Quantifying the Potential Scale of Mitigation Deterrence from Greenhouse Gas Removal Techniques

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Non-technical Summary

Greenhouse Gas Removal Techniques (GGR) appear to offer hopes of balancing limited global carbon budgets by removing substantial amounts of greenhouse gases from the atmosphere later this century. On the basis of a review of the expectations of GGR implied by integrated assessment modelling this paper categorises ways in which delivery or promises of GGR might deter effective climate mitigation, and estimate their extent. It questions the technical and commercial feasibility of delivering high levels of carbon removal, and highlights how promised GGR largely *substitutes* for possible emissions reductions rather than *supplementing* them (for example through various forms of climate offsetting). It also identifies and offers preliminary estimates of the scale of some possible rebound effects and other indirect increases in emissions arising from the pursuit of GGR. It concludes that the combined outcome of such deterrence effects could result in enough additional greenhouse gases in the atmosphere to raise global temperatures by 0.7-1.4°C.

Technical Summary

Greenhouse Gas Removal Techniques (GGR) appear to offer hopes of balancing limited global carbon budgets by removing substantial amounts of greenhouse gases from the atmosphere later this century. This paper seeks to estimate the extent to which delivery or promises of GGR might deter effective climate mitigation. It examines the expectations of GGR implied by integrated assessment modelling, and the changing role of emissions reduction in the models following the introduction of GGR technologies, and following the shift from a 2°C global target to one of 1.5°C. The paper suggests and illustrates a categorization of mitigation deterrence effects designed to enable theoretical quantification of the carbon at risk. *Type 1* is described as 'substitution and failure': around 80% of the 120-300Gt-C of expected GGR substitutes for emissions otherwise reduced, yet may not be delivered (as a result of technical shortcomings, leakage, or the diversion of captured carbon into short-term utilization. *Type 2* encompasses rebounds, multipliers and side-effects, such as those arising from land-use change, or use of captured CO2 in enhanced oil recovery. We estimate conservatively that this could add 30-140Gt-C to unabated emissions. Type 3, described as 'imagined offsets' is estimated to affect perhaps 20% of the residual emissions reductions required, adding a further 160-260 Gt-C to unabated emissions. The combined effect of these net additions of GHGs to the atmosphere is equivalent to 07-1.4°C additional temperature rise. The paper concludes that this merits further deeper analysis and serious consideration of measures which might limit the occurrence and extent of mitigation deterrence.

Contents

Introduction

In the context of aspirations to limit the average global temperature rise to 2°C or even 1.5°C, techniques which can draw greenhouse gases (GHG) from the air (variously called Carbon Dioxide Removal (CDR), Greenhouse Gas Removal (GGR) or Negative Emissions Techniques (NETs)) have become increasingly significant to climate policy. Integrated Assessment Modelling (IAM) has suggested that very substantial use of such techniques is likely necessary to stabilise atmospheric GHG concentrations at levels compatible with limiting temperature rises to 2°C or lower (Fuss, Canadell et al. 2014, Wiltshire and Davies-Barnard 2015, Minx, Lamb et al. 2018). In climate pathways that meet such goals, GGR is primarily deployed (notably in the form of bioenergy with carbon capture and storage (BECCS), and typically later in the century) as a supplement to accelerated levels of other mitigation. Even though within the pathways models some proportion of GGR inevitably substitutes for otherwise feasible - albeit costly - emissions reduction, GGR is presented in policy terms as an essential addition to otherwise constrained possibilities for effective and affordable mitigation. Moreover, this occurs despite the availability of a minority of studies that suggest that - with extremely ambitious mitigation - the deployment of GGR might be minimised or even eliminated (Grubler, Wilson et al. 2018, van Vuuren, Stehfest et al. 2018).[1]

In this context, it remains critical to better understand the interactions between GGR techniques and mitigation practices. In particular, might elevated consideration of GGR deter or delay otherwise anticipated mitigation? Do promises of GGR substitute for action to deliver or accelerate mitigation? In such cases, what happens if GGR cannot deliver on its promises? This is particularly important while GGR techniques remain largely technological imaginaries, unproven at the scales anticipated. In this paper we seek to categorise such interactions, and consider how significant they could be for the delivery of overall climate goals. Whilst some researchers have questioned the technical feasibility of delivering the high levels of carbon removal implied in pathways modelling towards futures in which global temperature rises do not exceed 2°C (Fuss, Canadell et al. 2014, Anderson and Peters 2016, Larkin, Kuriakose et al. 2017), here we combine such analysis with assessment of the extent to which promised GGR substitutes for emissions reductions rather than supplementing them. We also estimate the potential scale of rebound effects or other indirect increases in emissions arising from the pursuit of GGR.

The paper proceeds by defining mitigation deterrence. It discusses and begins to characterize possible mechanisms of mitigation deterrence within the modelling frameworks. It then describes a 'carbon at risk' approach designed to enable assessment of the scale and significance of mitigation deterrence. To estimate the quantitative range of carbon at risk it draws primarily on modelling studies targeting 2°C or radiative forcings of 2.6 W/m^2 in 2100 (RCP2.6). Although some of the 2°C pathways analysed show potential for achieving 1.5°C (typically following some overshoot), more generally the lower temperature goal could be expected to require more stringent emissions reductions and/or higher levels of GGR deployment than in 2°C pathways. The paper therefore additionally considers how the pursuit of 1.5°C might affect the carbon at risk in our approach. Finally conclusions are drawn. Our emphasis throughout is on estimating an upper bound, or worst-case outcome from mitigation deterrence, because of the irreversibility of decisions which permit substitution of future GGR for earlier emissions reduction.

Mitigation Deterrence: Definitions, mechanisms and issues arising

Mitigation deterrence (MD) is here defined as 'the prospect of reduced or delayed emissions cuts resulting from the introduction or consideration of another climate intervention' (Markusson, McLaren et al. 2018). Understood this way, MD will potentially, although not necessarily, lead to serious harm. Possible harms may arise in either or both of two forms (Markusson, McLaren et al. 2018). First in the form of greater climate risk arising from elevated GHG concentrations (resulting from delay of mitigation or failure of the alternative intervention). Second, in the form of reduced co-benefits or more serious side-effects where the alternative intervention substitutes for other mitigation. Here our focus is on GGR as an alternative climate intervention and on the potential that its introduction or consideration might (perversely) lead to a *net*

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[1] In early modelling of pathways with GGR (before the Copenhagen COP), BECCS is typically introduced as a means to reduce costs, but in recent years, and especially since the Paris COP, GGR appears as a technical essential, even though it still substitutes for other mitigation to some degree (see AMDEG WP3, forthcoming at http://wp.lancs.ac.uk/amdeg/).

increase in atmospheric GHG concentrations in comparison with a situation without such introduction or consideration. In this paper, as in current climate policy research more generally, we typically consider the evolution of emissions and removals over a timeframe to 2100.

There are three broad ways in which consideration or introduction of GGR could lead to unanticipated harmful additions to atmospheric GHGs over the coming century. First if GGR formally substitutes for emissions reductions, and then fails to materially deliver ('failure'). Second if side effects or rebounds from GGR generate increased emissions ('rebounds'). And third if the imagined future availability of GGR encourages or enables the avoidance or delay of emissions reductions without any planned or formal substitution mechanism (we call these 'imagined offsets'). We describe and categorise these as *three types* or mechanisms of MD.

These three types might alternatively be conceptualised as different ways in which GGRs *fail* to meet the objective of lowering concentrations. They might also all be understood as different ways in which decision makers, in relying on GGRs to help achieve their climate goals, are exhibiting *over-optimism*. In whichever way one conceptualises these mechanisms it is important to recognise that they encompass both intentional and emergent responses to GGR consideration or deployment. Failure here does not mean that the GGR technique itself necessarily fails to function, but that the system wide impacts are such that the purpose of GGR is not realised. The largely unproven nature of GGR (Larkin, Kuriakose et al. 2017, Rosen 2018)) means that such failures are clearly possible, but hard to quantify.

To unpack a little, in **Type 1**, the technique might *fail to perform* to expectations in one or more various ways in the chain between atmosphere and storage (See Figure 1). The technique might not prove commercially or technically viable, and thus not be delivered, so failing to capture any carbon. Or it may prove less efficient (while still viable) - with lower than anticipated rates of capture once energy inputs or other life-cycle carbon emissions are accounted for. As a result it would be more expensive than expected, and likely to be deployed less widely. The overall efficiency of carbon removal could also be depressed if carbon successfully captured were to leak from processing equipment, pipelines, or subsequent storage, or be diverted to carbon utilisation. Diversion to carbon utilisation simply delays the return of CO_2 to the atmosphere by months, years, or at best decades, through its use as synthetic fuels, plastics or building materials. All such failures reduce the climate effectiveness of the technique (as shown in the orange boxes in Figure 1). The maximum carbon at risk from such failures cannot, however, exceed the amount promised by successful deployment. Moreover such failures only result in net increases in atmospheric GHGs (and thus additional climate harm) insofar as GGRs have been permitted to substitute for emissions cuts or function as offsets for emissions growth (whether or not that substitution was intended, or appeared 'rational', in foresight).[2] Such substitution could come about in several ways. GGR removals could be traded in existing carbon markets. Policy makers could set reduced targets for emissions reduction, planning to make up the difference with GGR. GGR could be promoted within a specific sector as a means to avoid the reduction of recalcitrant emissions – for example, the agriculture sector might claim that soil carbon storage should be treated as an offset for remaining emissions form livestock or fertilizer. GGR could even be driven by a particular sector – the airlines might develop new voluntary offsetting schemes in which they, or even individual passengers, could purchase GGR removals. In summary, however, *harmful* Type 1 MD is the result of *both* substitution *and* subsequent failure. To estimate its extent we will need to quantify not only how much carbon might be at risk of performance failure, but also what proportion of this was an offset or substitute for other mitigation.

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[2] If GGR is promised as an addition to emissions reduction, but then fails, this will result in additional climate harm, but it is not strictly as result of mitigation deterrence. For further illustration see Figure 2: such additional GGR would reduce the amount of unabated emissions (the solid green area in column 2), and its failure merely [!] returns the outcome to that prevailing before the introduction or consideration of GGR. However should GGR which has substituted for emissions reduction (the hatched green area in column two) then fail, the outcome would be an increased quantity of unabated emissions in comparison with the situation in which GGR was never considered.

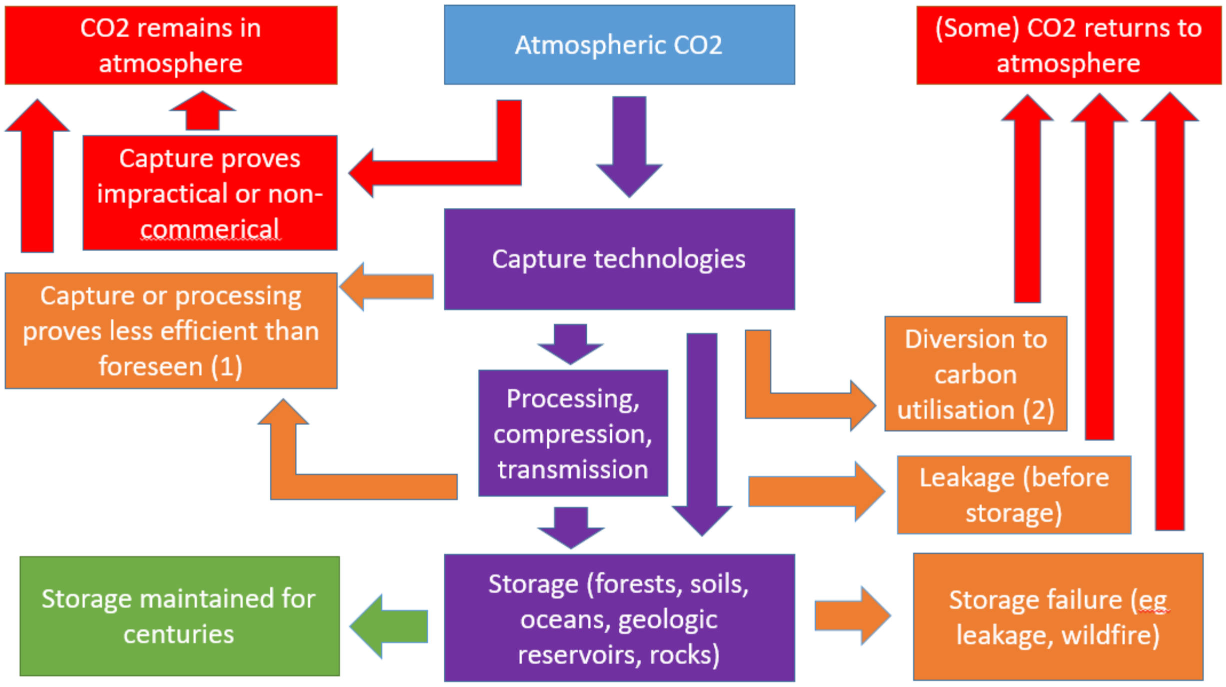

Figure 1: The GGR chain (and possible failures)

Notes to figure 1:

Possible failures are shown in orange and red boxes. Success requires negotiating the purple and green track.

1) Many capture routes require some energy (eg for grinding minerals for enhanced weathering, or to regenerate the capture medium). In the absence of a completely decarbonised energy system, lower energy efficiency of capture processes means lower net removal of GHGs.

2) Diversion to carbon utilization results in re-release to the atmosphere on various timescales shorter than the millennial timescales required for effective GGR. Utilization in enhanced oil recovery results in indirect generation of additional emissions from the additional oil produced.

The other two types of MD (ways in which GGRs might lead to additional atmospheric GHGs) are not limited to the carbon drawdown promised by GGRs. The second form of failure/overoptimism (**Type 2**), constitutes rebounds and similar indirect effects in which the GGR might trigger *additional emissions*, for example through enhanced oil recovery, carbon emissions from soils converted to biomass production, or additional economic activity stimulated by any part of the GGR supply chain. With perverse incentives, or even just inaccurate data, it is even possible that a GGR developer might continue to operate a technique which led to more emissions (from energy supply, for example) than it captured from the atmosphere.[3] Similar failings in the wider system (such as greater emissions from indirect land-use change (ILUC)) have been observed with biofuels, and therefore must be considered. One notable risk amongst such unintended effects of attempted material implementation of GGR would appear to be that of the injection of captured CO_2 as a tool in enhanced oil recovery (EOR), which is already practiced in some early BECCS schemes, and incentivised by tax breaks in the USA. There is typically more carbon in the oil recovered from EOR than stored (Godec, Kuuskraa et al. 2011, Armstrong and Styring 2015, Godec, Carpenter et al. 2017) and on average EOR appears to increase the GHG intensity of oil production (Masnadi and Brandt 2017).

Finally, in **Type 3** MD the (immaterial) promise alone of GGRs may stimulate excess reductions in mitigation (over and above any apparently 'economically rational' substitution or formal offsetting – as included in

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[3] One route in which such a result might arise is from a GGR using gas as a feedstock, or as a heat-source, failing to account accurately for methane leakage in gas production, where estimates of carbon intensity are disputed and differ by up to a factor of two (see, for example Alvarez et al 2018).

Type 1 above), leading to increases in emissions that total more than the anticipated, and practically limited, potential cumulative capacity of GGR technologies. The result would be a net increase in atmospheric GHGs, and additional climate harm (Markusson, McLaren et al. 2018). This is irrational at the system level, but not necessarily for individual actors, whose individual expectations that future GGR could replace each of their otherwise required emissions reductions might be reasonable, but in aggregate impractical. And many actors face political, financial or cultural incentives to postpone mitigation in favour of future alternatives. Without some mechanism to restrain such imagined offsetting it is entirely plausible that the total mitigation deterred would exceed any possible practical future GGR capacity.

Conceptually, it is important to be clear why we characterise all three routes as forms of mitigation deterrence, rather than merely as types of technological failure. Type 1 MD is a deterrent insofar as the modelled promise of GGR permits decision makers to reduce (or permit reductions in) mitigation, but unforeseen failures (over-optimism about the practical delivery of GGR) means these reductions are not replaced by GGR withdrawals in practice. In other words, the promise of GGR replaces some mitigation, but then the GGR does not deliver. As a result the carbon in anticipated GGR is at risk from mechanisms including technical failures or intentional diversion to utilisation.

Type 3 MD is distinguished from Type 1 because it represents additional reductions in mitigation that are never matched by additional promises of GGR. It leads to climate harms regardless of whether the GGR promised is delivered or not. While an amount of substitution of GGR promise for mitigation at the heart of Type 1 might be understood to be economically ‘rational’ if the expected mitigation cost exceeds the expected GGR cost, it becomes irrational or excessive if mitigation that is cheaper than GGR is so substituted, or if more mitigation is substituted than the maximum practical withdrawals achievable through GGR (which might be constrained by a range of factors other than cost). Both types 1 and 3 are therefore easily understood as forms of over-optimism, type 1 being over-optimism about the deliverability of GGR, and type 3 about its scale.

Type 2 MD is also a result of over-optimism, in that rebounds or system leakage effects arising from the development of GGRs are not foreseen: the ‘rational’, but actually optimistic, decision maker expects GGR to deliver as anticipated, and not to have any second-order effects on total emissions. Here the mitigation ‘deterred’ is, for example, that achievable through abandoning residual oil in wells, or protecting carbon in soils.

In most of the diverse potential mechanisms sketched in the descriptions of the three types above it is difficult to predict or quantify the scale and effects of mitigation deterrence. The counterfactuals are themselves riddled with uncertainties, and innovation is, by definition, unpredictable.[4] Failures, rebounds and both formal and imagined offsets themselves can be expected to intersect and interact in diverse ways. It is conceivable also that there may be positive synergies that offset or even outweigh deterrence effects. Nonetheless, because of the potential for harm associated with them, we focus here on the possible negative interactions.

For the sake of illustration, new synergies arising between the delivery of GGR and the delivery of mitigation might also take several forms. For instance, better biomass combustion efficiencies might benefit both BECCS and bioenergy. Or improved carbon capture technologies in direct air capture might cut the costs of fossil CCS. In the event of successful deployment of GGR, such synergies would result in greater reductions in GHG concentrations than anticipated in the modelled pathways. Here we do not pursue the possibility of synergies further. Unlike deterrence, some synergies are effectively included in RCP pathways through the learning curves embedded in the integrated assessment models (IAMS). Moreover, should synergies prove more significant than anticipated this reduces the lower bound of the harm below zero, while our focus is on defining the upper bound, as an initial step towards assessing the significance of different possible

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[4] Similarly the counterfactuals for modelling of climate policy outcomes are highly uncertain, so the estimates such models produce of the gap between predicted emissions and predicted mitigation vary significantly. We should therefore be cautious in predicting a need for GGR on the basis of such an analysis of residuals.

mechanisms of deterrence. In this respect, we believe it is incumbent on researchers and policy makers to consider the worst case scenarios associated with the promises of new technologies such as GGRs. In this case we see the possibility of unintended or deliberate efforts to deploy GGR promises to deter near-term emissions reductions as the worst case, in contrast with technologies such as AI, or even solar geoengineering, which might be deliberately weaponised. This paper therefore sets out an approach that permits us to derive an initial estimate of the upper bound of the quantitative scale of the possible effect of mitigation deterrence. In the next section we develop an estimation of carbon at risk, designed to permit the subsequent calculation of associated global temperature changes.

Carbon at Risk

This section aims to quantify the carbon at risk, taking each of the three types of deterrence set out above in turn. The three types are schematically shown in Figure 2.

Our approach builds on global carbon budget (Anderson and Bows 2008, Allen, Frame et al. 2009) and 'emissions gap' (UNEP 2017) analyses. Debate remains over the scale of budget available, the extent to which it has already been consumed, the degree of overshoot that might be safe, and how it might be fairly distributed (Peters, Andrew et al. 2015, Rogelj, Schaeffer et al. 2016, Millar, Fuglestvedt et al. 2017, Peters 2018, Rogelj, Popp et al. 2018). However, the IPCC's Special Report on 1.5°C (IPCC 2018), suggests a range of 115-210 Gt-C remaining for 1.5°C as of 2017. Given current emissions rates, the range for 2020 would be 80-176 Gt-C. This is higher than figures based on AR5 estimates (Pachauri and Meyer 2014) and subsequent emissions rates but still lower than remaining 2°C budgets based on AR5 (approx. 260 Gt-C) and the remaining 1.5°C budget would still be depleted by 2030 given continued emissions at today's rates.[5] In theory, to avoid exceeding these maximum target levels of temperature rise, by the time such additional emissions have occurred, the global economy must have achieved a net zero emissions state. In other words, if emissions were to immediately start declining, and then declined linearly, this implies achieving global net zero by about 2050, or experiencing overshoot of emissions which can only be reversed through GGR.[6] Moreover, most pathways assume that net zero emissions will be achieved through some deployment of GGRs to offset continuing (or 'residual') emissions from sectors or activities that are particularly hard to mitigate (often described as 'recalcitrant' emissions). After accounting for expected mitigation, any excess emissions above the remaining budget (overshoot) must *also* be offset by GGRs to limit temperature rise to the desired level (in the long term). Modelled estimates of the levels of GGR required therefore reflect assumptions about several factors: the overall budget, the level and rate of business as usual emissions, the level and rate of achievable mitigation, and the level of recalcitrant emissions.

Figure 2 shows global carbon budgets in three climate policy states. The first column depicts the carbon budget prior to consideration of GGRs. The total bar represents 'business as usual' carbon emissions. The blue section represents the emissions reduction required to avoid dangerous climate change, leaving residual cumulative unabated emissions (shown in the red section). The red and blue sections are schematically scaled to roughly reflect mainstream estimates of the remaining safe carbon budget and the overall cuts in emissions implied: that a safe residual budget might constitute perhaps 10-15% of the anticipated cumulative emissions to 2100 (80-176 Gt-C of otherwise anticipated emissions of 650-1300 Gt-C). In the second column the green zone represents the 'promises' of NETs, which contribute to, and may increase the mitigation expected. Modelling – albeit largely that exploring 2°C scenarios - suggests a substantial degree of substitution (60-100% - shown in the blue and green hatched area) as apparently affordable NETs replace more expensive emissions cuts. The precise location of the boundary between GGR removals that supplement mitigation and those that substitute for it is debateable. Again the overall scale of the GGR contribution roughly represents the amounts suggested in the literature (as summarised below

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[5] These figures take account of different temperature data sets, and different probabilities (50-66%). Larger budgets still can be suggested, depending in part on the assumptions made about other greenhouse gases and forcings (Millar et al 2017). These might delay the case/need for GGR, but do not appear to eliminate it.

[6] The likely associated subsequent overshoot of temperatures might be compensated for through solar geoengineering, but any emissions overshoot can only be corrected by carbon removal.

– a cumulative amount of roughly 150-300 Gt-C). All of the green area (both hatched and non-hatched) is at risk if NETs fail completely, as shown in the third column. But in addition there may be risks from the two further distinctive types of mitigation deterrence noted above (shown here as the orange and purple hatched areas). Again the relative scale of the sections roughly reflects our analysis below. But here the uncertainties are much greater, particularly with respect to the scale of type 2 and 3 effects.

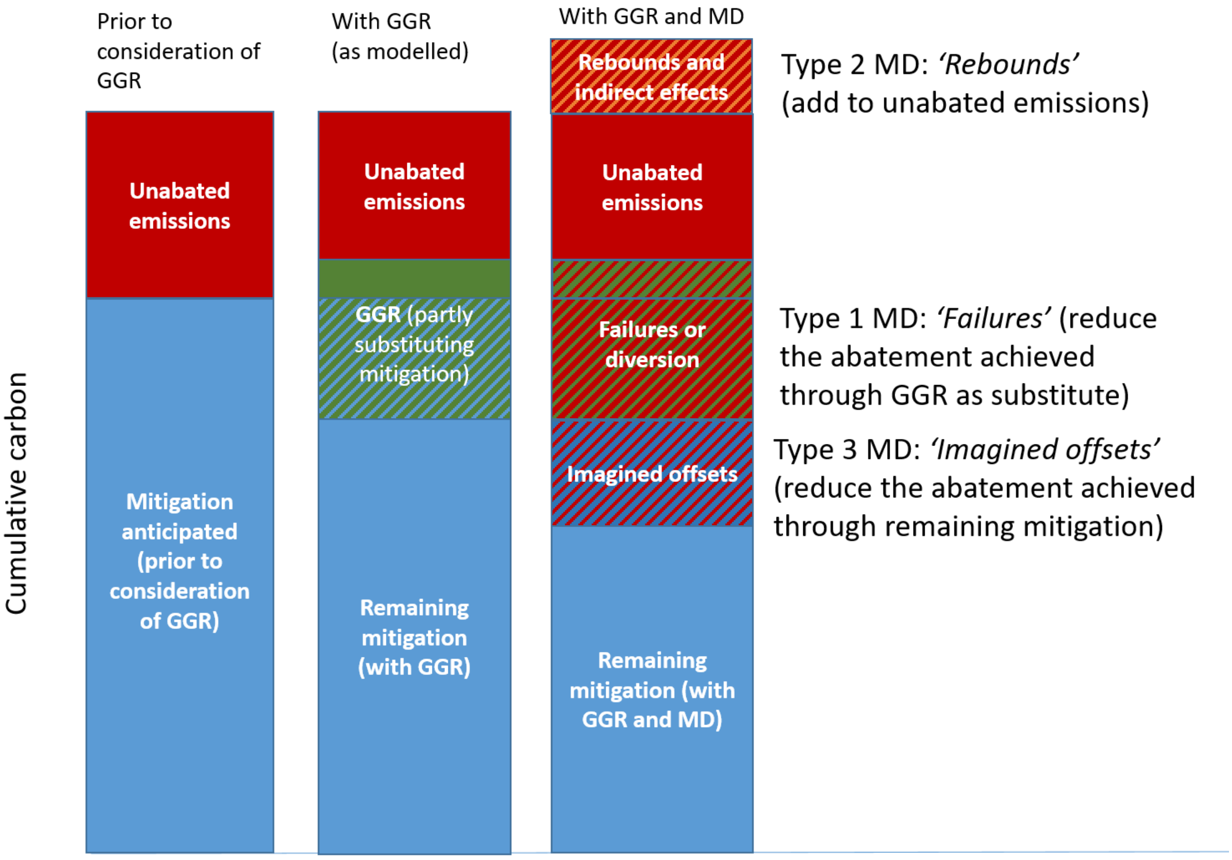

Figure 2: Schematic representation of the carbon at risk approach to mitigation deterrence

Methodologically, to estimate types 1 and 2 carbon at risk, we analyse modelled pathways to obtain estimates for the total contribution anticipated by GGR, the proportion of that contribution which (in the models) already substitutes for mitigation, and the total remaining mitigation that might be proportionally affected by GGR promises. We additionally apply estimates of possible rebound effects to offer an initial figure for the possible scale of type 3 carbon at risk. This paper next reviews expectations on the amount of carbon dioxide GGR is anticipated to remove, as an essential foundation for estimating carbon at risk.

Expectations of carbon removal by GGR, and the risk of failures (Type 1)

The amount of carbon at risk from type 1 MD depends fundamentally on how much carbon NETs are expected to remove. The whole of that amount will be at risk if complete failure of GGR to deliver removal and long-term storage is at all plausible (as suggested above), although only the substituted portion would fall into the category of 'mitigation deterrence'. Future work in this project will help evaluate the likelihood of such scenarios of failure. The extent of potentially harmful mitigation deterrence depends on how much of the expected carbon removed substitutes for emissions reduction, how much of the expected carbon removal actually arises, and how much of it might be replaced by other climate action after any failure becomes apparent. In this section we present a cumulative estimate of 144-304 Gt-C of expected GGR that substitutes for mitigation by emissions reduction, and may be vulnerable to failure.

There are a wide range of claims and estimates about the potential for different types of carbon removal. Here we focus only on the expectations embedded in integrated assessment modelling, treating these as a means to quantify current expectations amongst the climate policy community. This section examines the outputs of a range of modelling exercises targeting both 2°C and 1.5°C outcomes. While the outcomes of integrated assessment modelling do not determine the intentions and actions of climate policy, the expectations and technology choices that modelling embodies would appear to strongly influence policy makers' aspirations nationally and internationally, as well as reflecting them.[7] Almost all of the modelling to date has deployed BECCS as the only cost effective GGR option (alongside land-use carbon sinks, which are generally found at fairly similar levels in all scenarios). As a measure of the level of GGR needed in the models to meet particular carbon budgets and particular temperature outcomes, BECCS therefore functions as a placeholder for all GGR.[8]

To begin our quantitative estimation we review the prevalence of GGR in sub-2°C pathways (Tavoni and Socolow 2013, van Vuuren, Deetman et al. 2013, Rogelj, Luderer et al. 2015, Wiltshire and Davies-Barnard 2015, Fricko, Havlik et al. 2017, IPCC 2018, Luderer, Vrontisi et al. 2018). The results are summarized in Table 1 below, which shows a selection of pathways in which the cumulative contribution of GGR by 2100 is explicitly identified.

The studies considered use diverse terminology to discuss the targets, and their assumptions about climate sensitivity vary, but taken together they provide a good sense of the scale of GGR expected. They also begin to reveal the worrying extent to which GGRs substitute for emissions reduction, especially in 2°C pathways, as a result of cost-optimisation based on highly uncertain cost estimates. By considering a range of studies, we make some allowance for the underlying variation in models, as well as the variation in parameters in specific studies. It is important to note that the range of figures for GGR deployment, within and between models, reflects several factors. These include the underlying assumptions regarding the cost and practicality of deployment; and constraints set to the possible scale of deployment (such as limits to biomass supply, or rising costs); the assumptions about the costs and practicality of mitigation; and the scale of the counterfactual level of mitigation implied by the assumed underlying business as usual baseline.

From the studies summarised in Table 1 we identify a central range of GGR carbon removal anticipated to achieve 2°C, of 120-300Gt-C. This equates to 1.5-3.75Gt-C pa. Static carbon budget analysis would suggest that to achieve a 1.5C target, an additional 250Gt-C removals would be necessary (an extra 3.12 Gt-C pa). However, the dynamic modelling in those studies which have engaged with 1.5°C suggests a much lower increment. Using studies that have also examined a 1.5°C target, and published comparable results, suggests a median increment of as little as 60Gt-C, and a maximum of no more than 100Gt-C. This is – it would seem - achieved because the models have largely exhausted cost-effective GGR at 2°C, and therefore instead mobilise significantly more emissions reduction to achieve 1.5°C, bringing forward the net-zero emissions date by decades and increasing the overall spending on emissions reduction dramatically.

The effects of the new target can be seen in a range of studies. For all GGR (in practice BECCS plus land-use sinks), Rogelj, Luderer et al. (2015) find a median of around 125Gt-C for all scenarios with a 50% or better chance of achieving 2°C (and a range (from the 15th to the 85th percentile) of 75-230Gt-C). For scenarios with a 50% or better chance of delivering 1.5°C, the median rises by almost 100Gt-C to 220Gt-C, with a range of 125-275 Gt-C.[9] Rogelj, Popp et al. (2018) calculate BECCS removals (excluding land-use sinks) of 40-

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[7] See AMDEG Working Paper 3, forthcoming at http://wp.lancs.ac.uk/amdeg/

[8] We recognise that BECCS may have different susceptibilities to MD, and different failure routes to other GGRs, but as a means of calculating the GGR carbon 'at risk' we can treat it as a proxy for the total GGR deployment expected in models that do not include other GGR techniques. We return to the question of the feasibility of particular technologies to deliver particular levels of carbon removal later. We also note that the models may treat BECCS in different ways. Where BECCS is modelled generically, or included as separate technologies for electricity, fuels and hydrogen production, the models seem likely to deploy more of it that where it is restricted to fuels and electricity, or just the latter (Tavoni and Socolow 2013). Unfortunately such detail is rarely specified in the literature.

[9] Rogelj et al 2015 base their analysis on 200 scenarios from two 'highly responsive' IAMs, which would seem to explain why they

327Gt-C cumulative across three 1.5C SSPs (0.5-4.1Gt-C pa). [10] They note that 82-98% of the additional cumulative improvements over 2°C scenarios comes from reduced emissions, with more than a tripling of short term costs, and a decades earlier achievement of net negative for the energy sector – by 2040. Luderer, Vrontisi et al. (2018) et al also compare 1.5 and 2.0°C scenarios (both at 67% chance). In their modelling, BECCS delivers a median of 199Gt-C in 1.5°C scenarios, up by 60Gt-C (or 43%) from their 2.0°C scenarios. Net land use removals rise to 41Gt-C, up from 25Gt-C. But emissions reduction rises by 196Gt-C, suggesting the presence of very substantial amounts of technically feasible (but relatively expensive) mitigation that are not adopted in the pursuit of a 2°C target with GGR available. It appears that an economic substitution effect pushes up the total GGR in 2˚C scenarios, where it effectively replaces or offsets more expensive mitigation. But the tougher 1.5˚C target raises the implicit price of carbon in the models and some of this higher cost mitigation (eg improving energy efficiency of buildings) becomes competitive again.[11]

Table1: Estimates of the scale of GGR required to 2100

Source (context)	**Cumulative GGR (Gt-C, to 2100)(a)**	**Target**	**Notes**
Wilshire et al (2015)(median) (90% level)	166 372	2°C ('compatible with') 2°C (90% chance)	All compatible IPCC models/scenarios
Gasser et al (2015) (favourable) (unfavourable)	25-125 450-800	2°C (overshoot permitted)	Extreme counterfactual scenarios included
Peters and Geden (2017)	117-202	2°C (‘cost optimal’, BECCS only)	5 models
Rogelj et al (2015)	75-230 125-275	2°C (50% chance) 1.5°C (50% chance)	15th-85th percentile
Edmonds et al (2013)	180-376	RF 2.6	
Kriegler et al (2013)	128-248	RF 2.6 / stabilization at 450 ppm	
van Vuuren et al (2013)	130-218	2°C ('high chance')	
Fuss et al (2013)	436	sub 2°C	base case, unfavourable
Chen and Tavoni (2013)	212	stringent climate stabilization'	
McLaren (2012)	327	350 ppm	Favourable
Fricko et al (2017)	90-149 (b)	RCP 2.6	3 SSPs
Rogelj et al (2018)	38-262 44-327 (b)	2.0°C 1.5°C	6 models
Luderer et al (2018)	98-210 175-259	2.0°C (‘67% chance’) 1.5°C (‘50% chance’)	All GGR
IPCC (2018)	0-325 41-113	1.5°C (’50-66% chance’) ‘central range’	Very favourable emissions pathways

Notes to table 1: (a) Ranges reflect reported ‘dependency’ on GGR. (b) In these studies, some models/scenarios could not resolve for the target level

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estimate a lower need for GGR than Wiltshire et al (2015). Interestingly, almost half of their BECCS capacity is deployed on biofuel, which in current forms does not generate negative emissions, but merely offsets some of the remaining tailpipe emissions. In such forms it would not contribute to net removals in a net negative world.

[10] Landuse change might generate as much as 40-60 Gt-C (equivalent to 0.5-0.75Gt-C pa, also loaded heavily to later in the century where rates peak at 1.1-1.2 Gt-C pa) (Fricko et al 2017).

[11] This analysis seems to also eliminate the possibility of a GGR-CCS synergy at play. If BECCS were to generate learning on CCS and thus lower the costs of CCS, we would not expect it to have displaced so much mitigation in 2°C scenarios. However a definitive analysis of the interplay between BECCS and fossil energy CCS would require more detailed disaggregation of the model findings.

The studies which provide comparable figures for GGR deployment in 2°C and 1.5°C scenarios tend to be either those which present lower overall totals of GGR use, or find that staying within 1.5°C is only achievable in favourable scenarios, and thus only present figures for such favourable contexts. As a result we cannot simply take their average GGR figures as the total carbon at risk (these figures would be consistently biased on the low side). To estimate an average total carbon at risk, we therefore add a central range from the shift to 1.5°C (60-80Gt-C) to the central range for 2°C reported above, giving a best estimate of 180-380Gt-C (or 2.25-4.75 Gt-C pa). We will return to the implications of the elevated mitigation demanded by 1.5°C pathways in considering type 3 MD below.

The range of scenarios also reveals the significance of assumptions about the counterfactual levels of mitigation. Models that assume higher levels of business as usual emissions generate higher deployment of GGR even in achieving the same RCP pathway. Those, like the IPCC (2018) stylised pathways, which foresee relatively swift and easy emissions reductions generate much smaller GGR deployment. Tavoni and Socolow (2013) summarise five different studies, which taken together involve cumulative removal of between 128 and 436Gt-C by 2100. The top end of this range includes pathways in which the counterfactual involves very limited mitigation. Yet Gasser, Guivarch et al. (2015) suggest an even wider range of 25-800Gt-C by 2100. They calculate a range of 450-800Gt-C by 2100 in those 2°C scenarios (with overshoot of both temperatures and concentrations, and where stabilisation only occurs by 2300) where the counterfactual is a world in which emissions do not peak until 2030 and then only decline at 1% per year. In contrast they find a range of just 25-100 Gt-C GGR in a set of 2°C scenarios (again with permitted overshoots) where the counterfactual is a world where emissions peaked in 2015 and are already declining at 5% per year.

Across the set, for scenarios where the counterfactual broadly resembles a RCP 6.0 world, achieving the 2°C target (or RCP 2.6) demands cumulative removal of 128-376 Gt-C with a median value of 252 Gt-C (see Table 1). Fricko, Havlik et al. (2017) use the shared socio-economic pathways (SSPs) to undertake a similar analysis. They find that in SSPs 1-2 RCP2.6 could be achieved with around 90-100 Gt-C removals by BECCS , but that in SSP3, RCP2.6 becomes unachievable with their model, with 149 Gt-C removals required to achieve RCP3.4.[12] The levels of GGR that would be required in SSP3 are not feasible given their assumptions. Under SSP2 this means 330Gt-C more mitigation is delivered than in SSP1, due to the less favourable context, and the limited availability of GGR. That the achievement of even a 2°C target is constrained in their models to favourable contexts suggests that higher expectations of GGR found in other models might be inappropriate, and vulnerable to type 1 MD (failure). In the IPCC analysis (2018) a similarly favourable world is portrayed, in which dramatic emissions reduction (global cuts over 90% by 2050; and around 50% by 2030) can be achieved. These reduction rates are much faster than in most of the studies reviewed here, and unsurprisingly, leave a relatively low estimate of GGR required. The relatively low figures in the IPCC and other recent analyses (such as Fricko et al, 2017; and Luderer et al, 2018) presumably also reflect the higher permitted 1.5°C budget presented by the IPCC (2018), which - other things being equal - also reduces the apparent call on GGR to achieve a particular target.

The technical feasibility of the delivery of hundreds of gigatonnes of GGR has already been questioned, in particular given the prevalence in the models of BECCS as the GGR technique of choice (Wiltshire and Davies-Barnard 2015, Anderson and Peters 2016, Vaughan and Gough 2016, Rosen 2018). Such critiques have stressed competition for land, and the prospect of countervailing increases in emissions from direct and indirect land-use change. However such analysis has not been brought together with an assessment of the extent to which GGR substitutes for mitigation within the modelled pathways, rather than supplementing it (as we do here).

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[12] In SSP1 scenarios the counterfactual RCP6.0 emissions over the century are 1180Gt-C, in SSP2 scenarios they rise to 1510Gt-C and in SSP3 to over 2000Gt-C.

Box 1: DAC in the models

Direct Air Capture has only rarely been modelled, typically reflecting assumptions that limit BECCS deployment. Chen and Tavoni (2013) model DAC alongside BECCS, and find 130Gt-C DAC cumulative removals alongside 80Gt-C from BECCS. Marcucci, Kypreos et al. (2017) model scenarios ranging from a 50% chance of 2°C to a 50% chance of 1.5°C. They estimate 4.3-11.6Gt-C pa removals are necessary by 2100, of which 3.1-10.4Gt-C pa is delivered by DAC. In a perfect parallel to the early modelling of BECCS, the promise of affordable DAC (with constraints on biomass supply) brings out DAC later in the century as a means of reducing costly effort earlier: "the perfect foresight of the model allows for a decrease in the deployment of BECCS and coal with CCS and an increase in gas … resulting in lower quantities of captured carbon from energy sources. This is later compensated by additional CO2 captured in the second half of the century using DAC" (Marcucci, Kypreos et al. (2017): 188).

Why substitution matters, and how much it happens in models

If the carbon projected to be captured and stored in GGR were all additional to mitigation, then underperformance – for example because of technical shortcomings - would merely reduce the overall abatement achieved relative to the baseline scenario. Seriously harmful as that prospect might be, GGR would still be contributing, albeit in a limited way, to climate abatement. But if the projected GGR carbon substitutes partly or wholly for carbon that would otherwise have been abated through mitigation of emissions, then the net effect of reliance on underperforming GGRs could be a perverse and unexpected net increase in GHG concentrations relative to the baseline. In other words, where there is both substitution and failure, there is not simply deterrence, but necessarily harmful deterrence.

The extent to which GGR substitutes for, rather than supplements mitigation is therefore critical. Modelling using Integrated Assessment Models (IAMs) treats GGR to some degree as a substitute for expensive forms of mitigation, rather than as a supplement to practically limited mitigation. Reviewing findings from five IAM models, Tavoni and Socolow (2015) report that in all cases *"CDR availability reduces conventional mitigation early in the [current] century, relative to base cases where no CDR is available … The extent of late CDR and associated reduction in early conventional effort depends on the discount rate"* (pp6-7). Our default assumption should be that some degree of substitution will occur, and the evidence available suggests that the degree is likely to be significant (Azar, Johansson et al. 2013, Tavoni and Socolow 2013, Riahi, Kriegler et al. 2015).

We estimate the extent of substitution as about 80% of the total GGR deployment, basing this on studies that forecast emissions reductions to be 1.7-2.45Gt-C pa lower in pathways with substantial deployment of GGR (Azar, Johansson et al. 2013, Riahi, Kriegler et al. 2015). Riahi, Kriegler et al. (2015) find that annual emissions in 2050 reach a level around 2.45Gt-C (or 17%) higher in a model which deploys high levels of BECCS. Azar, Johansson et al. (2013) estimate that with BECCS expected in the later half of the century, cumulative emissions between 2010 and 2050 in 2°C pathways rise by 68 Gt-C (1.7Gt-C pa), and in total from 393 Gt-C to 461 Gt-C. The implications are made more problematic by the timing. Mitigation delayed in the first half of the current century largely cannot be substituted for by elevated mitigation in the second half of the century, but rather will continue to have a growing impact on cumulative emissions. In other words should GGR prove infeasible, the climate damage of delay will be largely irreversible. If the shortfall identified by Azar et al were to continue over the entire century, in the face of a constantly receding promise of GGR, it would reach 153 Gt-C (90*1.7Gt-C). 2.45Gt-C pa (Riahi et al's figure) extended over the century would accumulate 196Gt-C. A cumulative amount of 153-196Gt-C is not dissimilar to the range of 120-300 Gt-C removals estimated earlier and shown in Table 1. In Azar et al's pathways (2013) the shortfall in mitigation continues until 2070 or 2080, and the cumulative excess emissions significantly outweigh cumulative GGR in the remainder of the century (as removals continue until 2150). In other words treating 60-100% of cumulative GGR both as a substitute and 'at risk' is not unrealistic (at least in 2°C pathways). For illustration we here use a rate of 80% substitution.

So if no GGR materialises, then - as a first approximation - in the order of 96-296 Gt-C more carbon will accumulate in the atmosphere over the period to 2100, raising global temperatures by 0.2 – 0.6°C. In 1.5°C pathways the equivalent is 144-304Gt-C. Such scenarios may seem implausible, as they imply a period of 70-80 years in which GGR remains a technical promise, but delivers no practical results. However, experience with fusion power (noted above), should give us pause for thought, as should recent experience with CCS (Markusson, Dahl Gjefsen et al. 2017). Moreover, some modellers are already extending the timelines for overshoot into the 22nd century, in which case it becomes easier to postulate that unredeemed promises might continue to wield legitimacy even as this century comes to an end. 2°C scenarios already exhibit a significant degree of dependence on GGR. Our review indicates that a median of around 250 Gt-C, of a total abatement in the order of 650-1300Gt-C over the period to 2100, is delivered by GGR. But even the stringent mitigation scenarios we reviewed exhibit significant variation in the amount of GGR deployed. In (unfavourable) scenarios with higher underlying demand for fossil fuel use or higher costs for, or tighter constraints to, mitigation, the amount of GGR required to balance the carbon budget is larger, reaching 800 Gt-C in the least optimistic pathways. In those with more optimistic or favourable assumptions about mitigation, the amount is lower, with a minimum of 25 Gt-C. Such assumptions are being further explored in consideration of Shared Socioeconomic Pathways (SSPs) (Fricko, Havlik et al. 2017, Luderer, Vrontisi et al. 2018) – although, so far, so little work has been done in this area that the findings may well reflect more on the underlying model or particular input assumptions, than on the differences between SSPs.

Box 2: An example of substitution from the EU

Recent research and modelling shows how the introduction of GGR to the policy mix can affect emissions reductions at a more detailed scale (Solano Rodriguez, Drummond et al. 2017). Their study examines pathways for the EU towards its 2050 target of an 80% reduction in emissions over 1990 levels (reducing emissions to an absolute target level of around 0.6Gt-CO_2 pa). The conventional route to 'policy success' sees virtual decarbonisation of electricity generation (-97.5%), combined with aggressive policies to reduce emissions in other sectors (transport (excluding aviation and shipping) -61%, buildings -87% and industry -78%).

The introduction of BECCS transforms the picture. The 0.6Gt-CO_2 target level is then achieved with the help of around 0.8Gt-CO2pa BECCS removals. Emissions in the electricity sector fall by 152% over 1990 levels. But cost effective reductions in other sectors become smaller – in some cases dramatically. Emissions reductions in industry are only 65% in the presence of BECCS, rather than 78% without. In buildings the emissions cuts shrink from 87% to 36%. And in transport emissions reductions are decimated, falling from 61% to just 10%. The mitigation 'foregone' in these three sectors as a result of the introduction of BECCS adds to almost 0.7Gt-CO2 pa (almost 25% of the otherwise expected mitigation). In other words almost all of the carbon removed by BECCS simply substitutes for emissions reduction.

This demonstrates clearly the ways in which promised BECCS removals can act to substitute other potential mitigation. Perhaps more importantly it suggests the degree of lock-in to particular paths that would be involved, and the risk involved to overall emissions if BECCS were not delivered. For transport emissions to be cut by 61% would imply substantial investments in hydrogen (or electric) vehicles, requiring transformation of a major industrial sector. In the buildings sector, the different paths might imply very different standards for new buildings, very different replacement rates, and very different rates and standards of refurbishment. Retrospectively implementing such paths after a delay of decades waiting for BECCS to prove its viability would be impractical.

Carbon at risk from rebounds, multipliers and side effects (Type 2)

The carbon at risk from type 2 MD (rebounds, multipliers and side effects) is much more difficult to calculate. Our initial estimates indicate a cumulative range of 30-140 Gt-C based on conservative estimates combining diversion to enhanced oil recovery, and indirect land use change.

A conservative estimate of 20-80Gt-C from enhanced oil recovery (EOR) is calculated here. EOR can act as a multiplier of atmospheric carbon. One study calculates that EOR can lead to release of CO_2 more than six times (600%) greater than the CO_2 stored (Armstrong and Styring 2015), although this might be offset somewhat if the development of EOR sources resulted in lower exploitation of new reserves elsewhere. Others suggest lower rebounds (Godec, Kuuskraa et al. 2011, Azzolina, Hamling et al. 2017, Godec, Carpenter et al. 2017). We base our figure on a global potential for EOR related CO_2 storage of 38-87 Gt-C (140-320 Gt-CO2) and a multiplier of 6-47% (Godec, Kuuskraa et al. 2011). Additional recovery of 470-1070 bboe would generate 40-130 Gt-C (applying ratios of 118-139kg-C per barrel) while additional upstream emissions in the production process would add 5-15kg-C per barrel, even ignoring methane leakage associated with oil production, transport and refining.[13]

Attribution of emissions from land-use change resulting from bioenergy has proved difficult and contentious. Estimates of indirect land-use change (ILUC) factors range from as little as 5% to over 100% globally (with a central range of 10-20% even for well-managed bioenergy systems) (Souza, Victoria et al. 2013). Land use change associated with the bioenergy component of BECCS might generate a further 12-60 Gt-C, based on a range of 10-20% additional CO_2 emissions (Souza, Victoria et al. 2013).[14] Estimates have converged over time, although it is hard to know whether this is a result of better modelling or better management, and therefore predicting the impacts of a significant increase in biomass demand is difficult (as it may, or may not result in higher than average land-use carbon effects). It is possible that that direct and indirect LUC could lead to substantial additional indirect emissions, especially if land brought into new production held significant carbon reservoirs (eg old growth forest, deep prairie soils or peat swamps).

It is worth noting that the indirect effects of EOR and ILUC could be cumulative in a BECCS-based GGR economy.[15] BECCS would both support conversion of land to biomass production (with implications for ILUC), and generate compressed CO_2 requiring storage, which could be diverted to enhanced oil recovery. Financial market incentives to minimise the marginal costs of BECCS could also exacerbate both effects as developers seek to cut costs in the biomass supply chain, and obtain a return on the CO_2 stored. Similarly, careful design of interventions and incentives might help reduce either effect.

Our estimates of type 2 effects make no allowance for any possible Keynesian multiplier based on increased purchasing power resulting from public spending on GGR. The extent and even existence of such multipliers are contentious, but in some economic circumstances, stimulus through public spending is a commonly adopted policy option. We would note that decision makers making GGR investments would likely aim to increase any multiplier effects, because they want the economic co-benefits (of green jobs, skill development and exports that can come alongside the development of new green technology). Such multipliers may be particularly significant where the techniques involved might spin-off new technological breakthroughs (for instance DAC research might result in new catalysts, or new gas exchange technologies which could be deployed in other markets). There may also be generic multipliers from EOR (downstream use of more, cheaper, oil than without EOR), and ILUC (products of land converted; machinery and employment generated in forest clearance, land drainage etc) which are not included above. These are distinct from classic rebound effects, where efficiency of use makes a resource relatively cheaper. In this respect, if carbon removal leads to lower carbon prices than otherwise, there will be some rebound effects.

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[13] 470bboe at 123kg-C (low C-content and low upstream emissions) = 58 Gt-C, less 38 (stored) = 20Gt-C; 1070bboe at 154kg-C (high C-content and high upstream emissions) = 165Gt-C, less 87 (stored) = 78 Gt-C. Neither calculation includes methane leakage.

[14] Attribution of this to NETs may also be contentious, as non-NETs pathways also include substantial increases in land use for biomass energy. Nor is it simple to unpick the extent to which models already include these effects in their land-use calculations.

[15] Also note that EOR and ILUC effects may result from other GGR techniques, not just BECCS. Biochar, soil carbon storage and enhanced weathering all have land-use implications. DAC carbon could also be diverted to EOR.

This however is embodied in our Type 1 mitigation (the substitution effect).

Additional carbon at risk from GGR promises: 'imagined offsets' (Type 3)

The third form of MD is even harder to quantify. As we have seen in the previous section, IAMs with assumed rational agents imply significant substitution of future GGR for near-term mitigation. Here we are concerned with the ways in which real-world responses to the promise of GGR might exceed the 'economically rational' substitution generated in IAMs. This is not to concede that it is indeed rational to replace near term mitigation with carbon drawdown based on technological imaginaries, but rather to note that there are other mechanisms that could stimulate apparently irrational behaviours that are not captured by the models, and to assess their likely impacts on overall abatement. We use the term 'imagined offsets' to describe a situation in which an actor does not mitigate emissions, because they imagine that those emissions will be offset by other actions elsewhere now or in the future. Such imagination may not even be an active process, but the result of the actor simply experiencing less pressure or incentive to reduce emissions, because the promise of GGR has sustained weak policy. Imagined offsets are distinct from formal offsets, such as those generated in carbon markets, even though the latter might also fail to deliver in practice, as a result of double counting or leakage. Imaginary offsetting arises because, in a context where resource constraints or sustainability factors limit deployment rates, in the real world there could be many more emissions generated by near-term actors who act as though future GGR will be less costly than mitigation, than there are actual opportunities for future GGR. At the system level it would be irrational for all such actors to defer mitigation, but at the individual level all such decisions might seem rational. Moreover, such actors may apply higher discount rates to their individual actions than the model applies at a system level (where the discount rate typically reflects anticipated climate damages rather than contemporary time preferences) (Jouini, Marin et al. 2010, Goulder and Williams 2012). This too raises the possibility of mitigation deterrence by making future GGR appear even cheaper in comparison with near-term mitigation, and thus making a greater share of mitigation vulnerable to deterrence.

Such deterrence could arise without any deliberate intent to undermine or delay progress on mitigation, motivated by political or economic interests. Well-meaning promises of GGR could, for example, depress carbon prices in trading markets, affecting many decision makers unknowingly. But if we also accept that vested interests exist, and act to make near-term mitigation appear more costly and undesirable than it is portrayed in the models (Oreskes and Conway 2011), then there is an additional reason to anticipate that the promise of GGR might be mobilised to defer mitigation action (in the same way as previous promises of CCS have been deployed (Markusson, Dahl Gjefsen et al. 2017)). Moreover, from this perspective, the more GGR would impose a real economic cost on dominant political or economic actors, the less likely it would be to materialise in practice, and the more likely it would be to be pushed further into the future.

Here we use estimates of the amount of forecast mitigation costing between \$50 and \$100/t-CO_2 to derive a crude proxy for imaginary offsetting. NETs advocates often suggest that GGR might cost significantly less than \$100, or even below \$50 per tonne CO_2e (McLaren 2012, Wilcox, Psarras et al. 2017, Fuss, Lamb et al. 2018), while carbon markets currently trade at well below these values, so this appears a plausible range to consider.[16] According to AR4, by 2030, between 4.4 and 8.7Gt-C pa (or between 37 and 42% of the total potential mitigation) would cost in this range.[17,18] If we assume the 'rational substitution' noted previously -

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[16] In practice such costs for GGR often appear to be only possible in particular limited applications which struggle to deliver substantial levels of long term removal (such as BECCS on ethanol, enhanced weathering using slags, or DAC to produce dilute CO_2). However the impression of low costs tends to circulate more widely and misleadingly adhere to other - more expensive - formulations of the techniques.

[17] See figure 4.1 at https://www.ipcc.ch/publications_and_data/ar4/syr/en/mains4-3.html

[18] Other analyses suggest much higher marginal abatement costs for 2030 and 2050, and thus more mitigation at costs of over \$100 per t-C at risk of deterrence. McKinsey analysis puts the marginal cost at 2030 at \$90-150 t-C, and the IEA report \$150-500 t-C for 2050 (see https://hub.globalccsinstitute.com/publications/climate-risks-and-carbon-prices-revising-social-costs-carbon/6abatement-costs). And the IAMs cited above typically see carbon prices reaching \$400-500 per tonne for much of the century (although such figures represent a maximum cost of abatement, not an average). In such circumstances we should not

of 1.7-2.45 Gt-C pa - is part of this potential, there remains a further 2.7-6.3 Gt-C pa ‘at risk’), equivalent to 24-28% of mitigation otherwise foreseen. For a 2°C target, if just 20% were deterred against a counterfactual in which without mitigation, CO_2 grows on an RCP 6.0 pathway, this implies 162-172 Gt-C additional emissions (table 2). With a counterfactual of an RCP 8.5 world, the risk from a 20% mitigation deterrence effect grows to 226-236 Gt-C. Figures for both 2°C and 1.5°C pathways are shown in table 2.

The practical mechanisms involved are hard to quantify or compare. That would ideally require new scenarios in which implicit assumptions in the RCPs and SSPs are systematically revised or reinterpreted, alongside empirical deliberative work. Trade-offs between GGR and mitigation imply longer investment horizons than are usually considered, even in energy systems modelling. Moreover, assumptions regarding the underlying ease or difficulty of mitigation, and the underlying counterfactual significantly influence the potential impact of the mechanisms we postulate. Nonetheless we think the 20% figure offers a reasonable first order estimate, and that it makes sense to consider counterfactuals roughly based on RCP 8.5 and RCP 6.0. These represent two possible descriptions of business as usual without significant additional policy action.

Table 2: Carbon at risk through excessive promises/imagined offsetting

	Counterfactual	
	RCP 6.0	**RCP 8.5**
Anticipated emissions (2020-2100)	1200	1700
Residual safe budget 2°C (2020-2100)	220-270	220-270
NETs removals (2020-2100)	120	300
Anticipated mitigation (2020-2100)	810-860	1130-1180
20% deterrence (vs 2°C)	162-172	226-236
Residual budget for 1.5°C	80-176	80-176
NETs removals	180	380
Anticipated mitigation (2020-2100)	844-940	1144-1240
20% deterrence (vs 1.5°C)	169-188	229-248

This analysis suggests that it would be worth getting into the entrails of the IAMs to examine how much mitigation remains that costs more than the projected cost of GGR (and exploring the effects of different levels of projected cost). It would help to extract the projected GGR costs and compare them consistently with the costs promised by researchers and developers (and thus extant in policy circles, as it is the latter, rather than the former, that will influence decisions). It would similarly help to compare the discount rates modelled in the IAMs with those applied in practice by political and business decision makers with respect to energy and mitigation investments. Again it is the latter rather that the former that will most directly influence both individual decisions and the broader political economy of whether actors invest in mitigation, or wait. We note that discount rates become more significant here with the extended period over which a trade-off between mitigation and GGR becomes possible. Higher discount rates make both future GGR and future mitigation look cheap, but they will deter mitigation now more ‘effectively’ in the presence of GGR which notionally promises to remove CO_2 from the atmosphere to counterbalance emissions now.[19] This suggests that while the use of low discount rates might be normatively ‘right’ in terms of promoting the interests of future people faced with climate injustice, the use of discount rates in the models that are lower than those actually used by actors in politics and business will be another source of

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dismiss the possibility that the promise of GGR might deter even more than 20% of otherwise forecast mitigation.

[19] This is because future GGR can replace current emissions reduction in a carbon budget. But future emissions reduction cannot replace current emissions reduction within the same budget, so future GGR is a more effective deterrent than future emissions reduction (ceteris paribus).

mitigation deterrence.

Summarising the risks of mitigation deterrence

This section brings together our estimates for the three types of MD considered in this paper. While our focus has been on the 'worst case' scenarios (the upper bound for scale of MD), we have, for each individual element, used conservative estimates and noted various unquantifiable factors that might further increase the amount of carbon at risk.

Table 3 below provides our best estimates of the notional maximum carbon at risk from mitigation deterrence with a 1.5°C target. We conclude that mitigation deterrence must be taken seriously and directly addressed by both researchers and policy makers concerned with GGR.

The overshoot of carbon budgets resulting from the substitution effect of GGR is significant alone, Riahi, Kriegler et al. (2015) estimate a transient response of 0.6°C, raising the average temperature outcome of RCP2.6 scenarios to 2.5°C, rather than 1.9C. Our analysis suggests that the overall effect of overoptimistic reliance on GGRs could be more than twice this level, and, at worst leading to an overshoot to 2.9°C, despite policies designed to achieve 1.5°C.

Table 3: Summary calculations of carbon 'at risk' from mitigation deterrence

Scenario (a)	**Carbon at risk from NETs 'failure' (at 80% substitution) (*Type 1*)**	**Carbon at risk from multipliers, side-effects & rebounds (*Type 2*)**	**Carbon at risk from imagined offsetting (20% of the mitigation still required) (*Type 3*)**	**Total estimated carbon at risk**	**Temperature change**
Median	224	30-140	160-170	414-534	0.83-1.07
Favourable context	144	30-140	162-188	336-472	0.67-0.94
Unfavourable context	304	30-140	229-248	563-692	1.13-1.38

Note to table: (a) Our scenarios here are not explicitly linked to particular SSPs but illustrate similar principles, with the favourable circumstances being a baseline of RCP 6, and the unfavourable RCP 8.5.

We acknowledge that a scenario in which all three forms of MD arise to the maximum extent estimated above is unlikely. Nonetheless, complete failure may not be entirely implausible, given experience with fusion power, which is still typically promised 30-50 years into the future, after decades of research. A comprehensive consideration of the parallels with nuclear fusion power (as with other analogues) is beyond the scope of this paper, although some analogues will be considered in more depth in the course of the project. However the case of fusion appears more extreme, in the sense of requiring more fundamental scientific breakthroughs, and more expensive and hi-tech testing facilities in comparison with GGR. More generally, experience with nuclear fission and with CCS on fossil energy suggest, nonetheless, that significant underperformance is possible, and perhaps even predictable (Markusson, Dahl Gjefsen et al. 2017), while a recent analysis of the innovation path required to mainstream GGR (Nemet, Callaghan et al. 2018) suggests that a four-fold acceleration of technology development would be needed for DAC to fulfil the GGR requirement. And even in the event of complete failure, it seems unlikely that GGRs would continue to stimulate reduced mitigation even while delivering zero withdrawals. However, there is a critical issue of timing here: delayed or reduced emissions cuts cannot be reversed at a future date if GGR fails then (in this respect the promises of GGR are more pernicious than the promises of fusion). On the other hand, if GGRs were to promise but *never* materialise (which makes types 1 and 3 MD significant and harmful), they would be unlikely to generate any type 2 effects (such as economic rebounds). Yet the worst case could arise if GGRs were to materialise but then *subsequently failed* to deliver on their promises (type 1), in which case there may also be both type 2 and type 3 effects. As a hypothetical example of a worst case, see box 1.

Box 3: A hypothetical worst case scenario for mitigation deterrence

This is strictly a hypothetical scenario, offered here simply to demonstrate the plausibility of all types of MD appearing together.

Large-scale BECCS is promised and incorporated into IPCC pathways and countries' NDCs (where it largely substitutes for previously envisaged emissions reduction). It suffers serious delays, and when deployed, the carbon captured is directed to a combination of enhanced oil recovery (resulting in more additional emissions than the carbon stored) (Type 2) and carbon utilisation as synthetic fuels or plastics (from which the carbon returns to the atmosphere in weeks or months) (Type 1).

Competition for land simultaneously limits biomass supply, so overall deployment of BECCS is lower and more expensive than anticipated (Type 1), and stimulates carbon rebounds from indirect land use changes as farmers displaced by energy crops clear new forests and peat-swamps (Type 2).

In other areas, afforestation and other 'Natural Climate Solutions' are deployed, and significant areas of land are managed to promote carbon removal into forests, soils and ecosystems. However the inertia in the still warming climate means that carbon leakage from wildfires, droughts and erosion largely reverses any gains made during the latter half of the century (Type 1).

Research is commissioned to improve BECCS efficiencies, with innovative materials and processes, but while these fail to work in the BECCS process, they generate spin-off economic opportunities (with additional emissions) (Type 2).

Advocates and funders of BECCS (exhibiting investment bias) portray all such shortcomings as teething problems, while continuing to offer optimistic promises of future low-cost removals. The promises are taken up and magnified by companies marketing carbon intensive travel and consumption products, such that emissions reductions in those sectors also fall well short of planned levels (Type 3).

Conclusions

This working paper has identified three types of potential mitigation deterrence: type 1 is direct substitution coupled with subsequent failure; type 2 involves rebounds, multipliers and other indirect effects; and type 3 (the closest to a classic 'moral hazard' effect) is 'imaginary offsetting'.

We have shown that these effects could be additive, not just alternative ways in which emissions reductions might be delayed or deterred. In all three cases, however, the problem threatens harm in part because of the temporal dimension – they are promises of 'future retrospective fixing' in which the promised GGR can theoretically compensate for past emissions. By contrast, other action taken in response to failures, limitations or side-effects of GGR cannot prevent or compensate for emissions that have already happened. In this respect the impacts of techno-fix promises of GGR can be more pernicious than those of past climate techno-fixes such as nuclear power or fossil-CCS.

We have calculated a worst-case total level of 'carbon at risk' from the three types of MD. Type 1 risks might constitute about 80% of promised removals (although it must be remembered that across the modelling considered, the anticipated removals ranged widely, from less that 100Gt-C over the period to 2100, to as much as 800Gt-C, with a central range of 120-300Gt). The Type 2 risks we could quantify account for a cumulative additional 30-140Gt-C, and Type 3 risk could reduce remaining emissions cuts by 20%. Added together the cumulative carbon at risk to 2100 is 336-692Gt-C (in the order of two to three times the amount of carbon removals promised). This is a theoretical figure derived from modelling and other data sources: it has yet to be confirmed empirically.

The implications of this for global temperatures, using a simple ratio of 500Gt-C to 1°C, are that the committed temperature rise could be 0.7-1.4°C higher than anticipated. This assumes all other impacts on climate forcings remain equal, and that climate sensitivity does not prove much greater or lower than current expectations.

These findings carry serious implications for research and policy. We do not suggest that they constitute an argument to halt or reduce research into GGR. Our analysis rather confirms the great difficulty of meeting climate goals without deployment of GGR in some form(s). However if we are right about the nature and scale of these risks, it is incumbent upon both policy makers and researchers to consider and develop governance approaches for research and development which minimise the risks of MD. To do this will require greater disaggregation of the risks, and detailed analysis of the mechanisms by which they emerge. In this project we will be applying a cultural political economy perspective so that we can identify and analyse risks that emerge in the interactions between technologies, interests and regimes, not just those rooted in individual choices.

Our analysis here has also implicated models and model makers in the generation of mitigation deterrence. Models (notably IAMs) have been, and are, a primary way in which expectations of climate action are shaped and consolidated. Modellers tend to understand that models should be experimental sandpits, yet policy tends to treat them as truth-machines. Developing responsible and deliberative ways to deploy and interpret models in politically charged climate debates where misinterpretation is rife is a key challenge for preventing MD.

More generally, in seeking governance for NETs in the face of MD, we need to develop interventions that not only maximise delivery, but also minimise offsets and substitution, and minimise rebounds; and moreover, that reflexively raise ambitions for emissions reduction proportionately and rapidly in the face of failures to constrain rebounds and substitution effects.

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