill like California's Global Warming Solutions Act of 2006.

Our findings indicate that improving management of Colorado's lands can have a large impact on the amount of carbon stored in the state. Certain practices, such as reforestation of burn scars, have the potential to make a significant contribution towards Governor Hickenlooper's state climate goals. Policy decisions can provide the necessary incentives to increase carbon storage through improved land management. Although slowing global climate change can at times seem an insurmountable task, sub-national efforts are both necessary and effective.

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Introduction

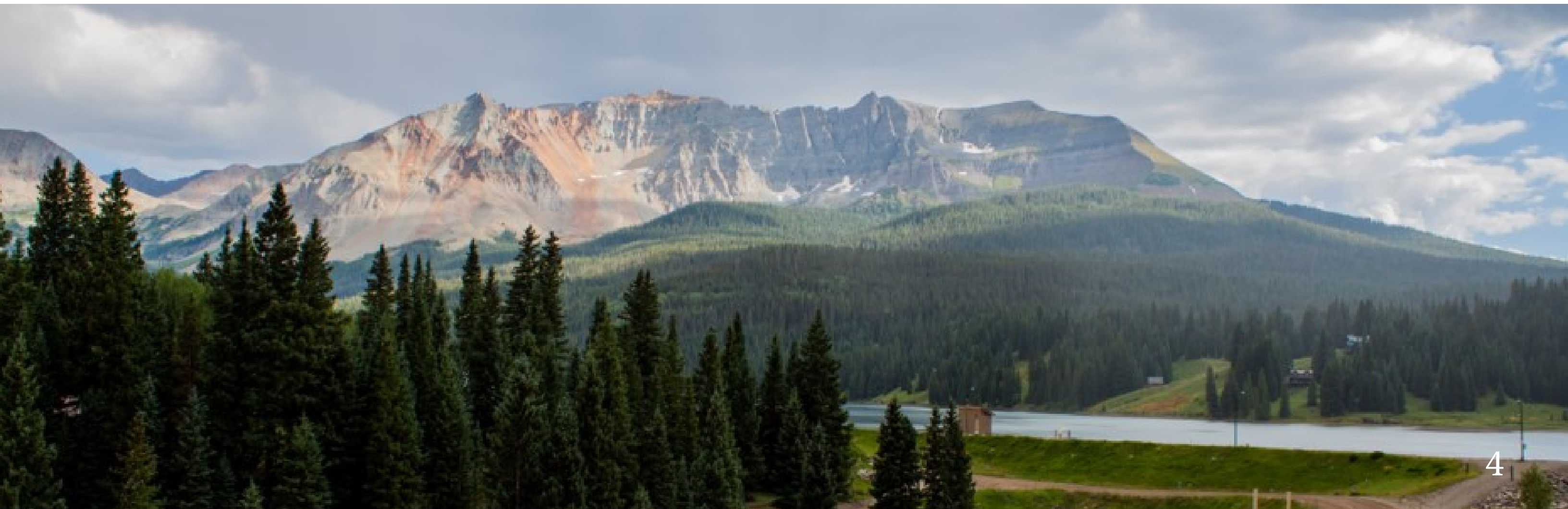
Climate

Climate scientists have unequivocally established that the Earth's climate is warming and that human activity is having a significant impact on the climate system (Cook et al., 2016; Hansen et al., 2013; Stocker et al., 2015). It is clear that global climate change will continue to have major human and environmental impacts. Reducing anthropogenic greenhouse gas emissions is necessary to slow or mitigate the most catastrophic of these impacts (Hansen et al., 2013; Department of Defense, 2015). Many of the observed climatic changes since the 1950s have been largely unprecedented, including the increased concentration of greenhouse gases in Earth's atmosphere. Global atmospheric CO_2 concentrations have increased by 40% from preindustrial times (Stocker et al., 2015). Though there is debate around the precise amount of carbon stored in Earth's lands, scientists agree that the global terrestrial carbon sink is large in the context of the carbon cycle (Pan et al., 2011; Scurlock & Hall, 1998; Ussiri & Lal, 2017). Although the burning of fossil fuels has been the main driver of greenhouse gas emissions, land-use change is the second largest contributor of emissions (Stocker et al., 2015). North America has been shown to be a net carbon sink, which emphasizes the importance of examining land management impacts on carbon in different geographic regions within the continent (Houghton & Nassikas, 2017; King et al., 2015).

Land Management

Land management decisions have high potential to impact atmospheric concentrations of carbon. Different land use practices contribute to either greenhouse gas emissions or carbon sequestration (Smith et al., 2014). Some land use practices, such as deforestation and the conversion of native grassland to agriculture, cause lands to emit CO_2 into the atmosphere. Avoiding the conversion of different carbon-rich land cover types can have a significant impact on maintaining carbon stocks (Guo & Gifford, 2002). The two categories of conversion that typically occur are anthropogenic and natural. Anthropogenic conversion, such as urban expansion into native lands, can often be avoided through land protection tools like conservation easements. Natural conversion, including diseases, pests, and fires, is sometimes unavoidable despite human intervention.

Research on land management suggests that switching from carbon-emitting practices to carbon-sequestering practices can have meaningful mitigation benefits in the context of anthropogenic climate change (Conant et al., 2017; Failey & Dilling,



2010; Pan et al., 2011; Paustian et al., 2006; Ussiri & Lal, 2017). Knowledge of current carbon stocks in different land cover types and the impacts of land management practices on carbon sequestration is critically important to land use decision-making (Ellenwood et al., 2012; Failey & Dilling, 2010; Hawken, 2017; Janowiak et al., 2017; Lal, 2008). Understanding land cover change trends and projecting those into the future can also help guide future land use decision-making.

Carbon Policy

Policies at many jurisdictional levels influence the ability of US lands to sequester carbon. Because mitigation potential varies widely across geographic regions and land cover type, it is important to look at carbon sequestration at a sub-national level (Smith et al., 2014). There are few US federal land management policies that identify carbon sequestration as a primary goal, however many indirectly affect carbon stocks. While some policies focus on a specific land type, such as the North American Wetlands Conservation Act, others are broader in scope and influence a wide range of lands. For example, the Agricultural Act of 2014 (i.e., Farm Bill) includes programs that regulate land use for several land cover types (e.g., grasslands and wetlands). The Agricultural Conservation Easement Program (ACEP) concentrates on agricultural lands, while the Wetland Reserve Program (WRP) focuses exclusively on wetlands. Many policies that indirectly impact carbon stocks could be altered to explicitly address the role of lands in climate change mitigation. A strong knowledge of carbon sequestration is crucial to informing those alterations. Therefore, understanding existing carbon stocks and the resulting effects of various management practices is key to crafting effective carbon policies at all jurisdictional levels (Lu, 2015).

Colorado Lands

With the recent US withdrawal from the Paris Agreement and the abandonment of accompanying Intended Nationally Determined Contribution (INDC) emissions reductions targets, there is a renewed focus on pursuing state-level opportunities for climate mitigation (U.S.A., 2015). In an era of US federal gridlock on climate policy, identifying policy options that could improve carbon sequestration at different jurisdictional levels within Colorado is a promising bottom-up approach to climate change mitigation. While 35% of Colorado's lands are federally owned, many land use decisions are made at the state, county, or local levels (Ellenwood et al., 2012; Vincent et al., 2017). However, the potential to leverage better management of Colorado's federal lands through multiple policy avenues remains high. Due to their carbon-rich nature, it is especially critical to improve management for the large percentage of Colorado's forests that are federally owned (68%) (Colorado Land Ownership, 2017). Opportunities also exist for non-governmental organizations

(NGOs), such as The Nature Conservancy (TNC), to influence land management on both public and private lands in the state.

The impacts of climate change in Colorado are contributing to increased landscape vulnerability to insect pests and extreme events, including forest fires and flooding. In addition, increasing rates of urbanization and population growth are putting high levels of pressure on native ecosystems (Gordon & Ojima, 2015). As these changes continue to occur, Colorado's lands have potential to be managed to improve carbon sequestration and avoid emissions. Currently, that potential is not being fully realized.

A 2007 report by Conant and co-authors, commissioned by the Colorado State Legislature examined Colorado's statewide carbon stocks and evaluated the sequestration potential of several management options. The researchers found that Colorado's lands are a net sink, sequestering 13 MMT CO_2 annually, and that the carbon flux of Colorado's agricultural lands could be improved by 3-4 MMT CO_2 annually through the implementation of different management practices (Conant et al., 2007). There have been no comprehensive assessments of Colorado's working and natural lands' ability to store carbon and/or avoid emissions since this 2007 report. This study builds on their work and the work of others to provide an updated assessment of carbon stocks in Colorado, a projection of land cover change into the future, and an examination of several land use scenarios. In addition, it includes an in-depth assessment of carbon policies and identifies the top policy opportunities to improve carbon sequestration in Colorado. The results of this study contribute to an improved understanding of the role of Colorado's working and natural lands in sequestering carbon, which is key to realizing their climate mitigation benefits.

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Colorado Policy

In 2017, Colorado's Governor Hickenlooper set emissions reductions targets of 26% below 2005 emission levels by 2025, in accordance with the former US INDC to the Paris Agreement (Executive Order D 2017-15). The 2014 Colorado Greenhouse Gas Inventory found that Colorado's GHG emissions totaled 130 MMT CO_2eq in 2010, with the electricity and transportation sectors contributing more than half of all emissions. The same report concluded that lands, land use change, and forestry together sequestered roughly 9 MMT CO_2eq in that same year (Arnold et al., 2014). To reach the targets set by the Executive Order, annual emissions must be cumulatively reduced by roughly 39 MMT CO_2eq by the year 2025. Projections currently indicate that emissions will increase by 5 MMT CO_2eq over that same period, suggesting that even further emissions reductions may be required (Arnold et al., 2014).

Governor Hickenlooper's administration has also established climate change mitigation and adaptation priorities for the state in the Colorado Climate Plan, which will be updated to reflect this new goal (Colorado Water Conservation Board, 2015). Unlike California, where the state legislature passed the California Global Warming Solutions Act of 2006 (AB32) and set aggressive emissions reductions mandates, Colorado's climate goals are currently voluntary. However, the Governor's recent commitments have the potential to drive policies that recognize the role of Colorado's lands in achieving these goals. Efforts by non-governmental conservation organizations, such as TNC, to support carbon-related policies are especially important in Colorado's current state policy context.

The Nature Conservancy

As a global leader in conservation and under CEO Mark Tercek's leadership, TNC is increasing its focus on ways the organization can contribute to climate change mitigation (Tercek, 2016). Tackling climate change (through both mitigation and adaptation strategies) is one of TNC's top eight global challenges, and TNC Colorado's 2015-2020 Strategic Plan includes climate change as a high priority for the chapter (The Nature Conservancy, 2015). Each TNC state chapter is building a strategy to address emission reductions within their state as part of the 50 State Climate Initiative ("Climate Change: Building Collective Action," 2017).

This report is intended to inform TNC Colorado of the greatest opportunities for improving carbon sequestration within the state and to help bolster the state chapter's contribution to the 50 State Climate Initiative.

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Methods

Our analysis includes: an updated carbon sequestration assessment of Colorado's lands, projections of Colorado's land cover and carbon stock change over time, models of land management scenario implications for Colorado's land cover and carbon stocks, a review of existing policies affecting carbon sequestration in Colorado, and an identification of 11 policies or programs that can increase carbon stock and sequestration in the state. To conduct this analysis, we completed a literature review, spatially analyzed land cover data using Geographic Information Systems (GIS), and evaluated policy options (see *Appendix B*).

Below are the research questions that guided our spatial and policy analyses:

How much total carbon is currently sequestered in each land cover type category in Colorado? How much carbon might be sequestered in the future?

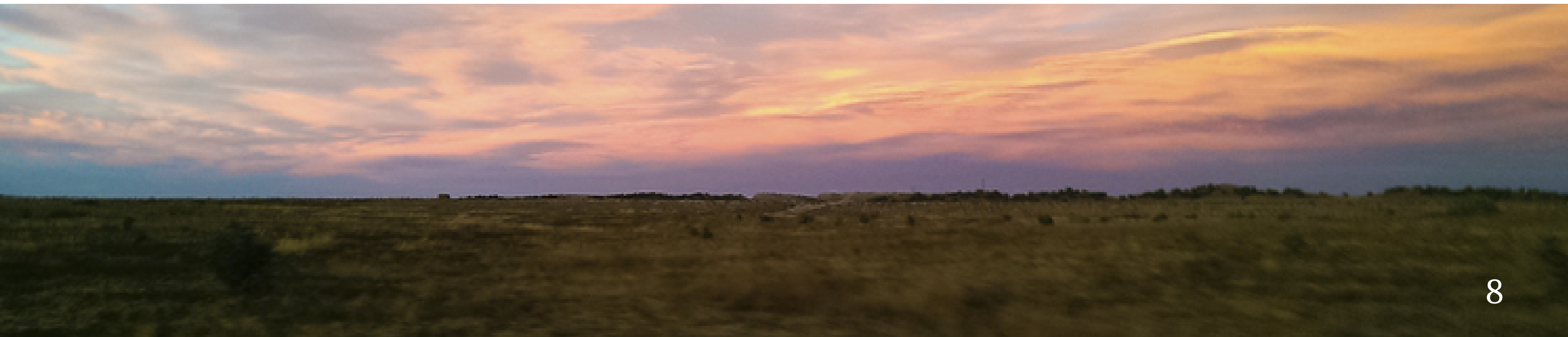
What programs, policies and tools exist to influence actions (either directly or indirectly) to provide incentives for increasing carbon sequestration in Colorado?

What programs, policies, and tools within Colorado have the greatest impact on improving carbon sequestration rates?

Literature Review

An extensive literature review of published studies and reports on carbon sequestration informed the baseline assessment. The purpose of the review was to collect carbon stock and flux data for the nine major land cover types we selected to represent Colorado and for a variety of land management practices. The nine land cover types are: Open Water, Forest, Grassland, Shrubland, Woodland, Agriculture, Wetland, Other Land (which includes snow, ice, and barren areas), and Developed. We chose these land cover types because they align closely with land cover categories in previous carbon sequestration studies (Conant et al., 2007; Failey and Dilling, 2010; U.S. Environmental Protection Agency, 2017; Zhu & Reed., 2012) and also represent the existing major land categories in Colorado (U.S. Geological Survey, 2016). These land cover types also aligned closely with the National Land Cover Dataset (NLCD) used for the spatial analysis (Homer et al., 2007; Homer et al., 2015). We did not seek data for Open Water, as it represents less than 1% of Colorado's land cover.

The collected data were represented in a Mitigation Action Summary Table (MAST). Data were organized by land cover type and detailed by: land cover subtypes, geographic area, management action, sequestration value and units, area of estimate and area units, source, and year of study (see *Appendix B)*. We chose to use negative flux values to represent carbon sequestered in the landscape and positive values to



represent carbon emissions, consistent with standard reporting measures in the literature (e.g., U.S. Environmental Protection Agency, 2017). These estimates do not include data from emissions related to energy use on the lands in question.

We reviewed 133 studies conducted in 2002 or later, of which 41 contained data suitable for use in our spatial analysis. Within these 41 studies, we identified 156 stock and 373 flux data points. We converted all stock and flux values to the same units (MT CO_2eq/ha/yr for flux and MT CO_2eq/ha for stock).

Spatial Analysis

We needed to understand the current state of Colorado's land cover and how land cover might change in the future in order to assess terrestrial carbon stocks in the state. We evaluated how projected changes would be impacted by different land management scenarios: 1) increasing amount of land placed under protection, 2) avoiding conversion of certain land cover types, and 3) reforestating of burned areas. Finally, we evaluated the carbon stock impacts associated with these land cover changes in order to support the policy analysis and evaluations (see *Appendix B*). To do this, we examined a 10-year period of land cover change in Colorado, projected those changes out to 2051, and altered those projections based on the aforementioned scenarios. Drawing from our literature review, we applied carbon data to each of these steps of the spatial analysis.

Stock and Flux Value Conversions

The first step in our spatial analysis was to apply the carbon data to Colorado. Since carbon stocks and fluxes vary significantly by geographic location within a land cover type, the data we collected in our literature review were not always immediately applicable to Colorado. The initial step in standardizing the data to Colorado was to examine major carbon sequestration drivers. We concluded that Net and Gross Primary Productivity are two important measures of an ecosystem's ability to increase and maintain carbon stocks. Research shows that precipitation is a significant driver of annual Net and Gross Primary Productivity in terrestrial ecosystems (Beer et al., 2010; Fensholt et al., 2013; Gilgen & Buchmann, 2009; Hicke et al., 2002; Sala et al., 1988) and is a better indicator than temperature (Del Grosso et al., 2008). We therefore chose to standardize our data based on precipitation and created a conversion factor unique to each region to apply to the stock and flux values. We used 30-year normal precipitation data for the continental US from the PRISM Climate Group at Oregon State University to create a proportion that would yield a conversion factor for each state or region (Daly et al., 2008). We first averaged precipitation data across the study regions from our literature review and applied it to the following proportion:

$$\frac{\text{Precipitation CO}}{\text{Precipitation Region}} = \frac{\text{Sequestration CO}}{\text{Sequestration Region}}$$

We used shapefiles of Level III Ecoregions from the US EPA and state boundaries to create regions that represented the geographic study areas from the MASTs. This allowed us to average precipitation regionally. In situations where the study regions did not align with a predefined Ecoregion or state boundaries, the regions were manually digitized using images directly from the sources. This proportion provided us with the standardized stock and flux values that we used in our assessment going forward.

Mapping Land Cover Types

Next, we needed to categorize all of Colorado's lands into broad classes in order to quantify their areas and analyze how they change over time. We analyzed land cover change to form the basis for assessing statewide carbon stocks. We utilized NLCD and the Landscape Fire and Resource Management Planning Tools (LANDFIRE) dataset (Homer et al., 2007; Homer et al., 2015; LANDFIRE, 2013). We reclassified NLCD land cover classes into nine land cover types based on similar studies and Colorado's existing land cover as mentioned above, as well as TNC staff consultation (see *Appendix B*). While these nine classes are broad, these classes or other similar classes have been used for large scale carbon stock assessments (Conant et al., 2007; U.S. Environmental Protection Agency, 2017; Failey & Dilling, 2010).

In order to project land cover and carbon stocks, we needed to examine changes in land cover over time. We used NLCD 2001 and 2011 to calculate decadal trends in land cover. This allowed for a decadal comparison that captured trends that were consistent with our understanding of land cover change in Colorado. Due to inconsistencies in EVT classifications between LANDFIRE vintages, we chose to use NLCD instead of LANDFIRE. However, NLCD did not feature a Woodland cover class, which was identified as one of our nine land cover types. After reclassifying NLCD into the nine broad cover classes, a conditional if/else evaluation was used to incorporate Woodland areas from LANDFIRE datasets in both vintages of NLCD. If Woodland from the LANDFIRE dataset overlapped with the Forest areas in the NLCD dataset, they were reclassified as Woodland in NLCD.

Then we quantified land cover trends between 2001 and 2011. Assuming these trends remain constant in the future, we projected future areas for our nine land cover classes at 10-year intervals from 2021 to 2051. We used a Markov Chain to accomplish those projections. The projected areas of each land cover type were then modified based on the following scenarios.

Scenario Projections of Land Cover Types

<u>COMaP/Protected Areas Scenario</u>

For our first scenario, we examined how the protection of 750,000 additional acres by 2020 would impact state carbon stocks. This reflects a stated conservation objective of TNC Colorado's 2015-2020 Strategic Plan. We first reclassified the Colorado Ownership, Management and Protection dataset (COMaP) into four broad classes (Colorado Natural Heritage Program and the Geospatial Centroid, 2011). These designations were chosen to represent land that is protected under different types of ownership and land use.

We chose to use version 9 of COMaP for this reclassification because it represented ownership in 2011, which matches the 2011 NLCD dataset. Upon staff consultation, we found that COMaP did not accurately represent the current state of TNC lands. We altered COMaP accordingly by adding up-to-date layers containing TNC Fee and Conservation Easement lands to COMaP, which were then adjusted to represent land protection in 2011. Once COMaP was reclassified from uniquely owned lands to our four broad ownership/protection categories, we combined the COMaP layer with NLCD 2001 and 2011 to examine the area changes in each land cover type within our four designations. Assuming these trends would remain constant, we projected them into the future. Based on the proportion of each land cover class within the ownership categories, 750,000 acres were moved from the Private Unprotected category to the Private Protected category. The resulting land areas are a representation of how Colorado's lands might look if TNC Colorado met their organizational targets.

Avoided Conversion Scenarios

Next, we ran three scenarios to determine the impact of avoided conversion of the Grassland, Wetland, and Forest cover types. We examined these cover types primarily because they are carbon dense and face potential conversion threats. We simulated complete avoided loss of each cover type and projected land cover change trends accordingly.

Fire Restoration Scenario

For our final scenario we simulated instant and total reforestation of major burned areas in Colorado in order to better understand the extent to which reforestation could impact Forest area and carbon stocks. We used the Monitoring Trends in Burn Severity (MTBS) Burned Areas Boundaries dataset (MTBS Data Access, 2017). The MTBS Burned Areas Boundaries dataset consists of the perimeters of major fires (fires with an area greater than or equal to 1,000 acres). Within the perimeters of all MTBS burned areas, we changed all pixels classified as Grassland, Shrubland, or Woodland to Forest. In order to examine the impact of forest fires on land cover change, we analyzed the percentage of Forest that transitioned to Shrubland within major burned areas.

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Applying Carbon Stock and Flux Values

The final step in our spatial analysis was to apply the carbon data we had collected to Colorado's lands. We first applied the carbon data from our literature review to the initial land cover area change projections. To do this, we created an equation that calculates carbon stock values at 10-year intervals (Figure 1).

$$C = \sum_{i=1}^{9} S_i A_i$$

$$S_i = S_{2011} - (F_i \times \mathrm{t})$$

C = Statewide total carbon stock (MT CO_2eq)

S = Carbon stock per area (MT CO_2eq/ha)

A = Area (ha)

S_{2011} = 2011 Stock value

F = Flux value (MT CO_2eq/ha/yr)

t = Time (years)

Figure 1: Carbon Stock Projection Equation

One challenge with our input data was that there is high variability in the reported values for carbon stock and flux. The variation in methodology and reporting of values created wide ranges for several of the land cover types. We used a Monte Carlo simulation[1] in order to account for the uncertainty associated with the wide range in carbon stock and flux values. Using all business-as-usual values[2] from the flux and stock MASTs, we ran the Monte Carlo simulation assuming a uniform distribution. Stock values were used to evaluate carbon sequestered in 2011, while flux values were applied to the projections for 2021-2051. When available, only Colorado specific values were drawn. When unavailable, the Monte Carlo simulation drew from all standardized stock and flux business-as-usual values. The Monte Carlo

[1] Monte Carlo methods provide repeated random samplings of a set of values to obtain numerical results.

[2] Business-as-usual values refer to no change in current land management. This differs from no management, under which native landscapes have no human intervention.

simulation was set up the same for each scenario. We analyzed the Monte Carlo results by examining means, medians, and extremes.

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Policy Analysis

Policy Research

We conducted a policy review to identify existing carbon-related policies at the federal, state, and local levels that impact sequestration in Colorado. We researched policies by land cover type and conducted interviews with professionals specializing in each. The policy review included policies that directly focus on terrestrial carbon as well as ones that have indirect carbon sequestration impacts. We met with 20 experts over the course of six months to inform our general understanding of carbon policies and their potential in Colorado, as well as barriers to their implementation. These experts included: scientists from Colorado State University's Natural Resource Ecology Laboratory, Colorado Natural Heritage Program, University of Colorado Boulder, University of Colorado Boulder Law School, Western Water Assessment, and U.S. Forest Service; staff from TNC Colorado, TNC Arizona, and TNC's Worldwide Office; government staff from the Colorado Department of Natural Resources, Colorado Department of Public Health and the Environment, and the City of Boulder; as well as several private consultants. These conversations helped to guide our policy review and to identify research gaps.

Policy Evaluation

We evaluated 11 key carbon policies identified in our research using methods that drew from both Bardach (2009) and Clark's (2002) approaches to policy analysis. Both Bardach and Clark advocate for clearly identifying the policy problem at hand. Research shows that lands around the world have the potential to improve carbon stocks through management (see *Introduction*). Based on this finding, we defined the policy problem as:

> *"Colorado's lands are not currently meeting their full potential to mitigate climate change through carbon sequestration and/or avoided emissions."*

We then engaged in a systematic analysis of potential policy pathways to address that problem. We analyzed existing data and conditions that may affect the policy problem (e.g., political climate, land use pressures), and identified policy alternatives. In this case, those included policies that impact carbon stocks and fluxes in Colorado.

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Table 1: Policy Evaluation Criteria and Definitions

Evaluation Criteria	Definition
Carbon Sequestration Impact	The potential of a policy to increase carbon stocks in Colorado. Higher rankings indicate greater potential.
Political Feasibility	The potential of a policy to be passed, enacted, or implemented. Higher rankings indicate greater potential.
Administrative Cost	The potential cost to the implementing organization or entity. Lower rankings indicate lower cost.
Stakeholder Equity	The distribution of potential impacts (both positive and negative) across related stakeholder groups. Higher rankings indicate more evenly distributed impacts.

To better compare the selected policy alternatives, we identified the following criteria for evaluation: Carbon Sequestration Impact, Political Feasibility, Cost Effectiveness, and Stakeholder Equity (Table 1). We scored each policy alternative qualitatively as “low,” “medium,” or “high” for each of the four criteria based on their potential outcomes. We utilized an outcomes matrix, as described by Bardach (2009) to evaluate and rank the selected alternatives according to the evaluation criteria.

We ranked the 11 alternatives according to their relative Carbon Sequestration Impact score because that evaluation metric directly addresses the defined policy problem. The other criteria were useful in evaluating each alternative but were not used to rank the policies because they do not address the policy problem directly. Where applicable, carbon impact quantifications from the spatial analysis helped inform this ranking. Some alternatives could not be quantified in a meaningful way due to their broad-reaching and uncertain nature. Those were ranked qualitatively based upon what we perceived as their relative impact compared to the other alternatives. Similar “matrix” or “scorecard” approaches have been well-established as effective policy evaluation tools (Clark, 2002; Walker, 2000).

Spatial Results and Discussion


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Our spatial analysis found that Colorado's lands currently hold **3,334 MMT CO_2eq**, compared to the US total of **48,382 MMT CO_2eq** (Zhu & Bouchard, 2011; Zhu & Reed, 2012; Zhu & Reed, 2014). Three key findings are:

1. Carbon stocks are largest for the Forest land cover type in the 2011 carbon assessment, with an estimated median of **1,490 MMT CO_2eq**.

2. Avoided conversion of the Forest, Grassland and Wetland cover types have wide-ranging impacts on carbon stocks, resulting in an increase in their respective stocks of **1,053 MMT CO_2eq** (77% increase), **32 MMT CO_2eq** (7% increase), and **36 MMT CO_2eq** (37% increase) respectively.

3. Reforestation of previously burned areas would increase Forest median carbon stocks to **1,650 MMT CO_2eq**, which is **160 MMT CO_2eq** (11%) higher than the median carbon stock without reforestation (**1,490 MMT CO_2eq**).

It is clear that land management actions can contribute to Colorado's emissions reduction goals (by 2025, cumulative statewide emissions must be 39 MMT CO_2eq lower than 2017 levels). For example, avoiding all projected conversion in the Wetland and Grassland cover types through 2051 would increase the carbon stored in those lands by 68 MMT CO_2eq. By 2025, this avoided conversion could contribute to **31% of Colorado's climate goals** (roughly 12 MMT). While the scenarios we ran represent the highest potential ceiling for carbon sequestration in Colorado's lands, the results still indicate that Colorado's lands can play a meaningful role in mitigating climate change.

Land Cover Change and Area Projections

The nine major land cover types across the state of Colorado are depicted below (Figure 2). The majority of the state's agricultural land is in eastern Colorado and the San Luis Valley. Other Land occurs at high elevations, and is generally surrounded by Forest. Shrubland is found mostly on the western half of the state and Woodland often occurs as a transition land cover between Shrubland and Forest. Much of the Developed land is in the Front Range at the intersection of the plains and the mountains. Developed lands consist of major cities such as Denver and Colorado Springs and their surrounding municipalities (e.g., Boulder, Golden, Lakewood, Littleton).

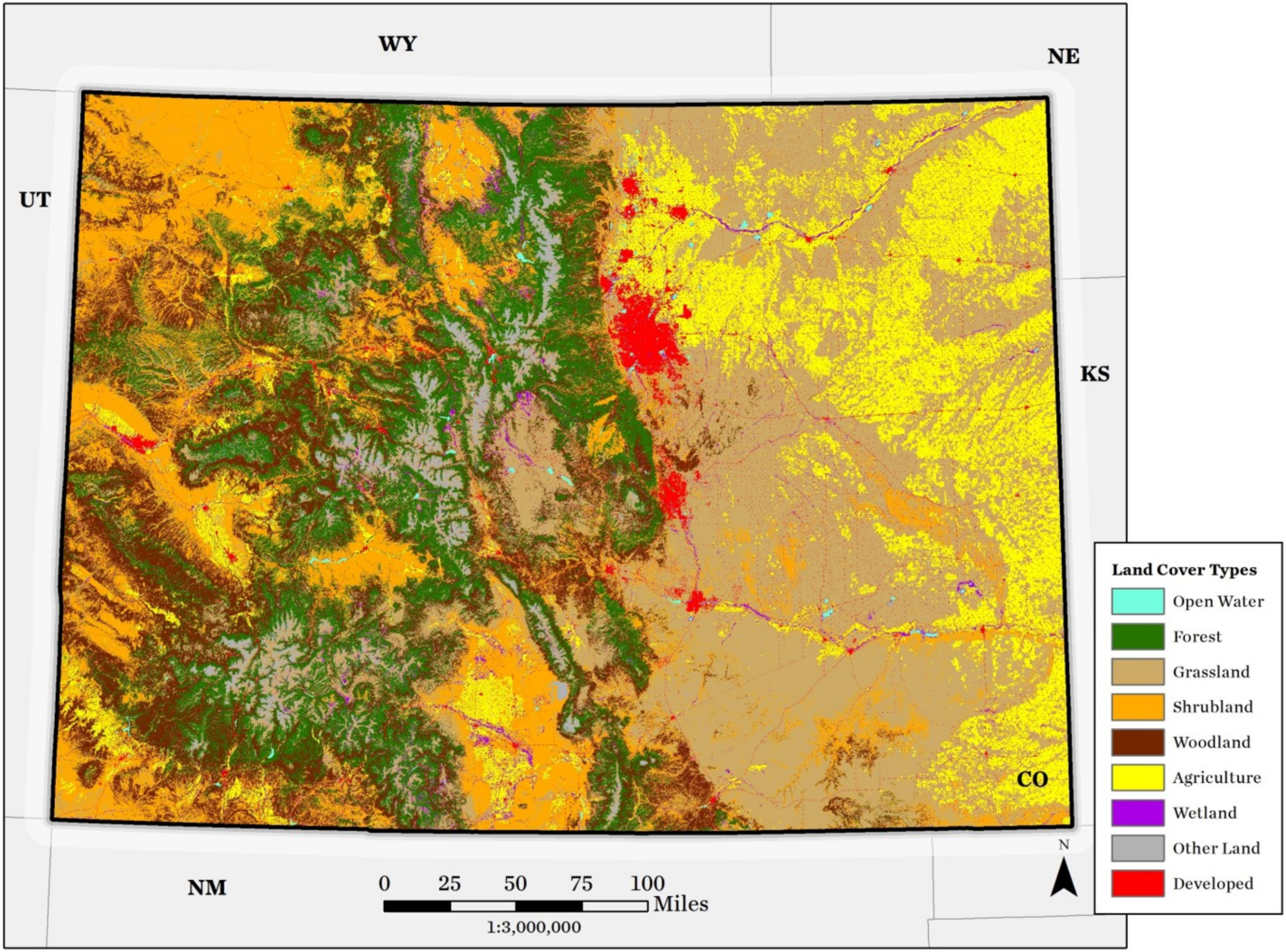

Figure 2: Land Cover Type Map: Land cover types across the state of Colorado in 2011. Land cover types were aggregated into nine general types from NLCD 2011. The Woodland class is from LANDFIRE 2012.

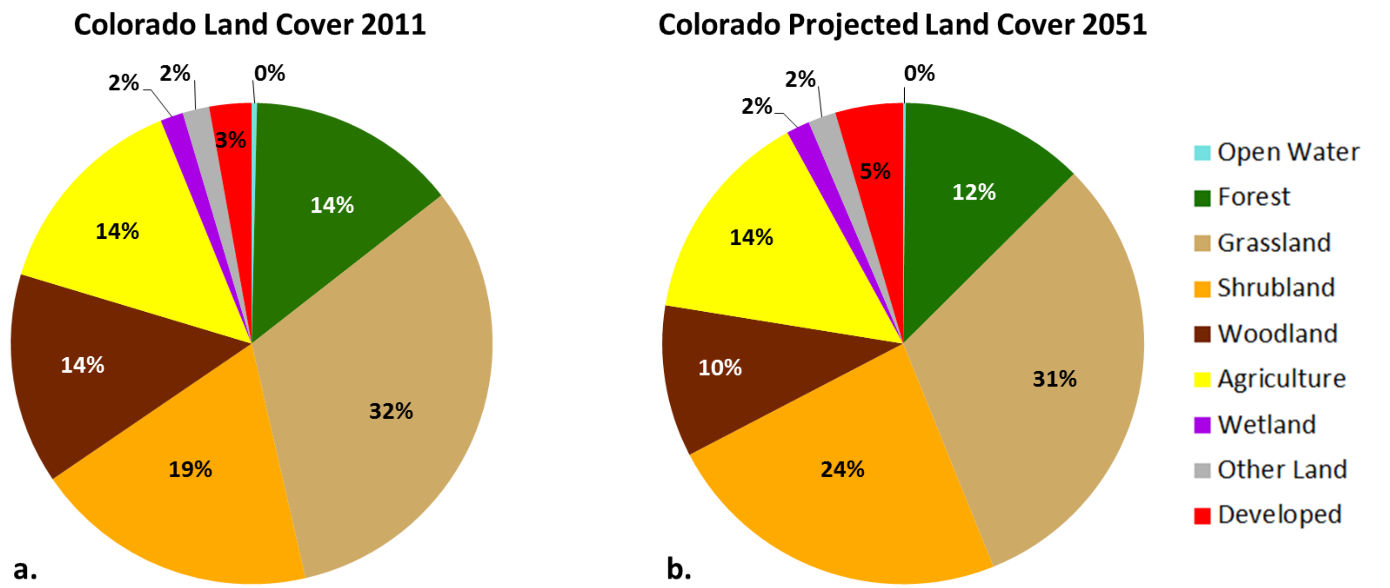

Figure 3: Land Cover Area Change Pie Charts: **(a)** Percent area of each land cover type in Colorado for the year 2011. **(b)** Projected percent area of each land cover type in Colorado for the year 2051.

The major land cover types in Colorado differ in area between 2011 and 2051 (Figure 3). Grassland is projected to decrease in area from **32% to 31%**, while Shrubland increases from **19% to 24%**. Forest and Woodland are both projected to decrease, from **14% to 12% and 10%,** respectively. Developed is projected to increase from **3% to 5%**. Agriculture, Wetland, Open Water and Other Land are projected to stay approximately the same.

Land Cover Change Drivers

Forest fires typically result in a transition from Forest to Shrubland, which is known as secondary succession (Bowman et al., 2009). According to Henry Horn's "The Ecology of Secondary Succession," "[s]uccession is a pattern of changes in specific composition of a community after a radical disturbance" (Horn, 1974). Secondary succession differs from primary succession because it occurs after a disturbance event. After a fire passes through, early-stage successional species such as various grasses and shrubs initially dominate the forest ecosystem. High severity fires lead to hydrophobic soil conditions, which slow natural reforestation (Debano, 2000). In these cases, manual tree planting is often required for full forest regrowth.

Fire frequency and intensity is expected to increase in Colorado due to increased spring and summer temperatures as well as an earlier snowmelt (Gordon & Ojima, 2015; Westerling et al., 2006). In 2002, the Hayman Fire burned over 138,000 acres of the South Platte Watershed in the Pike-San Isabel National Forest (Graham, 2003). Major fires like the Hayman Fire had significant impacts on land cover type composition by causing a large transition from Forest to Shrubland and Woodland. Our analysis showed that 32% of the total of this transition occurs in major burn scars (which represent 1.9% of all Forest area). This transition was captured in our ten-year study period (2001-2011), and the trend was assumed to be constant in our land cover class projections out to 2051. Therefore, we conclude that the Hayman Fire and others that occurred during this ten-year study period are major drivers of the large projected increase in the Shrubland cover type.

Colorado has experienced considerable


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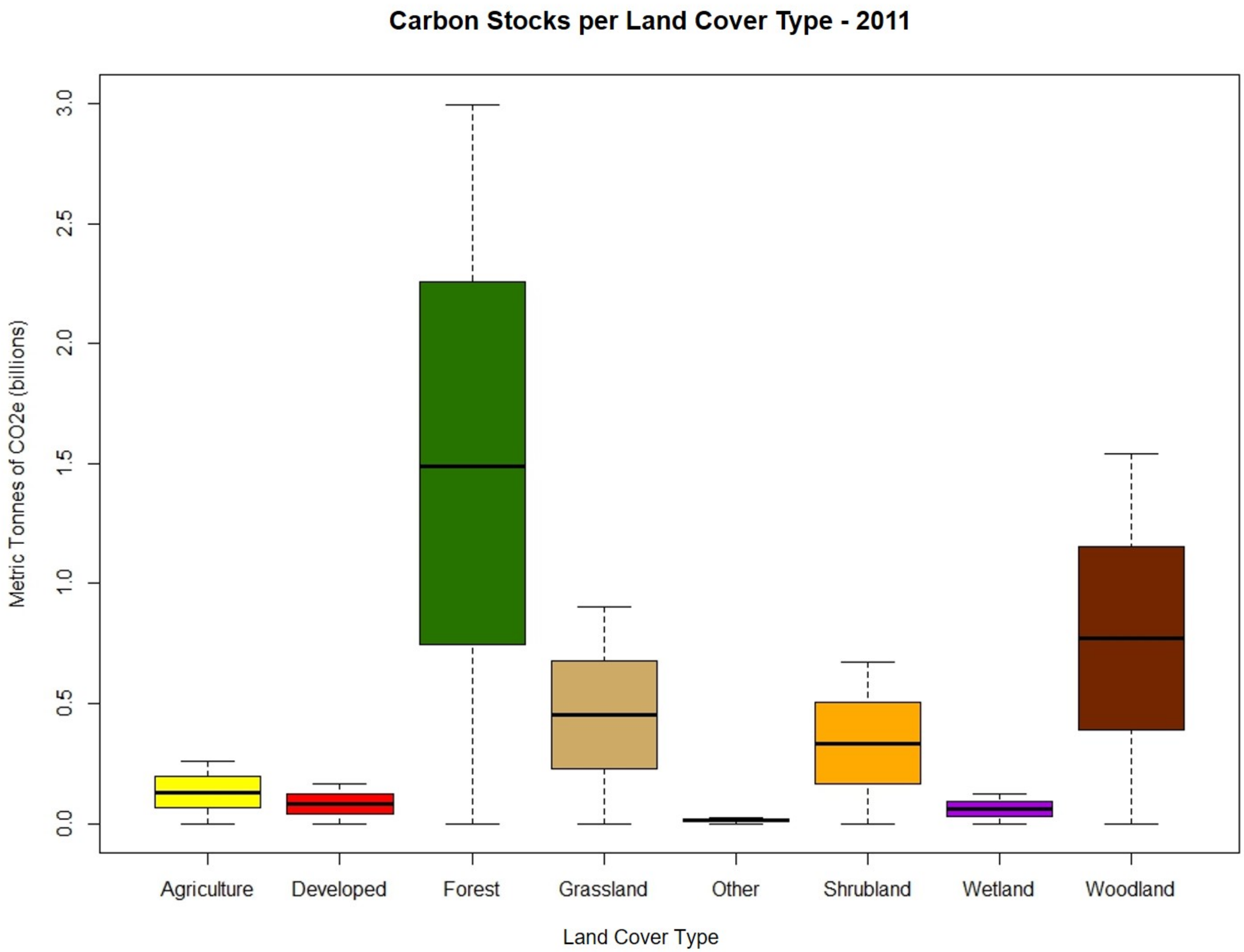
population growth since the start of the 21st century. The state's population increased from 4,302,261 residents in 2000 to 5,540,545 in 2016, representing a total population gain of 29%. Currently, Colorado is the third fastest growing state in the US, behind North Dakota and Utah (US Census Bureau, 2016).

This has resulted in rapid urban expansion, which is especially prevalent throughout the Front Range. Our projections show that Developed land has the second largest increase in percent area of all land cover types. Of the land cover types being converted to Developed land, Wetland is in the most danger of being converted. Although wetlands only make up a small portion of Colorado at 1.5% of state area (roughly 415,000 ha), they are carbon dense (147 MT CO_2eq/ha) and their projected conversion could result in an extensive loss of their carbon stocks.

Carbon Stock Analysis

Within each land cover type, the carbon values produced by the Monte Carlo simulation vary (Figure 4). The box plot shows the interquartile range (IQR) of potential carbon stock values of the nine land cover types. The whiskers of each box represent values that fall outside of the IQR. The largest spread is in Forest, followed by Woodland and Shrubland.

Forest holds the **largest** carbon stock in Colorado, followed by Woodland and Grassland. We draw this conclusion because the IQR of the Forest box is higher than and does not overlap with the IQR of any other land cover type except Woodland. In contrast, the **smallest** carbon stocks are in Other Land, Wetland and Developed. The IQR of the Grassland box is noticeably higher than the IQR of the Agriculture box. In addition, Forest and Woodland stocks are noticeably higher than Shrubland stocks.



Land Cover Type	Median Carbon Stock (MT CO_2eq)
Other Land	13,185,509
Wetland	61,627,277
Developed	82,274,769
Agriculture	130,618,113
Shrubland	331,455,693
Grassland	450,932,348
Woodland	773,948,397
Forest	1,489,913,146

Figure 4: 2011 Carbon Stocks by Land Cover Type Box Plot: Colorado carbon stock estimates by land cover type in 2011 based on the corresponding Monte Carlo simulation (left) and Median carbon stocks per land cover type in 2011 (right).

The density of carbon in each land cover type does not directly correlate with the size of its total carbon stocks (Table 2). For example, although statewide Wetland carbon stocks are low, Wetland is the third most carbon dense land cover type. It is important to note that Forest and Woodland are the most carbon dense land cover types, likely due to their high biomass content. In contrast, Agriculture, Grassland, and Shrubland are much less carbon dense.

Previous research suggests that urbanization and fires are key drivers of both the land cover change and carbon stock trends we see (Canadell & Raupach, 2008; Pataki et al., 2006; Schimel et al., 2002; Zhang et al., 2012). Our analysis confirms that forest fires are a major driver of the transition from Forest areas to Shrubland areas. This correlates closely with observed carbon stock changes in these categories.

Statewide carbon stocks are projected to **increase until 2031** and then **decrease over the next two decades** (Figure 5). We believe this estimate to be conservative because the land cover transitions that we projected from 2011-2051 are typically associated with larger carbon stock losses, such as biomass carbon losses during the transition from Forest to Shrubland in the event of a forest fire. This could be due to the wide range in our collected flux data, perhaps representing subtype heterogeneity and geographic differences that are not adequately captured in this approach. Therefore, the overall statewide decline may be greater than portrayed in this study. Nonetheless, this statewide decrease emphasizes the need to intervene with meaningful policies that can either maintain or increase Colorado's total carbon stock over time.

Table 2: 2011 Carbon Stock Density by Land Cover Type

Land Cover Type	Carbon Stock per ha (MT CO_2eq/ha)
Forest	409.3
Woodland	249.5
Wetland	229.3
Developed	128.7
Shrubland	82.7
Grassland	52.1
Agriculture	33.4
Other Land	17.9

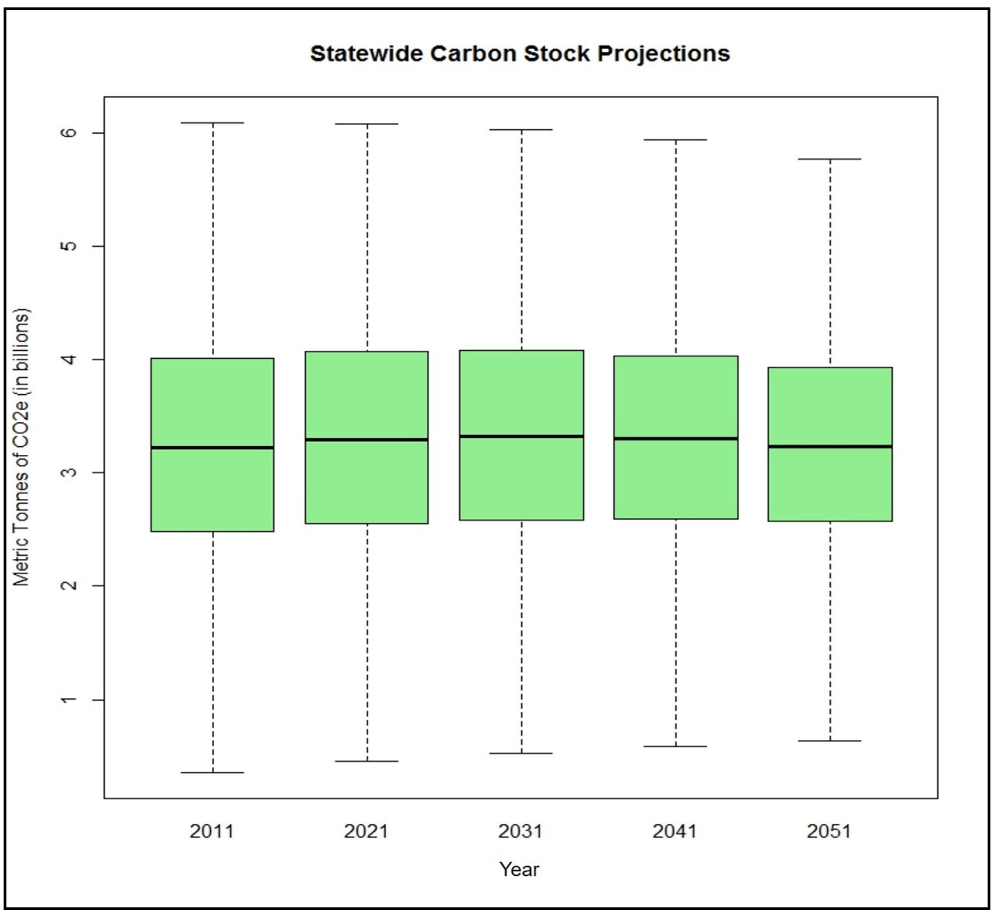


Figure 5: Statewide Carbon Stock Projections Box Plot; From 2011 to 2051 based on the corresponding Monte Carlo simulation

A more robust understanding of current and future statewide carbon trends is needed to help inform policies and land use decisions. Our research highlights the need for regular Colorado-specific carbon accounting in order to accurately identify best practices and related policy incentives.

Protected Areas Scenario

Colorado's lands were reclassified based on four different ownership/protection categories (Table 3; Figure 6). These categories are Public Restricted Use, Public Multi-Use, Private Unprotected and Private Protected.

Category	Definition	Example
Public Multi-Use	Publicly owned land with restrictions on use	Wilderness Area
Public Restricted Use	Publicly owned land with multiple designated uses	BLM grazing land
Private Unprotected Use	Privately owned land with no protection status	Private agriculture
Private Protected Use	Privately owned land with protection status	Land trust lands, conservation easements

Table 3: Ownership and Protection Categories for the Protected Area Scenario

TNC Colorado's Strategic Plan established the goal of protecting 750,000 acres of land with significant conservation or biodiversity values between 2015 and 2020 (TNC, 2015). This is in addition to the 762,000 acres of land that TNC Colorado has directly conserved over the past 50 years. This scenario takes the initial steps towards quantifying the carbon impact of TNC reaching that goal.

The simulation indicated that protecting an additional 750,000 acres does not have a meaningful impact on statewide carbon stocks. A contributing factor to this result is that 750,000 acres represents less than 1% of the state's total area (roughly 66 million acres). Therefore, it is not surprising that protecting an additional 750,000 acres is not enough to change the trajectory of statewide carbon stocks over a 40-year period. Another important element of this scenario is that protecting land does not completely prevent future land conversion. While anthropogenic conversion, such as development or conversion to agriculture, is largely avoided, natural conversion, such as forest fires and insect pests, can be inevitable even when protection status is given. In addition, this scenario simulated proportional land protection based upon the land cover types present in existing conservation easements, the majority of which is grasslands. Overall, a shift towards protecting more carbon-rich lands, such as forests, could potentially result in a larger impact on statewide carbon stocks. This scenario established a framework that can be further refined (see *Further Recommendations*).

It is important to note that protecting

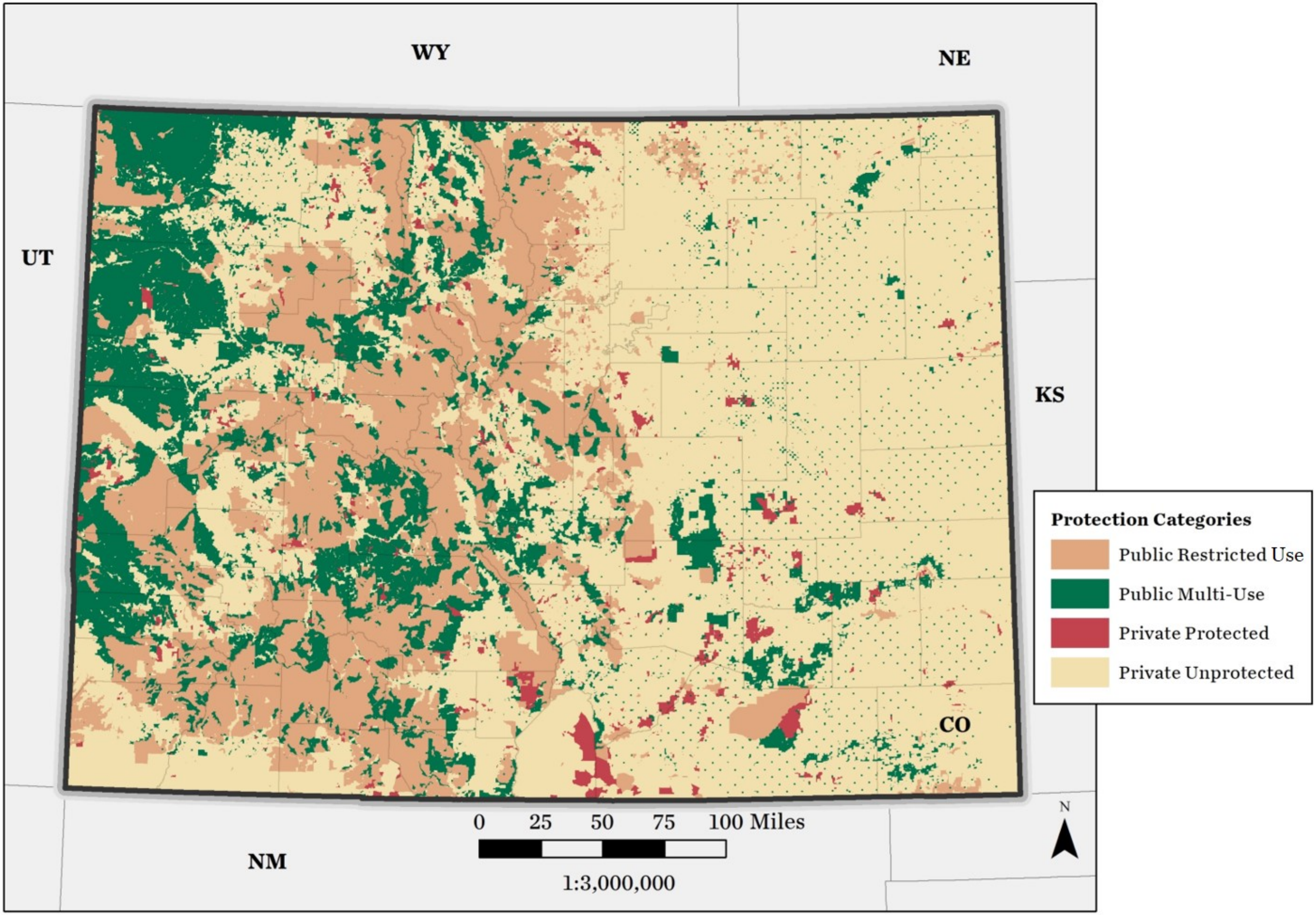


Figure 6: Colorado Protected Lands Map: Map of protected lands across Colorado by ownership category, based on the reclassification of COMaP version 9

750,000 acres has other co-benefits in addition to carbon. There are many other conservation benefits associated with land protection, such as biodiversity, water quality, species richness, and wildlife habitat (Miles & Kapos, 2008). Although this scenario indicates that land protection needs to reach a certain scale before impacting statewide carbon stocks, protecting land remains one of the best ways to preserve Colorado's ecosystems.

Avoided Conversion Scenarios

Projecting 100% avoided conversion for the Forest, Grassland, and Wetland land cover types has varying impacts on carbon stocks (Figure 7). Avoiding the conversion of each land cover type results in carbon stock increases when compared to the business-as-usual scenario. These increases are **1,053 MMT CO_2eq** for Forest (77% above baseline), **32 MMT CO_2eq** for Grassland (7% above baseline), and **36 MMT CO_2eq** for Wetland (37% above baseline).

Forests have significant potential to preserve carbon stocks through avoided conversion. However, as discussed earlier, much of the anticipated conversion will directly result from forest fires, not from development. The long-term net carbon impacts of fire mitigation are debated in the literature, largely because fire mitigation generally results in short-term carbon losses or emissions. While several studies suggest potential for a long-term net carbon benefit (Hurteau & North, 2010; North & Hurteau 2010; Volkova et al., 2014), others conclude long-term net negative impacts on carbon stocks (Campbell & Ager, 2012; Campbell et al., 2012; Mitchell et al., 2009). Others remain undecided about the carbon impacts of fire mitigation treatments (Reinhardt & Holsinger, 2010).

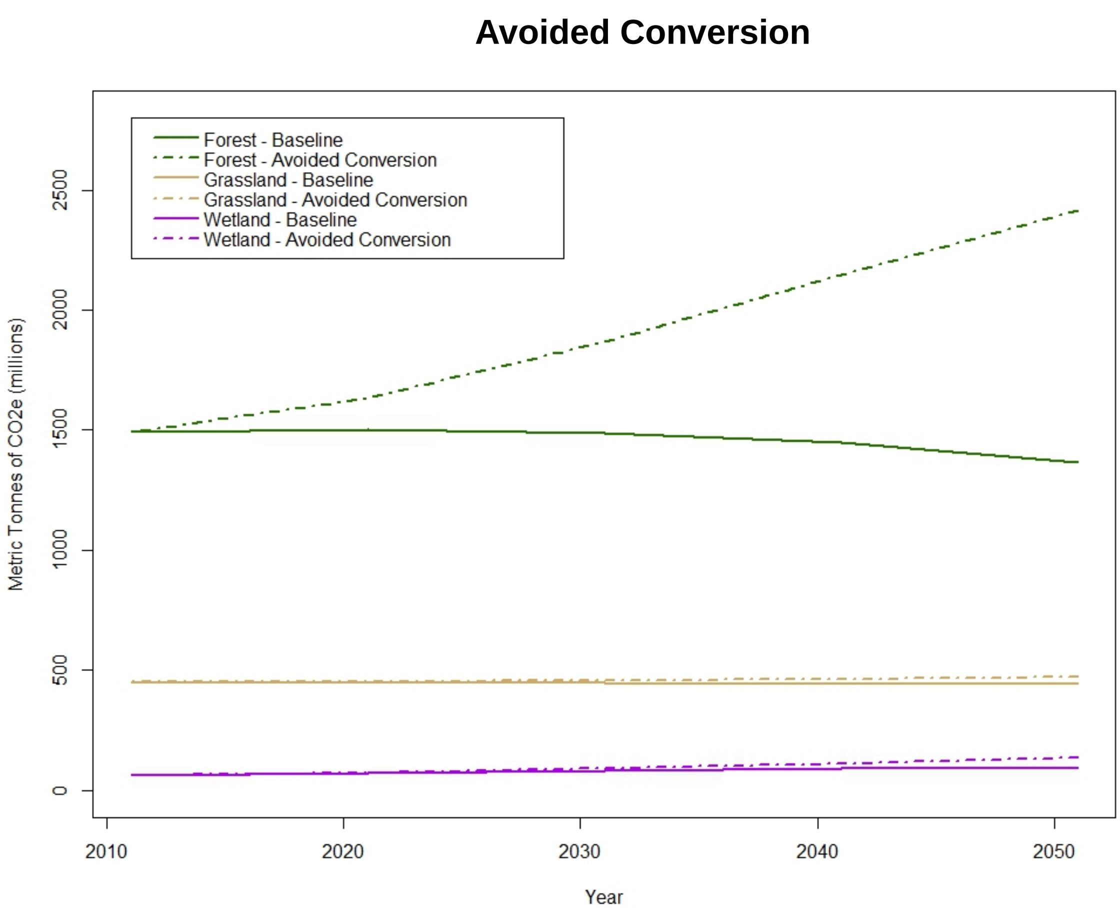


Figure 7: Avoided Conversion Line Chart: Comparison of the projected baseline and avoided conversion carbon stocks for the Forest, Grassland, and Wetland cover types

Despite lingering uncertainty about their carbon implications, fire mitigation efforts have other demonstrable benefits, including preserving water quality and reducing the probability of future catastrophic fires (Matocha et al., 2012). In a strictly carbon context, however, reforestation has better-established carbon benefits than fire mitigation. As such, post-burn reforestation may be a more viable approach to improving long-term carbon stocks.

In contrast, the carbon benefits of avoiding conversion of grasslands and wetlands may be more directly achievable. Historically, grasslands have been converted by expanding agricultural operations in Colorado (Conant et al., 2001). Similarly, wetlands have faced development pressure from agriculture, both directly from conversion and indirectly from floodplain disconnection, as well as from urban expansion. In the 2001-2011 time period we examined, these transitions may have been less prevalent than in previous decades. Created wetlands store 80-90% less carbon than natural wetlands, and restoration of wetlands is less effective for preserving carbon stocks than avoiding conversion in the first place (Hossler et al., 2011). Likewise, restoration of grasslands has fewer carbon benefits than avoiding initial conversion (Conant et al., 2001). While federal wetland protections exist under the Clean Water Act, further protections are still needed at all jurisdictional levels. Protecting grasslands and wetlands with conservation easements can ensure that conversion is avoided for the duration of the easement.

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One assumption placed on this simulation is that it is possible to avoid both anthropogenic land conversion and naturally occurring land conversion. Conversion due to natural processes such as ecological succession or disturbances like forest fires is often unavoidable despite human intervention. The simulation models a 100% avoided loss for each land cover type, which is unlikely to occur. In addition, land protection rarely occurs in a single land cover type so modeling complete avoided conversion of one land cover type at a time is not fully realistic. Although these limitations exist, the simulation illustrates the ceiling of potential carbon benefits.

Reforestation Scenario

Statewide forest carbon stocks under the reforestation scenario are noticeably higher than the baseline forest carbon stocks (Table 4). This simulation also showed that statewide carbon stocks are largely dependent on the total acreage of forests within the state.

Table 4: Impact of Reforestation Scenario on Statewide Carbon Stocks

	Area (million ha)	Forest C Stock (MMT CO_2eq)
With Reforestation	4.21	1,649.8
Without Reforestation	3.80	1,489.9
Difference	0.41	159.9 (11% Increase)

Total reforestation of all existing major burn scars in the state would increase the amount of carbon stored in forests up to **160 MMT CO_2eq**. This represents more than **four times** the state's cumulative emissions reductions goal of 39 MMT CO_2eq by 2025. However, the simulation unrealistically assumes instant and total reforestation and ignores the time trees take to fully mature. Despite the limitations of this simulation, the results are meaningful because they explore the highest potential gains of this specific management action.

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Policy Results and Discussion

This section details and evaluates the top 11 carbon policies identified. The findings of the spatial analysis indicated that avoided conversion of grasslands, wetlands, and forests as well as reforestation of burned areas can have large positive impacts on carbon stocks in Colorado. We chose to consider only management options that were supported by our literature review as being beneficial to carbon stocks, leading to the exclusion of fire mitigation and grazing practices from our policy analysis.

Based on the spatial analysis results and the findings of our policy review, we developed a list of 35 key policies with the potential to increase terrestrial carbon stocks in Colorado. Some were adapted from existing policies, while others were crafted to meet needs not yet addressed. Further review and consultation with TNC staff helped us narrow the list of policies down to 11. The policies that were not selected for evaluation are included in *Further Policy Recommendations*.

Top Carbon Policy Recommendations

The evaluation matrix (Table 5) provides a summary of the scoring of the 11 recommended policies. Each policy is explored and evaluated below, and several are accompanied by case studies that serve as real world examples.

Table 5: Policy Evaluation Matrix

Policy Alternative	Carbon Sequestration Impact	Political Feasibility	Administrative Cost	Stakeholder Equity
Pass an Emissions Reductions Bill through the State Legislature	**High** Has high potential if designed to emphasize terrestrial carbon sequestration	**Low** Unlikely to pass in a divided state legislature	**High** Significant resources required for implementation and enforcement	**Medium** Impacts and benefits will be likely unevenly distributed across stakeholder groups
Pass a Statewide Post-Wildfire Carbon Incentives Program Bill	**High** Has high potential to reforest privately-owned burn areas across the state	**Medium** Incentive-based program would likely have support, though establishing new funding mechanisms may be more difficult	**High** Significant resources are required for implementation and enforcement	**High** Incentive-based: few direct impacts to stakeholders and participation is voluntary
Create a Carbon Task Force Via Legislative Authorization	**Medium to High** Has potential to guide (not mandate) future statewide climate policy	**Medium** Non-controversial and relevant given the recent Executive Order	**Low to Medium** Few additional resources required for research	**High** Few direct impacts to stakeholders
Conduct Carbon Offset Projects	**Medium to High** Has potential to avoid conversion of private lands in Colorado, though impact varies based upon level of landowner engagement	**High** Passage of new policies is not required for this option	**Medium** TNC would need to pay for initial verification, but financial returns are likely for many projects	**High** Few direct negative impacts to stakeholders, and positive potential impacts for participating landowners
Implement or Improve Wetland Protection Plans	**Medium** Has potential to avoid conversion of wetlands within city limits, though impact will vary based on adoption rates	**Low to High** Varies significantly based on public and political will and prevalence of wetlands	**Low to Medium** Administrative cost of adoption is low, but mitigation and monitoring may require additional capacity	**Medium to High** Private landowners with wetland areas on their property will likely be more impacted than those without
Continue to Preserve CRP-Enrolled Lands As Contracts Expire	**Medium** Has potential to continue restoration of croplands to grasslands and preserve those restored grasslands and their carbon stocks	**Medium** Due to the numerous coalitions involved, reallocating funding within Farm Bill programs may be contentious	**Medium** Would require more ACEP funding	**High** Enrollment in longer contracts is voluntary

Policy Alternative	Carbon Sequestration Impact	Political Feasibility	Administrative Cost	Stakeholder Equity
Include Carbon Sequestration in the Amended Colorado Climate Plan	**Low to Medium** Has potential to guide future statewide climate policy. However, the Climate Plan does still only provide recommendations and not mandates	**High** Relatively non-controversial and relevant given the recent Executive Order	**Low** Few additional resources required for initial inclusion	**High** Few direct impacts to stakeholders
Influence the NRCS Colorado State Technical Committee to Consider Carbon in CRP Recommended Practice List	**Low to Medium** Has potential to alter management practices on CRP lands, though carbon impact will vary based on adoption rates	**Medium** Engaging with the State Technical Committee is a viable option for many stakeholders, but the Farm Service Agency may be resistant to change	**Low** Few additional resources required	**High** Few direct impacts to stakeholders
Improve Farm Bill Programs for Carbon Sequestration	**Low to Medium** Varies depending on program	**High** No funding mechanisms need to be identified, and the program changes suggested are not significant overhauls	**Low** Few additional resources required	**Medium to High** Varies depending on which program is altered
Increase ACEP Enrollment in Colorado	**Low** Has potential to protect additional native grasslands, but current enrollment covers a low percentage of the state's total grasslands	**Medium** Due to the numerous coalitions involved, reallocating funding within Farm Bill programs may be contentious	**Medium** Would require additional funding in Farm Bill, but would still represent a small percent of Farm Bill spending	**High** Improve stakeholder access to easement funds
Develop a Carbon Accounting Tool to Incorporate Carbon in Great Outdoors Colorado (GOCO) Grant Applications	**Low to Medium** Has limited potential for additional carbon benefits from future GOCO projects, but a carbon tool could be scaled and applied more broadly	**Low to High** The different implementation options vary widely in their political feasibility.	**Medium** Development of the carbon tool will require research and development funding	**High** Few direct impacts to stakeholders

Details and Evaluation

1. Pass an Emissions Reductions Bill Through the State Legislature:

Governor Hickenlooper's recent Executive Order (D 2017-015) commits Colorado to the United States' former emissions reductions targets under the Paris Agreement (26% below 2005 GHG emission levels by 2025). The Colorado General Assembly could pass a bill that would mandate those emissions reductions be achieved by 2025, ensuring that Colorado plays a significant role in mitigating global climate change. The bill should acknowledge the current capacity of Colorado's lands to sequester carbon and recognize the potential to improve terrestrial carbon sequestration within the state. It would require the establishment of a price on carbon using a cap-and-trade program, a cap-and-dividend program or a carbon tax. Whatever the instrument, we recommend including specific mechanisms to incorporate terrestrial carbon stocks, such as carbon offset projects (see *Case Study 1*).

Case Study 1: California Global Warming Solutions Act of 2006 (AB32)

California's State Legislature passed AB32 in 2006, which established an economy-wide **emissions reduction mandate** for the state. The bill required California to reduce its GHG emissions to 1990 levels by the year 2020, roughly 15% below expected emissions from a Business-As-Usual scenario (California Air Resources Board, 2014). The California Air Resources Board (ARB) chose to utilize a cap-and-trade program to achieve the necessary emissions reductions. California's cap-and-trade program covers 85% of total GHG emissions within the state, regulates multiple gases, and focuses on key GHG-emitting sectors (California Air Resources Board, 2014; Environmental Defense Fund, 2012). Proceeds from the auctions of emissions allowances go to a Greenhouse Gas Reduction Fund, which contributes to funding a variety of environmental programs including the Healthy Soils Initiative ("California Climate Investments," 2017).

One key feature of the cap-and-trade program is **carbon offsets**. Carbon offset projects improve carbon stocks and quantify the emissions reductions benefits which generate offset credits. The ARB allows regulated entities to offset up to 8% of their compliance obligation through several categories of offset projects. Voluntary carbon standard organizations develop protocols for each project type, which are then assessed and adopted by the ARB for use. The ARB assesses individual projects to ensure that their emissions reductions benefits are real, permanent, quantifiable, verifiable, enforceable, and additional (Table 6) ("Assembly Bill 32 Overview," 2014; Environmental Defense Fund, 2012). While California's offset projects are geographically restricted to North America, regulated entities can purchase offset credits from projects conducted in other states across the US.

AB32 serves as a useful example of **state-level** leadership on climate change mitigation. The cap-and-trade program also highlights the importance of managing lands for terrestrial carbon. The California State Legislature recently renewed the cap-and-trade program through 2030 in a bill (AB 398) that solidified the program and reduced long-term uncertainty. A new Compliance Offsets Protocol Task Force was convened as part of the bill for the purpose of helping develop offset protocols that focus on direct benefits to communities in California (Assembly Bill No. 398, 2017).

Evaluation: The passage of an emissions reductions bill has the potential to have a large impact on Colorado's terrestrial carbon stocks. That potential would be maximized if the bill was designed to specifically emphasize terrestrial carbon sequestration. Although the chance of such a bill passing through Colorado's state legislature in the immediate future is currently low, there is potential for passage by future state Assemblies. The administrative cost of an emissions reductions bill is likely high due to the necessary resources required for designing and implementing a robust carbon reduction instrument. In terms of stakeholder equity, such a bill would place additional financial and compliance burdens on extractive and manufacturing industries, fuel importers, and other polluters. However, the benefits to public health and the environment would likely be substantial. Overall, this policy could have the largest carbon impact for the state, but may be one of the most difficult to pass and implement effectively.

2. Pass a Statewide Post-Wildfire Carbon Incentives Program Bill:

Forest fires in Colorado are expected to intensify and increase in coming decades (Gordon & Ojima, 2015; Schoennagal et al., 2017). Forests may naturally regenerate after fires, but regeneration can be slow and many burn scars require manual replanting due to hydrophobic soil conditions after high intensity fires (Debano, 2000). In Colorado, forests with major burn scars comprise 1,243,101 acres. Of these burn scars, 30% are located on privately-owned lands (MTBS Project, 2017). Our reforestation scenario indicated that reforesting these privately-owned burned scars could yield an increase in carbon stocks of roughly 53 MMT CO_2eq. This increase would surpass Colorado's statewide cumulative emissions reduction requirements of 39 MMT CO_2eq (although

Case Study 2: Maryland Forest Preservation Act of 2013 (HB706)

Maryland's State Legislature passed the Maryland Forest Preservation Act of 2013, which established the statewide requirement of "**no net loss of forests**" going forward (House Bill 706, 2013). The Forest Preservation Act builds upon Maryland's 1991 Forest Conservation Act, and aims to improve its compliance (Maryland Department of Natural Resources, 2017). The bill expanded the purpose and authorized uses of an existing **Reforestation Fund**, in order to incentivize reforestation efforts across the state through tax benefits and credits to private landowners. It also includes tools such as disincentives for redevelopment projects on impervious surfaces, the creation of a statewide forest resource inventory (to be updated every five years), and increased penalties for intentionally starting forest fires.

Because the Forest Preservation Act is an incentive-based law, forest loss in Maryland hasn't completely halted. Lawmakers in Maryland are currently considering adopting a more **regulatory approach**, with a requirement for developers to reforest areas equivalent to those cleared for development. In addition, a "no net loss" policy for Western states would have to take into account the complexities of unpredictable wildfire regimes. Nonetheless, the Maryland Forest Preservation Act of 2013 serves as a useful case for how reforestation efforts can be successfully incentivized at a statewide level.

it is important to note that this may or may not be achievable by the year 2025).

The Colorado General Assembly could pass a law that establishes a "Reforestation Incentives Program" to incentivize post-wildfire reforestation on private lands. The bill could be modeled after the introduced Forest Incentives Program Act of 2015 (SB 1733, 2015). Incentives could include direct financial aid, tax credits, or technical assistance for conducting reforestation projects. This bill could also establish funding for ongoing monitoring efforts to identify post-burn sites in need of reforestation. Replanting efforts would need to be sustainably managed to avoid creating more dense, fire-prone forests (see *Case Study 2*).

Evaluation: This policy could have a large impact on carbon stocks by providing incentives to private landowners for reforestation of burn scars. It is unlikely that state funds will be appropriated for reforestation on federal lands but they could be used to fund efforts on private and state lands. The most difficult political aspects would be establishing adequate funding sources and securing continuous funding for the administrative costs of implementation. Participation would be voluntary so a reforestation bill would have high levels of equity among stakeholders.

3. Creating a Carbon Task Force Via Legislative Authorization:

Short of creating and passing a binding emissions reductions mandate, the Colorado General Assembly could convene a task force for the purpose of studying the role of Colorado's lands in achieving the goals of Executive Order D 2017-015. The task force would identify specific conservation, restoration, and management practices that improve carbon stocks and fluxes in Colorado. It would also suggest incentive mechanisms to land managers for adopting these best practices. To maximize impact, the task force would make formal recommendations to the Colorado General Assembly as well as to federal land management and agricultural agencies (see *Case Study 3*).

Evaluation: Passing climate-related legislation through a divided state legislature typically has low political feasibility, but creating a task force is likely to be less controversial due to its primary focus on research and recommendations. A carbon task force has the potential to have a medium to high impact on Colorado's carbon stocks, though its efficacy depends greatly on adequate funding and the willingness of land managers to adopt recommended practices.

Case Study 3: Hawaii's Carbon Farming Task Force (HB 1578)

Hawaii's State Legislature passed HB 1578 in June 2017, which established the Carbon Farming Task Force within the Office of Planning (Hawaii House Bill 1578, 2017). The Task Force focuses on identifying key agricultural and aquacultural practices to both **improve soil health and carbon sequestration** on farming operations within the state. The Task Force is charged with making recommendations to the governor and the legislature based on their findings and is given deference to develop funding mechanisms for incentivizing adoption of identified practices. These could include loans, tax credits, grants, educational materials, technical assistance, or research (Hawaii House Bill 1578, 2017).

The Carbon Farming Task Force may have a significant impact on terrestrial carbon sequestration in Hawaii and could play a large role in shifting conventional agricultural and aquacultural practices towards those that improve carbon sequestration.

4. Conduct Carbon Offset Projects:

TNC Colorado could consider the potential for generating carbon offset credits when negotiating conservation easements. Offset projects produce verified carbon benefits and can yield financial gains. There are both compliance-based and voluntary markets currently operating in the US. Compliance-based offset credits are used in California's cap-and-trade market, verified by the California Air Resources Board (ARB), and currently are trading above the price floor of $13.57/credit (Air Resources Board, 2017). Voluntary offset credits can be sold more broadly into existing voluntary markets and are verified by carbon offset standard organizations including the American Carbon Registry, the Verified Carbon Standard, and the Climate Action Reserve. Voluntary credit prices range widely from $0.50/credit to over $50/credit, but the average price ($3/credit) is lower than the compliance market's floor price. It is worth noting that Forestry and Land Use accounts for the second highest volume of credits traded by category, and has a higher average price than the total voluntary market, at $5.10/credit[3] (Hamrick & Gallant, 2017) (see *Table 6* and *Table 7*).

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When TNC protects land in Colorado via a conservation easement, a cost-benefit-analysis (CBA) for offset credit generation could be conducted before the easement is written. In particular, Avoided Conversion offset projects align closely with the existing organizational approach to land acquisition. However, in order to be eligible for Avoided Conversion offset credits, TNC would have to prove additionality (*Table 7*) and would need to show an imminent threat of conversion for the property. Much of the forest conversion in Colorado is expected to result from forest fires rather than from development. As such, Improved Forest Management (IFM) and Reforestation projects should be considered. IFM and Reforestation credits sell at the highest average prices by project type within the voluntary market, at $9.50/credit and $8.10/credit respectively (Hamrick & Gallant, 2017). If the CBA indicates a net financial benefit from generating and selling offset credits, TNC could use the proceeds to protect more land and further improve carbon stocks in Colorado. In addition, TNC could encourage public-private partnerships on offset projects in order to influence carbon stocks on public lands (see *Case Study 4*).

Evaluation: Much of Colorado's private lands may be eligible for carbon offset projects. Depending on the level of engagement by landowners and organizations, offsets have a large potential to impact Colorado's carbon stocks and produce verified carbon credits. For example, our spatial analysis shows that avoided conversion of the Grassland cover type has the potential to increase Colorado's carbon stocks by 40.2 MMT CO_2eq by 2051. Avoided conversion of forests has even greater potential, though much of the conversion will be driven by (*continued on Page 34)*

[3] These averages include international offset projects, which typically produce cheaper credits than projects in North America.

Case Study 4: USFS San Juan National Forest Carbon Offset Project

In 2002, the Missionary Ridge forest fire severely burned portions of San Juan National Forest. Fourteen years later, Disney was working towards its goal of net zero emissions from its amusement parks and approached the USFS about conducting a **reforestation carbon offset project** ("Carbon Demonstration Project San Juan National Forest," 2016). Disney channeled its funds through the National Forest Foundation, enabling the USFS to reforest 760 acres of the burned area. The reforestation effort has been verified by the American Carbon Registry, currently the only registry that will verify projects on federal lands, and is generating voluntary carbon offset credits (National Forest Foundation, 2016). While the USFS is federally charged with reforesting burned sites like Missionary Ridge, budgetary constraints have consistently limited their ability to address all reforestation needs on their lands. Thus, this carbon offset project has been shown to have "additionality" (Table 6) and is therefore eligible for generating **verified carbon credits**.

The Missionary Ridge project represents an innovative approach to leveraging **private funding for restoration of federal lands**. Over the past 20 years, the USFS's spending towards managing and maintaining the National Forest System has decreased from 58% of its total budget in 1995 to 20% in 2005 (USFS, 2015). Spending for wildland fire management has increased from 16% to 52% over the same timeframe. With a bleak outlook for public funding for restoration, public-private partnerships are an increasingly effective strategy for enabling critical restoration efforts and improving carbon stocks across the West.

Table 6: Key Terms and Definitions for Carbon Markets

Term	Definition[1]
Additionality	Additional carbon removals are those that would not have occurred in the absence of an offset project
Permanence	Occurs when carbon removals due to offset projects will remain fixed for the long term
Leakage	Occurs when conducting an offset project causes an increase in emissions in an area outside the geographic boundary of the project
Offset Credit	A credit generated from an offset project, typically equivalent to the removal of 1 MT CO_2eq from the atmosphere
Verification	Offset projects generate verified offset credits which result from a verification process conducted by standard organizations. This process includes periodic greenhouse gas monitoring and reporting by third parties

[1] ("Markets and Standards," 2017)

Table 7: Carbon Market Offsets Overview

Market Type	Organization	Offset Protocols[1]	Offset Project Type[2]	Offset price/ton
Compliance	California Air Resources Board	Forests	Reforestation	Floor Price: $13.57/credit[3] 324,731,247 allowances sold in 2016
			Improved Forest Management	
			Avoided Conversion	
		Urban Forests	Tree Planting	
			Urban Forest Maintenance	
Voluntary	American Carbon Registry	Forests	Afforestation & Reforestation of Degraded Lands	Avg. price for Forestry and Land Use offset credits: $5.10/credit $67 million offset credits sold in 2016 =13.1 $MMTCO_2eq$[5]
			Improved Management for Non-Federal Forestlands	
			Improved Forest Management for U.S. Timberlands	
			REDD - Avoiding Planned Deforestation	
		Grasslands	Avoided Conversion of Grasslands and Shrublands to Crop Production	
			Compost Additions to Grazed Grasslands	
	Climate Action Reserve	Forests	Reforestation	
			Improved Forest Management	
			Avoided Conversion	
		Grasslands	Avoided Conversion of Grasslands and Shrublands	
		Urban Forests	Tree Planting	
			Urban Forest Management	
	Verified Carbon Standard	Agriculture	Agricultural Land Management	
		Forests	Afforestation, Reforestation and Revegetation	
			Improved Forest Management (IFM) for U.S. Timberlands	
			REDD	
		Grasslands	Avoided Conversion of Grasslands and Shrublands	
		Wetlands	Wetlands Restoration and Conservation	

[1] Only land use based offsets protocols included here
[2] Only project types that are applicable to Colorado included here
[3] (“Auction Notice”, 2017)
[4] (“California Cap and Trade Program”, 2017)
[5] (Hamrick & Gallant, 2017)

Case Study 5: City of Boulder Wetland Policies

The City of Boulder has adopted stringent wetland policies that regulate development on and near wetlands within the city limits. These policies, detailed in Chapter 9-3-9 of the Boulder Revised Code, **go above and beyond federal wetland definitions and regulations** in terms of inclusivity, protection, and mitigation (Boulder Revised Code 9-3-9, 2009). The City of Boulder's wetland regulations apply to wetlands of 400 sq. ft. or larger and require both 25-50 ft. buffer zones and regular functional evaluations of mitigation work. They also have higher mitigation requirements than the federal minimum of a 1:1 ratio, mandating up to a 2.5:1 ratio for required creation of rare or hard-to-create wetlands (Boulder Revised Code 9-3-9, 2009). Boulder remains one of the only cities in Colorado to have enacted strict wetland policies with **regulatory force.**

Without such policies, wetlands that are not protected under Section 404 of the Clean Water Act are in danger of dredging, draining, filling, and excavation. Boulder's policies require any project likely to impact wetlands apply for a Stream, Wetland, or Water Body Conditional Use or Standard Permit (in addition to the CWA Section 404 Permit Program). Boulder's robust wetland policies can serve as a **model for adoption** by other cities around Colorado.

forest fires and may be unavoidable. The costs of engaging in the existing carbon markets vary, although the initial verification fee can be cost-prohibitive if the carbon benefits from the project are too small.

Forest offset projects are likely to be the most feasible in a Colorado context. Reforestation and Improved Forest Management protocols are most attractive, for the reasons discussed above. More research should be done and existing pilot projects, such as the Environmental Defense Fund's ongoing grassland offset pilot project, should be monitored to evaluate the feasibility of Avoided Conversion grassland projects in a Colorado context (Haynes, 2016). Offset projects can directly benefit involved stakeholders with little or no detrimental effects to the wider population, and investments in offset projects can have multiplicative carbon benefits. In addition, offsets represent a unique pathway to enhancing carbon stocks because they can result in direct financial gains that can be used to fund further conservation efforts.

5. Implement or Improve Wetland Protection Plans:

If a native wetland is converted, 80-90% of the carbon lost in the conversion cannot be regained via restoration efforts (Hossler et al., 2011). As such, wetland protection, not restoration, should be the focus of policies seeking to preserve wetland carbon stocks. Wetlands enjoy some federal protection under Section 404 of the Clean Water Act (CWA). However, due in part to the lack of coverage provided by the CWA's definition of wetlands, wetlands still often face conversion pressure (40 CFR §404). This provides opportunity for additional wetland protections to be developed at the subnational levels. Cities across Colorado could enact policies mandating greater wetland protection standards than federal minimums. Robust wetland protection policies should have regulatory force, include mandatory buffer areas, recognize smaller wetland areas, and mandate stronger mitigation requirements. There is significant potential for adoption of stringent wetland policies by municipalities across the state (see *Case Study 5*).

Evaluation: As described above, avoiding wetland conversion is the most effective way to preserve their carbon stocks. Wetland Protection Plans would play a large role in protecting existing wetlands. According to our spatial analysis, avoided conversion of all wetlands in Colorado through 2051 would increase wetland carbon stocks by 37%. However, it is unlikely that these plans will be universally adopted. Political feasibility of adoption varies by city, based on public and political will as well as administrative capacity. The mitigation and monitoring aspects of this option may require additional funding and staff. It is also likely that private landowners with wetland areas on their property will be the most impacted stakeholders due to restrictions on management and development.

6. Continue to Preserve Conservation Reserve Program (CRP)-Enrolled Lands As Contracts Expire:

Our spatial analysis shows that in 2011, there were 9.5 million acres of agricultural land in Colorado. Roughly 1.8 million of these acres are enrolled in CRP as of May 2017, with 1.4 million acres set to come out of contract in the next five years ("Conservation Reserve Program Monthly Summary," 2017). The Farm Bill could create more options for CRP contract lengths (e.g. 15 years, 30 years, or permanent) with tiered incentive options that prioritize longer-term contracts, since carbon sequestration in Colorado happens over long temporal periods. The Agricultural Conservation Easement Program (ACEP) project ranking process could also be changed so that lands that have CRP contracts expiring within a year receive a higher score than the 15/200 points currently given. In addition, the National Resource Conservation Service (NRCS) could consider distributing payments year by year rather than in lump sums.

Evaluation: Depending on which approved practices are implemented, carbon stocks and fluxes on CRP lands will vary. While it is difficult to quantify the exact carbon benefit, transitioning expiring acres to ACEP could result in a medium carbon impact. Due to the numerous stakeholders involved in Farm Bill deliberations, the political feasibility of implementing this policy is moderate. For this transition to be successful, Farm Bill funding for ACEP would need to be increased. Enrolling in longer contracts or transitioning to ACEP would stay voluntary yet become better incentivized, so stakeholder equity would remain high.

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7. Include Carbon Sequestration in the Amended Colorado Climate Plan:

In addition to setting emissions reductions goals, Executive Order D 2017-015 calls for the incorporation of those goals into the 2015 Colorado Climate Plan. Governor Hickenlooper's Executive Order also calls for the solicitation of stakeholder input on additional measures or strategies to advance those goals. A draft of the new plan will be open for a 30-day public comment period on October 2, 2017. Carbon sequestration should be included in the Climate Plan and the mitigation potential of Colorado's lands should be explicitly recognized.

Evaluation: As the process of amending the Colorado Climate Plan is already in motion, the political feasibility of this recommendation is high. Avenues for stakeholder input are already established, so the addition of language that recognizes the carbon sequestration potential of Colorado's lands is relatively low cost and straightforward. While the Colorado Climate Plan may guide future statewide climate policy, it only provides recommendations, limiting the potential for associated carbon benefits. However, including carbon sequestration in the Climate Plan is an important step in Colorado's efforts to reduce GHG emissions, despite its lack of regulatory force.

8. Influence the NRCS Colorado State Technical Committee to Consider Carbon in CRP Recommended Practices:

The NRCS Colorado State Technical Committee could add a metric detailing the carbon impacts of each management practice when forming its CRP Recommended Practices list. Proposals should be weighed based on that carbon metric in addition to existing conservation metrics. We recommend that NRCS also strongly consider the removal of practices that are found to decrease carbon stocks from the Recommended Practices list.

Evaluation: This policy's impact on carbon stocks varies from low to medium, depending on which practices are selected and the rate of adoption by producers. Opportunities exist to engage with the State Resource Conservationist, who makes recommendations to the State Technical Committee. The State Technical Committee then submits recommendations for approval to the Farm Service Agency (FSA) State Committee. This option has moderate political feasibility because the FSA may be resistant to change. Few additional resources would be required to pursue this option. Some stakeholders may be negatively impacted by the removal of less carbon beneficial practices from the CRP-Recommended Practices list.

9. Improve Farm Bill Programs for Carbon Sequestration:

The following Farm Bill programs can be modified to incentivize land management for carbon sequestration:

a. The Environmental Quality Incentive Program (EQIP) should maintain biological carbon storage and sequestration as a national priority ("EQIP," 2017).

b. NRCS could eliminate EQIP incentive payments for landowners converting native grassland to "organic crop production."

c. The CRP could add carbon sequestration to the Environmental Benefits Index used to rank lands for CRP awards.

d. The Conservation Reserve Easement Program (CREP) could eliminate or disincentivize 10-year contract easements and incentivize longer term or permanent contracts.

e. The Conservation Stewardship Program (CSP) could include terrestrial carbon storage as a targeted resource concern. We also recommend that CSP increase contract length options beyond the current 5-year standard to include perpetual or permanent options.

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Evaluation: Depending on which programs are improved, carbon benefits could range from low to medium. Political feasibility of all recommended improvements is generally high, since no new funding mechanisms need to be identified and the changes are not significant overhauls of any program. Stakeholder equity of this policy option would vary depending on which programs are targeted. Of the recommended improvements, the EQIP program alterations would likely have the most negative impacts for the small group of stakeholders who currently engage in practices that convert native grasslands.

10. Increase ACEP Enrollment in Colorado:

Colorado-allocated ACEP funding could be increased to expand the total area of lands protected by easements in Colorado. Currently, Colorado demand for ACEP enrollment exceeds allocated funding, which forces Colorado to tap into excess funds from other states to meet demand. ACEP also currently offers both 30-year and permanent easements. By making all conservation easements permanent, carbon stock benefits would be maintained in perpetuity. In order to incentivize permanent easements, ACEP could also model payment structures after CREP, where payments are continuous over a set period of time rather than lump sum.

Evaluation: There are currently only 6,185 ACEP-enrolled acres in Colorado ("Agricultural Conservation Easement Program," 2017). However, applications exceed state allocations of ACEP funding. While ACEP only covers a small percentage of total state land area, the program funds the protection of carbon-rich lands. As demand for this program is larger than current funding allocations, increased ACEP funding would likely yield carbon benefits through avoided conversion. However, the effect on carbon stocks will likely be minimal due to the small amount of acreage currently enrolled. Political feasibility is moderate as it would require reallocation of Farm Bill funds. Stakeholder equity is high as more agricultural producers would have access to this program.

11. Develop a Carbon Accounting Tool to Incorporate Carbon in Great Outdoors Colorado (GOCO) Grant Applications:

GOCO has funded the protection of over one million acres in Colorado since 1992 and continues to play a large role in conservation efforts around the state ("About Us," 2017). A carbon metric could be incorporated into grant applications to supplement existing conservation criteria. In order for applicants to easily estimate the carbon implications of a project, a user-friendly carbon accounting tool would likely need to be developed. Such a tool could be closely modeled after COMET-Farm, an online tool that allows producers to quantify the carbon impacts of various agricultural practices (COMET-Farm, 2017). Adding a carbon metric would be especially applicable to GOCO's Land Conservation Grants, including the Conservation Easement Transaction Costs Grants and the Open Space Grants. This policy could be implemented either as part of a reauthorizing legislation package or by lobbying GOCO to include a carbon metric, as well as this tool, as part of its grant applications.

Evaluation: It is likely that GOCO's protection efforts already have carbon benefits due to impacts from avoided conversion. Additional carbon benefits that accrue from the explicit consideration of carbon may be limited. Nonetheless, a carbon accounting tool could have broader applications and may influence decision-making of other philanthropic organizations. The development of such a tool would have high political feasibility, but would require funding for research and development. Incorporating carbon as a decision-making metric into reauthorizing legislation for GOCO may be politically challenging, whereas working with GOCO directly to encourage them to use a carbon metric would likely be more feasible. In either scenario, the development of a readily-implementable carbon accounting tool would make a carbon metric more attractive to GOCO staff and legislators. To minimize negative stakeholder impacts, the inclusion of a carbon metric would need to be carefully designed as to avoid unintended consequences. For example, the carbon metric should not overly disincentivize activities with verifiable conservation benefits such as invasive species removal.

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Recommended Policies for TNC Colorado Engagement

In order to better impact carbon sequestration in Colorado, we recommend that TNC Colorado consider engaging with several of the policies we evaluated. These are the top four policies we recommend that TNC Colorado pursue. These are also policies that have been identified to have a high potential impact on Colorado's carbon stocks in our matrix analysis.

1. **Help Pass a State-Level Emissions Reductions Bill**: While current political feasibility for this option is low, there is certainly future potential for its passage. We recommend that TNC Colorado engage with legislators when appropriate to emphasize the need for including terrestrial carbon in such a bill. In addition, there may be opportunities after its passage to advocate for proceeds from carbon allowance auctions or a carbon tax to be distributed towards conservation programs.

2. **Carbon Task Force**: We recommend convening a government task force to study the role that land management can play in meeting the climate targets established by the Governor's recent Executive Order. The task force should have the power to make formal recommendations to the Colorado General Assembly, as well as to federal land management and agricultural agencies. TNC Colorado could advocate for the creation of a carbon task force through legislative or executive authority.

3. **Incentivize Reforestation of Private Lands:** We recommend the passage of a bill that establishes a Carbon Incentives Program to incentivize post-wildfire reforestation on private lands through direct financial aid, tax credits or technical assistance for reforestation projects. The bill could be modeled after the Maryland Forest Preservation Act of 2013, which includes a Reforestation Fund for private landowners. TNC Colorado could help establish a Carbon Incentives Program by advocating for the passage of such a bill.

4. **Pursue Carbon Offsets**: Carbon offsets align closely with TNC Colorado's protection and conservation efforts. Engaging in carbon markets requires no political interventions and therefore is highly feasible. Carbon offset projects could help fund future conservation efforts and generate returns for both TNC Colorado and participating landowners. We recommend that TNC Colorado consider adding language to new conservation easements that allows for offset generation. In addition, consideration of the potential to generate offset credits should be implemented into TNC Colorado's land acquisition decision-making criteria.

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Further Policy Recommendations

Included here are additional policies that would increase terrestrial carbon sequestration in Colorado. They were not explored fully in this policy evaluation analysis due to time and resource constraints. However, we identified these policies as having real potential to improve carbon stocks in Colorado, and we recommend pursuing them.

- Reauthorize GOCO through legislation to ensure funding for future conservation purchases.
- Incorporate carbon metrics into Colorado Conservation Exchange's optimization models, so as to include consideration of carbon sequestration into project area selection.
- Submit public comments on federal agency plans and programs, including BLM and USFS, urging the agencies to engage in mitigation efforts in order to offset impacts from federal land use decisions.
- Engage with county-level land use planning to integrate carbon benefits into decision-making.
- Maintain, increase, and improve the Colorado Conservation Easement Tax Credit.
- Purchase (or facilitate the purchase of) in-stream flows to protect and preserve native wetlands that rely on seasonal flooding.
- Consider carbon sequestration impact as a metric in land protection decisions and include best land management practices for sequestering carbon in future conservation easement agreements.
- Ensure that adequate funding is available for conservation and restoration through the USFS. This could be accomplished through establishing a separate USFS fund for emergency fire management to avoid the necessity of fire borrowing (e.g. the proposed National Wildfire Disaster Funding Act) (HR 167, 2015).
- Fully fund the Land and Water Conservation Fund (LWCF) and consider carbon sequestration in purchasing decisions.
- Create a Colorado state GHG reduction fund ("California Climate Investments," 2017).

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Conclusion

Colorado's lands currently play an important role in mitigating anthropogenic climate change. There is significant potential to improve Colorado's carbon stocks through different management practices and policies. Policy options exist at multiple jurisdictional levels that, if altered or adopted, will help preserve and increase those stocks. Of the major land cover types in Colorado, Forest currently holds the largest carbon stock. It is likely that in coming years, this stock will be threatened by increased wildfire. Reforestation after wildfires and avoiding conversion of carbon-rich land cover types are both key to maintaining and/or improving Colorado's carbon stocks. Managing lands to improve carbon sequestration can contribute to meeting climate goals. For example, complete reforestation of all current burn scars in Colorado could contribute up to 72% of Colorado's cumulative emissions reductions target of 39 MMT CO_2eq (Arnold et al. 2014; Executive Order No. D 2017-015). Organizations like TNC have many opportunities to actively engage policymakers and stakeholders to encourage better management of Colorado's natural and working lands in the context of climate change.

Understanding Colorado's terrestrial carbon resources is key to making informed land management decisions. This work can serve as a model for other state-level carbon analyses and can be applied at larger or smaller scales. The study also serves as an example of how spatial analysis can be used to inform land management decisions in a carbon sequestration context.

Recommendations for Further Research

Several opportunities exist to further refine this analysis. The variance within land cover types could be reduced by conducting primary carbon data collection, analyzing land cover types by subtype (e.g., breaking the Forest cover type into aspen, spruce-fir, ponderosa pine etc.), and including exclusively state-specific data. In addition, different climate scenarios could be applied to all projections in order to more realistically model land and carbon stock changes in Colorado. The land protection scenario could also be modified to incorporate actual land acquisition plans, simulate recurring land protection, and model the carbon impacts of avoided conversion from land protection.

There are also several distinct priorities for further research. Using the methods established in this analysis, more specific management simulations could be conducted to better understand the effects of land management on carbon stocks. We have identified a need for comprehensive, long-term studies to examine the net carbon impacts of grazing practices and fire mitigation, including separate studies for prescribed burns and fuel treatments. Finally, similar studies should be conducted across the US to help inform local, state, and federal policies.

Glossary

Additionality: Additional carbon removals are those that would not have occurred in the absence of an offset project

Administrative cost: The potential cost to the implementing organization or entity for a given policy alternative

Afforestation: The planting of trees in areas that were not previously forested

Business-as-usual: Business-as-usual values refer to no change in current management. This differs from no management, under which native landscapes have no human intervention

Carbon dioxide: A greenhouse gas produced by burning carbon and organic compounds and by plant respiration

Carbon flux: Annual change in carbon stock (MT CO_2eq/yr or MT CO_2eq/ha/yr)

Carbon sequestration: Process by which atmospheric carbon dioxide is taken up by plants through photosynthesis and stored as carbon in biomass and soils

Carbon sequestration impact: The potential of a policy to increase carbon stocks in Colorado

Carbon stock: Amount of carbon stored in a landscape (MT CO_2eq or MT CO_2eq/ha)

Climate change mitigation: Efforts to reduce or prevent greenhouse gas emissions

Greenhouse gas: Gases that store heat in the atmosphere

Interquartile Range: The difference between the first and third quartiles in a statistical distribution

Land cover type: One of nine broad land cover classifications found in Colorado: Agriculture, Developed, Forest, Grassland, Open Water Other Land, Shrubland, Wetland, Woodland (see *Appendix B*)

Leakage: Occurs when conducting an offset project. Causes an increase in emissions in an area outside the geographic boundary of the project

Markov Chain: A statistical method for producing transition probabilities to predict future states based on previous states (Grinstead & Snell, 2009)

Monte Carlo simulation: A method that computes output statistics (means, variances) by repeating simulations with random sampling of input variables and model parameters (Li & Wu, 2006)

Offset credit: A credit generated from an offset project, typically equivalent to the removal of 1 MT CO_2eq from the atmosphere

Glossary

Permanence: Occurs when carbon removals due to offset projects will remain fixed for the long term

Policy alternative: Policy options that address a policy problem

Policy problem: The definition of the key problem or issue used when selecting alternatives in a policy evaluation analysis

Political feasibility: The potential of a policy to be passed, enacted, or implemented

Reforestation: The planting of trees in areas that were previously forested

Stakeholder equity: The distribution of potential impacts (both positive and negative) across related stakeholder groups. Higher rankings indicate more evenly distributed impacts

Subtype: Land cover classifications with more specificity than land cover type. For example, aspen, birch, and spruce-fir are subtypes of the Forest land cover type

Transition: The process by which one land cover type becomes another

Verification: Offset projects generate verified offset credits which result from a verification process conducted by standard organizations. This process includes periodic greenhouse gas monitoring and reporting by third parties

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Appendix A - MAST Summary Tables

Table A1: MAST Summary Table 1: Number of data points used in the current carbon stock analysis and projections

	Stock	Flux
Open Water	0	0
Forest	49	34
Grassland	4	7
Shrubland	4	4
Woodland	5	1
Agriculture	10	12
Wetland	6	15
Other Land	4	3
Developed	7	24
Total	89	100

Table A2: MAST Summary Table 2: Number of data points collected in the literature review before reclassification

	Stock	Flux
Forest	76	86
Grassland	14	61
Agriculture	25	110
Wetland	9	39
Other Land	3	31
Developed	8	44
Total	162	371

Appendix B - Supplemental Spatial Methods and Justifications

This section gives further details into the Literature Review and Spatial Analysis methods. Additionally, it provides justifications for several of the methods used in the spatial and statistical analyses.

Literature Review

Research studies primarily expressed Forest and Developed data in aboveground and belowground carbon, so only studies that included both measures were considered in the Forest and Developed stock and flux data we collected. In contrast, Wetland, Grassland, and Agriculture data were expressed primarily in soil carbon. We did not exclude studies that included aboveground carbon due to limited available data.

We constrained the temporal scope to studies published in 2002 or later in an effort to capture the most recent and relevant data available and to provide an updated assessment of Colorado's carbon stocks. This constraint was also imposed due to the scope and timeline of this study. Papers that provided general conclusions about carbon sequestration impacts from certain management actions or land types but did not include any specific quantitative estimates of stocks or fluxes were omitted from the literature review. We focused on data specific to Colorado when available. When Colorado data were not available, we collected data specific to western states or to the US more broadly.

Spatial Analysis

Ecoregions and Conversion Factor

The USGS report on Carbon Sequestration in the Western US and the Great Plains regions modified the US EPA's Level III ecoregions from 1999 (Zhu et al., 2012). This modification created some discrepancies in the ecoregion boundaries, specifically in Montana and New Mexico. Since the PRISM precipitation data was averaged over each region, these discrepancies accounted for only a small amount of error, which we recognize as a fault with the data.

Climates are varied across the given study regions from our literature review. Since they are often different from the climate in Colorado, we needed to scale our data. Net and Gross Primary Productivity are two important measures of an ecosystem's ability to grow and sequester carbon, respectively. Research has shown that precipitation is a significant driver of annual Net and Gross Primary Productivity in terrestrial ecosystems (Sala et al., 1988; Hick et al., 2002; Gilgen & Buchmann, 2009; Beer et al., 2010; Fensholt et al., 2013) and is a better indicator than temperature (Del Grosso et al., 2008). Therefore, we chose to use 30-year normal precipitation data from PRISM to scale our carbon stock and flux data to Colorado.

LANDFIRE vs. NLCD

We chose to use the NLCD dataset over the LANDFIRE dataset for our study due to classification changes between LANDFIRE 2001 and 2014, making a comparison across the two vintages difficult.

Land Cover Classifications

Because NLCD does not have a classification category for Woodland, we reclassified LANDFIRE 2012 where any EVT with Woodland in the classification and an open tree canopy cover as Woodland, with everything else as not Woodland. We repeated this for LANDFIRE 2001. Raster calculator was then used to input a conditional statement to incorporate the Woodland data from LANDFIRE 2012 into NLCD 2011, as well as Woodland data from LANDFIRE 2001 into NLCD 2001.

Table B1: Land Cover Class Reclassifications

Land Cover Type	Classification Description	Dataset (value)
Open Water	Open Water	NLCD (11)
Forest	Deciduous Forest, Evergreen Forest, Mixed Forest	NLCD (41, 42, 43)
Grassland	Grassland/herbaceous	NLCD (71)
Shrubland	Shrub/scrub	NLCD (52)
Woodland	Reclassified LANDFIRE 2012 where any EVT with Woodland in the classification and an open tree canopy cover as Woodland. Anywhere that the LANDFIRE Woodland layer overlapped with NLCD Forests was classified as Woodlands in NLCD.	LANDFIRE
Agriculture	Pasture/hay, cultivated crops	NLCD (81, 82)
Wetland	Woody wetlands, emergent herbaceous wetlands	NLCD (90, 95)
Other Land	Perennial Ice/Snow, Barren Land (Rock/Sand/Clay)	NLCD (12, 31)
Developed	Developed, Open Space, Developed, Low Intensity, Developed, Medium Intensity, Developed, High Intensity	NLCD (21, 22, 23, 24)

Uncertainty

Where available, we held constant Colorado specific values for the nine land cover classes. In addition, we ran standard deviation and variance calculations for the uniform distribution simulation to identify the largest source of the uncertainty.

COMaP Classifications

We used COMaP versions 9 and 10 in our analysis of Protected Areas. We used COMaP version 9 in order to calculate land cover class transition probabilities as it is from 2011, which corresponds directly to NLCD 2011. COMaP version 10 was used as the starting point for the land cover area projections because version 10 represents the most updated and accurate portrayal of land ownership across the state. The first step was to reclassify COMaP versions 9 and 10. When we compared the two reclassifications, there were differences in the cell counts between the two versions. This difference is likely due to the changes in classifications between the two versions, as COMaP version 9 was more detailed and had more specific classifications than version 10. In order to standardize the two versions to make them comparable and more accurate, we reassigned 355,000 cells to Private Protected from Private Unprotected in COMaP version 10, as those two categories had the most prominent differences in cell counts. Based on the percent of land cover classes in the Private Unprotected ownership category, the same percent of the 355,000 cells was taken from those land cover classes in Private Unprotected and reassigned to the corresponding land cover class in Private Protected. For example, if the Private Protected category was 40% Grassland, 40% of the 355,000 cells would be added to Grassland. Similarly, if 40% of the Private Unprotected category was Grassland, 40% of the 355,000 cells would be subtracted from the Private Unprotected Grassland cell count total.

Avoided Conversion

To simulate land cover change from avoiding conversion we manually altered the initial transition probabilities from the Markov Chain. This allowed us to accurately represent the area of each land cover under complete avoided loss. The new transition probabilities reflected an avoided loss scenario, meaning that the probability of the cover class in question remaining the same was set to one while the probability of converting to other land cover classes was set to zero. These new transition probabilities produced an area for each cover class out to 2051.

Appendix C - Research Questions

Spatial Analysis Research Questions

How much total carbon is currently sequestered in each land cover type category in Colorado? How much carbon might be sequestered in the future?

a. What are the current carbon stocks for land cover classes within Colorado? What is the total carbon stock for the state?

b. Assuming that current land cover change trends continue, what will be the carbon stocks for land cover classes in Colorado by 2051? What will be the 2051 carbon stock for the state?

c. Assuming that no losses occur for the Forest, Grassland, or Wetland cover types, how much carbon will be stocked in these three cover classes by 2051?

d. How much carbon stock would be gained if we were able to reforest all large wildfire burn scars (>1,000 acres) in the state?

e. If an additional 750,000 acres of conservation easements were protected, how would trends for carbon stock change between 2011 and 2051?

Policy Analysis Research Questions

What programs, policies and tools exist to influence actions (either directly or indirectly) to provide incentives for increasing carbon sequestration in Colorado?

a. Where have counties, states, and NGOs successfully enacted policies and tools that promote carbon sequestration?

b. What incentives or policies currently exist as barriers to improving carbon sequestration in Colorado?

c. How do these policies nest under or contribute to Colorado's state climate goals?

d. What programs, policies, and tools within Colorado have the greatest impact on improving carbon sequestration rates?

Which programs, policies, and tools are most politically and economically feasible within the current political landscape in Colorado?

a. Considering these policies, how can TNC Colorado best improve carbon sequestration in Colorado?

Appendix D - Carbon Stock Range Table

Table D1: Range of Estimated Carbon Stocks by Land Cover Type (Units: MT CO_2eq)

Land Cover Type	2011	2021	2031	2041	2051	Stock n=	Flux n=
Forest	2,996,072,733	3,000,309,704	2,976,303,769	2,888,629,624	2,722,011,253	12	6
Grassland	900,962,860	899,217,199	895,910,115	890,633,569	883,062,664	3	7
Shrubland	670,977,956	728,804,053	810,417,576	913,922,363	1,035,947,765	5	6
Woodland	1,543,359,975	1,561,485,979	1,528,068,580	1,454,898,924	1,358,247,635	4	1
Agriculture	260,454,972	260,630,536	261,410,627	262,867,589	264,934,531	4	15
Wetland	122,515,504	138,913,347	156,624,228	174,303,301	191,237,628	7	3
Other Land	26,447,543	26,441,057	26,660,349	26,989,977	27,397,554	5	6
Developed	164,674,829	182,015,092	211,802,522	255,092,173	313,418,712	5	8