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

Duncan McLaren
Lancaster Environment Centre
d.mclaren@lancaster.ac.uk

Abstract
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 hope rests on an assumption that GGR will largely supplement emissions reduction. The paper reviews the expectations of GGR implied by integrated assessment modelling, categorises ways in which delivery or promises of GGR might instead deter or delay emissions reduction, and offers a preliminary estimate of the possible extent of three such forms of 'mitigation deterrence'. *Type 1* is described as 'substitution and failure': an estimated 50-229 Gt-C (or 70% of expected GGR) may substitute for emissions otherwise reduced, yet may not be delivered (as a result of political, economic or technical shortcomings, or subsequent leakage or diversion of captured carbon into short-term utilization). *Type 2,* described as 'rebounds', encompasses rebounds, multipliers and side-effects, such as those arising from land-use change, or use of captured CO_2 in enhanced oil recovery. A partial estimate suggests that this could add 25-134Gt-C to unabated emissions. Type 3, described as 'imagined offsets', is estimated to affect 17-27% of the emissions reductions required, reducing abatement by a further 182-297 Gt-C. The combined effect of these unanticipated net additions of CO_2 to the atmosphere is equivalent to an additional temperature rise of up to 1.4°C. The paper concludes that such a risk merits further deeper analysis and serious consideration of measures which might limit the occurrence and extent of mitigation deterrence.

Keywords
Greenhouse gas removal
Mitigation deterrence
Climate policy
Climate modelling

Acknowledgements
The author would like to thank his colleagues in the AMDEG project at Lancaster Environment Centre, especially Andrew Jarvis, for their constructive feedback on earlier drafts.

Financial Support
The manuscript was written with support from grant NE/P019838/1 from the programme Greenhouse Gas Removal from the Atmosphere, funded by NERC, EPSRC, ESRC, BEIS, Met Office & STFC in the UK.

1. Introduction

In the context of aspirations to limit the average global temperature rise, techniques which can draw greenhouse gases (GHG) from the air have become increasingly significant to climate policy. Integrated Assessment Models (IAMs) suggest that very substantial use of such techniques (variously termed Carbon Dioxide Removal, Negative Emissions Techniques or Greenhouse Gas Removal (GGR)) is likely necessary to stabilise atmospheric GHG concentrations at levels compatible with limiting average global temperature rises to 2°C or lower (Fuss, Canadell et al. 2014, Wiltshire and Davies-Barnard 2015, Minx, Lamb et al. 2018). In modelled climate pathways that meet such goals, GGR is typically deployed later in the century (notably in the form of bioenergy with carbon capture and storage (BECCS)), alongside accelerated levels of other mitigation. In such pathways GGR acts to balance carbon budgets in two ways: it promises to reverse an overshoot of emissions through future removals of CO_2 from the atmosphere, and it offsets recalcitrant (difficult to eliminate) residual emissions. In policy terms, therefore, GGR is typically understood as an essential *addition* to otherwise constrained possibilities for effective and affordable mitigation. However, because IAMs typically seek to optimise costs, within such modelled pathways some proportion of the anticipated GGR inevitably substitutes for otherwise expected emissions reductions, especially in the near-term (Azar, Johansson et al. 2013, Riahi, Kriegler et al. 2015). In other words, late GGR typically replaces early mitigation.

It is therefore critical to better understand the interactions between GGR techniques and mitigation practices. In particular, might elevated consideration of GGR deter or delay otherwise anticipated emissions reductions? Might *promises* of GGR substitute for *action* to deliver or accelerate emissions cuts? In such cases, what happens if GGR fails to deliver on its promises? This is particularly important while GGR techniques remain largely technological imaginaries, unproven at the scale implied by modelling work. This paper seeks to categorise such interactions and the effects of such failures, and consider how significant they could be for the delivery of overall climate goals. Many researchers have questioned the technical feasibility of delivering the high levels of carbon removal implied in sub-2°C pathways modelling (Fuss, Canadell et al. 2014, Anderson and Peters 2016, Larkin, Kuriakose et al. 2017). Some have begun to explicitly estimate the additional risk to the climate should anticipated GGR fail to materialise (Realmonte, Drouet et al. 2019). This paper combines such analysis with assessment of the extent to which promised GGR may substitute for emissions reductions rather than supplementing them. It also presents estimates of the potential scale of rebound effects or other indirect increases in emissions arising from the pursuit of GGR.

The paper first defines mitigation deterrence. It then discusses and begins to characterize possible mechanisms of mitigation deterrence within the modelling frameworks, and in relation to carbon budgets. It describes a 'carbon at risk' approach designed to enable assessment of the scale and significance of mitigation deterrence, and applies this to modelled estimates of GGR and emissions reduction to offer preliminary estimates of the possible impact. In doing so it focuses on plausible worst-case scenarios, because of the irreversibility of decisions which substitute future GGR for earlier emissions reduction.

2. Mitigation Deterrence: Definitions, mechanisms and issues arising

If mitigation is understood as planned at-source reductions in greenhouse gas emissions, then *mitigation deterrence* can be defined as the prospect of reduced or delayed at-source emissions reductions resulting from the introduction or consideration of another climate intervention (Markusson, McLaren et al. 2018). Understood this way, mitigation deterrence will potentially, although not necessarily, increase climate risk. While climate interventions may also differ in their co-benefits or side-effects (Markusson, McLaren et al. 2018), the focus here is on GGR as the 'other climate intervention', and on the potential that its introduction or consideration might (perversely) lead to a *net increase in atmospheric GHG concentrations* in comparison with a situation without such introduction or consideration. Interpreted in terms of carbon budgets, the concern is that the net result of the addition of GGR could be – rather than the achievement of a smaller residual emissions budget – a perverse increase in the scale and duration of any overshoot or exceedance of the budget.

This paper identifies three broad ways in which consideration or introduction of GGR could lead to unanticipated net additions to atmospheric GHGs over the coming century. First, if GGR formally substitutes for emissions reductions in plans and policies, and then fails to deliver removals matching the scale of the promised substitution (Type 1 or 'substitution and failure'). Second, if rebounds or other side effects from (attempted) GGR implementation generate emissions outside their anticipated budget (Type 2 or 'rebounds'). And third, if the anticipated or 'imagined' future availability of GGR encourages or enables the avoidance or delay of emissions reductions without any planned or formal substitution mechanism (Type 3 or 'mitigation foregone'). Together the three types encompass both intentional and emergent responses to GGR consideration or deployment.

These *three types* or mechanisms of MD are briefly described and categorised below.

2.1 Type 1: Substitution and Failure

In Type 1, *failure* implies that at a system level long-term removal of CO_2 is not realised. That any given GGR technique itself may fail to capture CO_2 from the atmosphere is only one of the diverse reasons why the complete socio-technical system may not deliver long-term removal. The largely unproven nature of GGR (Larkin, Kuriakose et al. 2017, Rosen 2018)) means that failures are clearly possible, but hard to quantify. Such failures might arise at various steps in the chain between atmosphere and storage (see Supplementary Figure 1 for illustration). The technique might not prove commercially or technically viable, and thus not materialise, so failing to capture any carbon. Alternatively, it may prove less efficient (while still viable), with lower than anticipated rates of capture once full life-cycle carbon emissions are accounted for. In turn, this would imply higher unit costs and lower deployment rates. The overall efficiency of removal could also be depressed by carbon leakage from processing equipment, pipelines, or subsequent storage, or if carbon were diverted to utilisation. Utilisation as synthetic fuels, plastics or building materials would only delay the return of CO_2 to the atmosphere (by months, years, or perhaps decades). Leakage from storage may happen after some time, for example if a forest carbon store were to burn.

The maximum carbon directly at risk from failures in Type 1 cannot, however, exceed the amount promised by successful deployment. Moreover such failures only result in net <u>increases</u> in atmospheric GHGs (and thus additional climate change) insofar as GGRs have been permitted to substitute for emissions cuts or function as formal offsets for emissions growth. However, such effects can arise even if that substitution appeared 'rational' – cost-optimal, for example - in foresight.

Substitution could come about in several ways. Actual or future GGR removals might be traded for emissions reductions in carbon markets. Policy makers could fail to increase targets for emissions reduction (which currently fall short of those required to deliver 1.5 or even 2°C), planning to make up the difference with GGR. GGR could be promoted as a substitute for feasible emissions cuts within a sector. For example, the agriculture sector might claim that soil carbon storage should be treated as an offset for remaining emissions from livestock that might otherwise be reduced by dietary change. GGR substitution could even be driven by an unrelated sector, such as by airlines developing voluntary offsetting schemes based on the purchase of GGRs.

Type 1 mitigation deterrence that adds to climate change is the result of *both* substitution *and* subsequent failure. To estimate its extent means quantifying not only how much carbon might be at risk of performance failure, but also what proportion of this was an offset or substitute for planned mitigation actions. Type 1 mitigation deterrence constitutes budgeted emissions reductions that are substituted by GGR which fails to deliver. As a result, unabated emissions increase in comparison to the allowable carbon budget.

2.2 Type 2: Rebounds

Unlike Type 1, the carbon impacts of the remaining types of mitigation deterrence are not quantitatively limited by the scale of the carbon removal promised by GGRs. Type 2 constitutes rebounds and similar *indirect* and typically unintended effects in which GGR might trigger *additional emissions*. This could arise, for example, through use of captured carbon for enhanced oil recovery, from carbon emissions from soils converted to biomass production (or from associated indirect land use change), or from additional economic activity stimulated by any part of the GGR supply chain. With perverse incentives, or even just inaccurate data, a GGR developer might even continue to operate a technique which led to more emissions than it captured from the atmosphere. Such a problem could arise, for example, if a hypothetical GGR technology relying on gas as feedstock or energy source, failed to account accurately for methane leakage in gas production (where estimates are disputed and differ by up to a factor of two (Alvarez et al 2018)). Similar failings in the wider system (such as greater emissions from indirect land-use change (ILUC)) have been observed with biofuels, and therefore cannot be rejected here.

One notable risk amongst such unintended rebound 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). EOR is already practised in most early BECCS schemes but could be used as a revenue source by any GGR producing compressed CO_2 suitable for geological storage. Moreover it is already incentivised by tax breaks in the USA (Bennett and Stanley 2018). There is typically more carbon in the additional oil recovered from EOR than stored (Godec, Kuuskraa et al. 2011, Armstrong and Styring 2015, Godec, Carpenter et al. 2017) and on average EOR may even *increase* the GHG intensity of oil production (Masnadi and Brandt 2017).

All such rebound emissions are additional to the residual unabated emissions foreseen in the allowable carbon budget, and effectively increase baseline emissions. A comprehensive accounting of Type 2 effects would require a detailed technical and economic analysis of the likely forms of GGR anticipated. Section 3.2 below gives an initial – and likely incomplete - estimate focusing on land-use and EOR effects related to BECCS.

2.3 Type 3: Mitigation Foregone

Finally, in Type 3 mitigation deterrence the (immaterial) promise alone of GGRs may stimulate reductions in mitigation (or more likely, failures to increase mitigation) which exceed any apparently 'economically rational' substitution or planned formal offsetting – as included in Type 1 above. This type more closely approximates fears of a classic 'moral hazard' effect in which merely considering an alternative triggers reduced effort to cut emissions (McLaren 2016). Type 3 is distinguished from Type 1 because it represents mitigation foregone that is not matched even by any additional *promises* of GGR. It might help the reader to consider a simple example: assume that volunteers plant trees that are expected to capture 100 tonnes of carbon. That activity might be treated as a licence to continue emitting to that level, not only by the volunteers themselves, but also by the organisers of the event, by the landowner, and also potentially by a purchaser of credits for the trees on a voluntary market. Only one of these 'offsets' is real (at best), the rest are imaginary. In reality one might foresee even more complex situations where the potential removal is merely a promise or expectation, rather than an actual removal claimed multiple times.

Mitigation foregone through imagined offsetting leads to increased unabated emissions beyond those allowed within the carbon budget, regardless of whether the GGR that has been promised in modelled scenarios is delivered or not (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. Many actors face political, financial or cultural incentives to postpone mitigation in favour of future alternatives, with the promise of future GGR providing an ideal motivation to do so. Without some mechanism to restrain such imagined offsetting it becomes plausible that the total mitigation deterred could exceed any possible practical future GGR capacity. It seems plausible that this effect is most likely where anticipated mitigation is – or appears to be – very costly. To make an initial estimate this paper uses figures for the amount of mitigation anticipated to cost over $100 per tonne of CO_2, taking this threshold as representative of the 'promised cost' of large scale carbon removal (Keith, Holmes et al. 2018).

2.4 Synergies and the 'Plausible Worst Case'

Given the diverse potential mechanisms included above it is difficult to predict or quantify the possible scale and effects of mitigation deterrence. The counterfactuals are themselves riddled with uncertainties, and the innovation driving the evolution of this area is, by definition, unpredictable. Substitutions, 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. For instance, the hope that carbon budgets can be balanced despite limited mitigation so far might galvanise action to cut emissions, or (somewhat contradictorily) that awareness of the downsides of large scale GGR, such as pressure on food supply, might galvanise more rapid mitigation. Technical synergies might arise, for example if improved carbon capture technologies in direct air capture then cut the costs of fossil carbon capture and storage, enabling swifter emissions cuts. In the event of successful deployment of GGR, such synergies would result in greater reductions in GHG concentrations than anticipated in the modelled pathways.

This paper does not pursue the possibility of such positive synergies further. Unlike deterrence, some synergies are effectively already embedded in the learning curves applied by IAMs. Also, because of the potential risks involved, the focus here is on the possible negative interactions between GGR and mitigation. It should be incumbent on researchers and policy makers to consider the worst case scenarios associated with the promises of new technologies such as GGRs. The remainder of this paper therefore focuses on an attempt to derive an initial estimate of the possible effect of mitigation deterrence should all the forms of deterrence identified here emerge in practice. To do this it first explains how mitigation deterrence can be interpreted through carbon budget analysis.

2.5 Mitigation deterrence and carbon budgets

The approach builds on global cumulative carbon budget analysis (Anderson and Bows 2008, Allen, Frame et al. 2009) which identifies the cumulative emissions compatible with a particular chance of staying within a certain temperature. Despite various uncertainties (Peters, Andrew et al. 2015, Rogelj, Schaeffer et al. 2016, Millar, Fuglestvedt et al. 2017, Peters 2018, Rogelj, Popp et al. 2018, Rogelj, Forster et al. 2019), the IPCC (2018) suggests a range of 115-210 Gt-C remaining for 1.5°C as of 2017. Given current emissions rates, by 2020 this implies just 80-176 Gt-C remaining (in the Supplementary material, this is termed $CBUD_{1.5}$).

Figure 1 illustrates the three types of mitigation deterrence and how they relate to carbon budgets. It shows comparative cumulative global carbon budgets to 2100 in three climate policy states. The first column depicts a carbon budget prior to consideration of GGRs. For the sake of illustration, imagine that this budget is commensurate with restricting temperature rise to 2°C. The total bar represents the aggregate carbon emissions anticipated between 2020 and 2100 in the absence of any intervention. The lower pale grey section represents the emissions reduction required to avoid dangerous climate change, leaving an allowance of cumulative residual unabated emissions – the 'permitted budget' for 2°C - (shown in the upper dark grey section). The dark and pale grey sections are schematically proportionately scaled to reflect mainstream estimates of the remaining permitted carbon budget and the overall cuts in emissions implied.

The residual budget for a 1.5°C target would be smaller than that for a 2°C target, constituting perhaps just 10-15% of the otherwise anticipated cumulative emissions to 2100 (80-176 Gt-C of otherwise anticipated emissions, under RCP 4.5 or RCP 6.0, of around 650-1300 Gt-C). In an effort to meet this reduced budget and deliver the tighter temperature target, policy makers might turn to GGR. Alternatively, GGR (shown as the dotted central portion in column 2) might be seen as a way to respond to delays in mitigation, or to increase the likelihood of meeting the temperature goal: all three of these goals effectively shrink the remaining residual emissions allowance. The second column represents the ways models portray the introduction of GGR. In practice they interpret the 'promises' of GGRs, as partly *contributing to*, and partly *increasing* the mitigation expected (represented by the dashed line dividing the GGR portion of the column). Previous modelling suggests a substantial degree of substitution (represented by the dotted area below the dashed line), as apparently affordable later GGR replaces more expensive early mitigation (Azar, Johansson et al. 2013, Riahi, Kriegler et al. 2015). The precise location of the boundary between GGR removals that supplement emissions reduction and those that substitute for it is debateable (and depends partly on the modelling techniques applied). The proportionate scale of the GGR contribution shown here is roughly indicative of the amounts suggested in the literature.

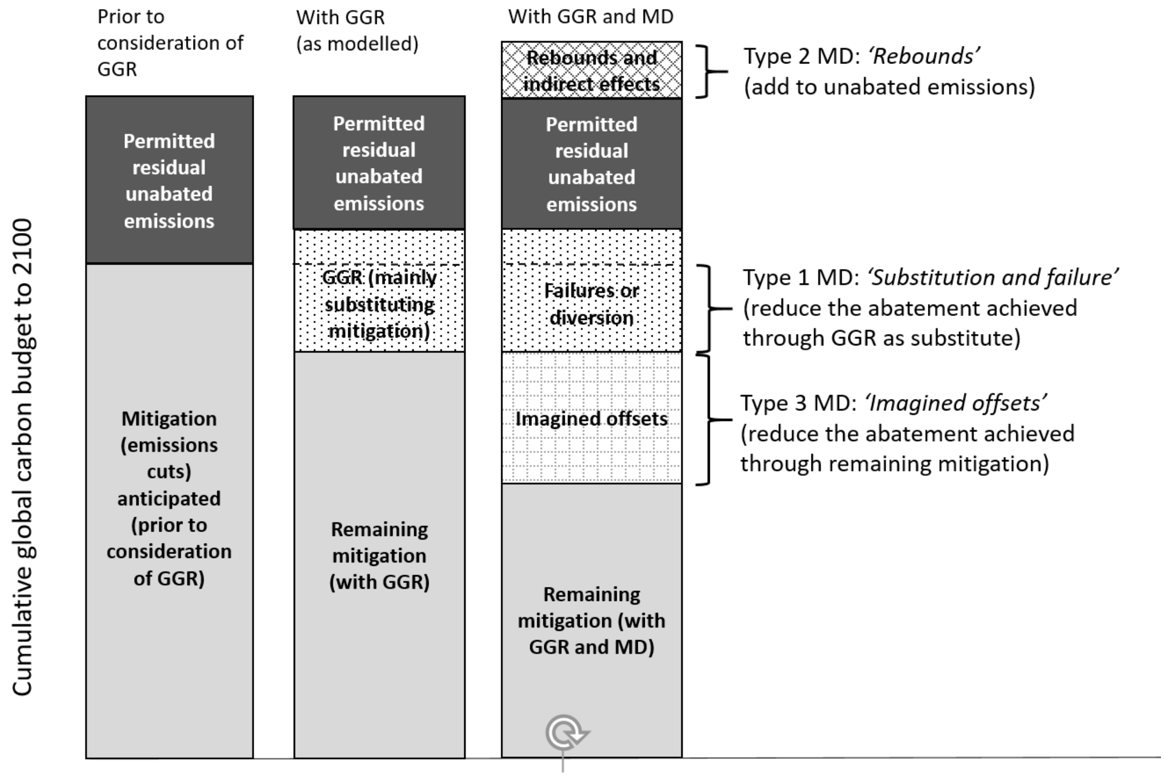


Figure 1: Schematic representation of putative global carbon budgets to 2100 under three different climate management scenarios including mitigation deterrence (see text for full explanation).

Our central argument in this paper is that the picture provided by column two is misleading, as it ignores a series of plausible dynamic responses to the introduction of GGR promises. These are represented in the third column. Firstly, all of the GGR contribution (dotted area) would be at risk if GGRs were to fail completely (with the part of the dotted area below the dashed line representing Type 1 mitigation deterrence as described above). In addition there may be substantial risks from the two further distinctive types of mitigation deterrence noted above (shown here as cross-hatched areas). Again the relative scale of the sections schematically reflects the numbers in the analysis below, but here the uncertainties are much greater. The diagonally crosshatched area (type 2) represents additional unabated emissions from rebounds and other side effects of GGRs, and thus increases overall emissions (raising the height of the column). Like Type 1 it can be estimated as a function of the promised or attempted deployment of GGR, and the risk grows the more GGR is anticipated. On the other hand, the horizontally crosshatched area (type 3) represents mitigation foregone in the hope of GGR, and thus increases the residual unabated emissions by reducing anticipated mitigation (shown as a reduction in the pale grey portion of the column). As can be seen in column three, the more GGR substitutes for mitigation in Type 1, the smaller the remaining volume of mitigation anticipated becomes, and thus there is less anticipated mitigation for Type 3 to affect (and vice versa). The relationship between the quantity of GGR anticipated and Type 3 deterrence is therefore an inverse one.

'Recalcitrant' (or hard to eliminate) emissions up to 2100 are included in the dark grey blocks in this schematic, although their extent is a matter of contention. GGR as a tool to offset recalcitrant emissions forms a part of the dotted area above the dashed line. Failure of such GGR is not considered mitigation deterrence, as it has not substituted for emissions reductions. However, given uncertainties over which emissions are genuinely recalcitrant, especially over multi-decadal timescales, one must also note that GGR promises could enable a growth in spurious 'recalcitrant emissions' (if, for example, new near zero carbon technologies for steel and cement production (Material Economics 2019) are resisted to prolong the life of existing industrial assets).

It must also be noted that any continuing 'recalcitrant' emissions beyond 2100 would need to be offset by continuing GGR deployment, in addition to any GGR needed to recover overshoot emissions accrued by 2100. Such deployment of GGR beyond 2100 is not considered further here. Nor are the implications of there being potentially 'stranded' GGR assets once any overshoot has been dealt with, even though this might create political and financial incentives to permit continued emissions.

This paper uses estimates derived from modelling work, despite the shortcomings of IAMs, for three reasons. First, such models provide figures within a consistent framework, enabling the derivation of a preliminary estimate. Second, this approach should make the estimates more accessible to the policy communities that make use of existing modelling results as an input for their deliberations. The promises embedded in modelling are here treated as indicative of current expectations amongst the climate policy community. 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 both reflect and influence policy makers' aspirations nationally and internationally (Beck and Mahony 2018). Third, by relating the estimates made here to the outcomes of IAMs, the paper can indicate ways in which such models – or their interpretation - might be improved to take more account of the risks of mitigation deterrence.

The next section outlines quantitative estimates of the amount of carbon at risk from mitigation deterrence.

3. Carbon at Risk

This section aims to quantify the carbon at risk from mitigation deterrence, taking each of the three types of deterrence set out above in turn. Throughout, figures are presented in terms of carbon equivalents ((giga)tonnes of carbon), and in cumulative amounts from 2020-2100 except where otherwise specified. A detailed account of the methodology can be found in the Supplementary material and Supplementary Table 1.

3.1 Carbon at risk from 'substitution and failure': Type 1 mitigation deterrence

This section presents a preliminary cumulative estimate of 50-229 Gt-C of expected GGR that substitutes for mitigation and may be vulnerable to failure (MD_1 in the Supplementary material).

There are a wide range of claims and estimates about the potential for different types of carbon removal. This section relies primarily on the summary of the range of GGR deployment required in the IPCC special report on 1.5°C, both as a way to simplify a complex field, and to focus on the way in which modelled expectations influence policy makers.

In no- and low-overshoot scenarios achieving 1.5°C the special report suggests a range of cumulative GGR to 2100 of 71-281Gt-C (IPCC 2018). This may be conservative in several respects: it excludes high overshoot scenarios which return to 1.5°C after exceeding 1.8°C; it reflects a larger permitted budget than previous analysis (based on Millar, Fuglestvedt et al. (2017)); and it is based largely on modelling using Shared Socio-Economic Pathways (SSPs), which imply significant inbuilt decarbonisation from historically unprecedented high efficiency uptake, and low growth rates. Furthermore, because studies targeting 1.5°C tend to present figures only for favourable contexts in which the models can still resolve for 1.5°C, their GGR figures may actually be underestimates compared to the amounts that may be deployed in practice in an effort to restrain temperature rises. These factors may also help us understand why the IPPC's 2018 GGR requirement for 1.5°C is *lower* than the 362Gt-C calculated by Wiltshire and Davies-Barnard (2015) for all IPCC pathways with a 90% chance of avoiding 2°C (and similar to the same authors' figure for the median of all 2°C pathways (166Gt-C)).

Moreover, almost all modelling to date has deployed BECCS as the only cost effective technological GGR option. As a measure of the level of GGR mobilised in the models to meet particular carbon budgets and particular temperature outcomes, BECCS has therefore functioned as a placeholder for all GGR, even though it has been increasingly constrained in models because of concerns that the levels modelled might not prove practical. However, the IPCC synthesis figure based on such studies is significantly lower than the 164-327 Gt-C contribution of GGR modelled by Realmonte et al (2019) in the only intermodel study to incorporate both BECCS and DAC technologies. The analysis in the paper therefore also uses this higher range (described as GGR_{dac} in the Supplementary material) in calculations of the upper bound of type 1 deterrence (see Supplementary Table 2, and Table 1 below), recognising that in the real world, promises of future DAC circulate alongside promises of future BECCS.

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 (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 previously been brought together with an assessment of the extent to which GGR substitutes for mitigation within the modelled pathways, rather than supplementing it (as done here).

3.1.1 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 anticipated emissions reductions, then underperformance would merely <u>reduce</u> the additional abatement achieved relative to the baseline scenario. As undesirable as that prospect might be, GGR would still be contributing, albeit in a limited way, to the abatement of climate change. But if the projected GGR substitutes partly or wholly for carbon that would otherwise have been abated through emissions reductions, then the net effect of reliance on underperforming GGRs could be a perverse and unexpected <u>net increase</u> in GHG concentrations relative to the baseline. In other words, if there is both substitution and failure, there is deterrence which increases climate risk.

Here a figure of 70% is applied to illustrate a plausible rate of substitution. This is a central figure derived from two different approaches, as detailed in the Supplementary material. First the GGR requirements modelled in recent work exploring extremely ambitious mitigation (Grubler, Wilson et al. 2018, van Vuuren, Stehfest et al. 2018) are compared with the median GGR requirement in SR1.5. Second, a figure is calculated from previous studies that quantify the decrement in emissions reduction arising from the introduction of GGR in the same model (Azar, Johansson et al. 2013, Riahi, Kriegler et al. 2015).

On the basis of 70% substitution, if no GGR materialises, then - as a first approximation, as a result of Type 1 mitigation deterrence - in the order of 50-197 Gt-C more carbon will accumulate in the atmosphere over the period to 2100 than anticipated by the IPCC (70% of the IPCCC range of 71-281 Gt-C). At the same ratio, the higher GGR requirement modelled by Realmonte et al would translate to a range of carbon at risk of 115-229 Gt-C. On the other hand, in low GGR scenarios one might wish to assume that less of the remaining GGR is a substitute, and more of it deals with genuinely recalcitrant emissions (and vice versa in high GGR scenarios). In this case, applying the lower and upper figures calculated from Grubler et al (35%, and 84%, as shown in Supplementary Material), the Type 1 range extends to 25-235 Gt-C. In what follows, a low figure of 50 Gt-C (from the IPCC-based calculation), and a high figure of 229 Gt-C based on the more recent Realmonte et al study (2019), are used.

Scenarios of continued substitution and complete failure may seem unlikely, as they imply a period of 70-80 years in which GGR remains a technical promise, but delivers no practical results. However, decades of unfulfilled promises of fusion power 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.

GGRs substitute for emissions reduction in IAMs as a result of cost-optimisation (and discounting) (Bednar, Obersteiner et al. 2019). In comparison to a 2°C target, a 1.5°C target tends to increase the contribution of GGR to the overall carbon budget by a greater relative amount, but a smaller absolute amount, than the increased contribution of emissions reductions (Rogelj, Popp et al. (2018), Luderer, Vrontisi et al. (2018)). In cost-optimising models the absolute level of such substitution might be expected to grow with higher carbon prices resulting from smaller available carbon budgets. But it cannot be taken for granted that such high carbon prices will emerge in practice, nor that they would actually deliver high GGR deployment. Substitution might be reduced in modelling by preventing even temporary exceedances of the outcome temperature goal, which in turn would prevent the models from using late GGR to recover from a temperature overshoot driven by delayed emissions reduction. This could reduce the risk of Type 1 MD, but might imply earlier GGR deployment, possibly thereby exacerbating Type 2 risks, and would likely reduce overall expected GGR deployment, thus *increasing* the scope of Type 3 risks.

Box: An example of mitigation substitution from the EU

Recent research shows how the introduction of GGR to the policy mix could affect emissions reductions at a more detailed scale (Solano Rodriguez, Drummond et al. 2017). Conventional pathways for the EU towards its 2050 target of an 80% reduction in emissions over 1990 levels (an absolute target of around 0.6Gt-CO_2 pa) involve virtual decarbonisation of electricity generation (-97.5%), combined with aggressive policies to reduce emissions in other sectors. The introduction of BECCS transforms the picture. The target is then achieved with the help of around 0.8Gt-CO_2 pa BECCS removals. Emissions in the electricity sector fall by 152% over 1990 levels. But cost effective reductions in other sectors become much smaller. 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. This is equivalent to almost 25% of the otherwise expected mitigation, and almost 90% of the carbon removed by BECCS simply substitutes for emissions reduction.

This demonstrates how promised BECCS removals might substitute other potential mitigation. It also highlights the degree of pathway lock-in, and risk to overall emissions if BECCS were not actually 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 largely impractical.

3.2 Carbon at risk from rebounds, multipliers and side effects: Type 2 mitigation deterrence

The carbon at risk from type 2 mitigation deterrence (rebounds, multipliers and side effects) is more difficult to calculate. It cannot be derived simply from an analysis of modelled outcomes. The initial estimates here indicate a cumulative range of 25-134 Gt-C (MD_2 in the Supplementary material) based on combining conservative estimates of diversion to enhanced oil recovery, and indirect land use change.

An estimate of 25-79Gt-C from enhanced oil recovery (EOR) is suggested here. EOR can act as a multiplier of atmospheric carbon. Godec, Kuuskraa et al. (2011) estimate a global potential for incremental production by EOR of 470-1070 billion barrels of oil. For each barrel 82 kg-C (300 kg-CO_2) would be stored (Godec et al), and 117-155 kg-C emitted (see Supplementary material), with the higher figure accounting for additional upstream emissions, and co-products. However, in low GGR scenarios, there may not be enough compressed CO_2 produced to meet even the low potential for EOR storage, especially if there is no BECCS deployed, and this would reduce the carbon at risk below 25 Gt-C. On the other hand, if EOR potential exceeds the estimates cited here, then more of the anticipated carbon capture in BECCS and DAC might be diverted to EOR. In high-GGR scenarios the supply of compressed CO_2 could be 3-4 times greater than the maximum amount directed to EOR here, potentially increasing the rebound proportionately.

Attribution of emissions from land-use change (LUC) resulting from bioenergy has proved difficult and contentious. Estimates of indirect land-use change (ILUC) factors for net carbon emissions 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). On the basis of a 10-20% emissions rebound from land use change associated with the bioenergy component of BECCS, a BECCS deployment of 0-273Gt-C (IPCC, 2018), might generate 0-55 Gt-C of additional emissions. However, with elevated demands for land in comparison with bioenergy so far, it is possible that that BECCS-driven LUC could lead to higher additional indirect emissions, especially if land brought into new production held significant carbon reservoirs (e.g. old growth forest, deep prairie soils or peat swamps).

These rebound effects are not limited to BECCS, and could result from other GGR techniques also. Biochar, soil carbon storage and enhanced weathering all have land-use implications. DAC carbon could also be diverted to EOR. However, EOR and ILUC effects could easily both arise in a BECCS-based GGR economy. 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. Commercial incentives to minimise the marginal costs of BECCS would drive 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 combined estimate of type 2 effects (25-134 Gt-C) makes no allowance for any possible Keynesian multiplier based on increased purchasing power resulting from public spending on GGR. However, it should be notes that decision makers investing in GGR would likely aim to maximise any such multiplier effects, because the economic co-benefits of green jobs, skill development and exports that can come alongside the development of new green technology are politically desirable. Such multipliers may be particularly significant where the techniques involved might spin-off new technological breakthroughs. Such multipliers are distinct from classic economic rebound effects, where efficiency of use makes a resource relatively cheaper. If carbon removal leads to lower carbon prices than otherwise, there will be some classic rebound effects. This, however, is already embodied in the substitution effect in Type 1 mitigation.

3.3 Carbon at risk from 'mitigation foregone' in 'imagined offsets': Type 3 mitigation deterrence

The third form of deterrence is also hard to quantify. Here an estimate of 182-297 Gt-C (MD_3 in the Supplementary material) is presented.

As noted in section 3.1, IAMs with assumed rational agents imply significant cost-optimising substitution of future GGR for near-term mitigation. Type 3 concerns instead 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 (not captured by the models) that could stimulate apparently irrational behaviours, and to assess their likely impacts on overall abatement. The term 'imagined offsets' is used to describe a situation in which an actor foregoes mitigation because they imagine that the emissions involved will be offset by other actions elsewhere or in the future. In this way promises of GGR could add to existing excuses for delay and inaction, while their inter-temporal nature would appear to make them more pernicious in this respect than promises relating to more conventional mitigation technologies.

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 (see section 3.1). Imagined offsetting arises where near-term actors behave as though future GGR will be less costly than current mitigation, and thus continue to emit, effectively assuming that their emissions will be offset by unspecified future removals. But collectively their expectations of GGR exceed possible deployment rates, limited by resource constraints or sustainability factors. At the system level it would be irrational for all such actors to defer mitigation, but at the individual level each such action might appear reasonable. In practice such actors may well face private costs per tonne of mitigation that are higher than the estimated social costs which drive policy. 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). Both these factors raise the possibility of imagined offsetting by making future GGR appear relatively cheap in comparison with near-term mitigation, and thus making a greater share of modelled mitigation vulnerable to deterrence.

Such deterrence could arise even 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 in the presence of vested interests, which deliberately 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 promises of GGR might be mobilised to defer mitigation action. This echoes ways previous promises of CCS have been deployed (Markusson, Dahl Gjefsen et al. 2017). Markusson et al's analysis of CCS further implies that the more GGR might impose a real economic cost on dominant political or economic actors, the less likely it would be to rapidly materialise in practice, and the more likely it would be to be pushed further into the future.

Estimates of the amount of mitigation forecast to cost more than \$100/t-CO_2 are used here to derive a proxy for imaginary offsetting. Advocates often suggest that GGR might cost significantly less than \$100 (McLaren 2012, Wilcox, Psarras et al. 2017, Fuss, Lamb et al. 2018, Keith, Holmes et al. 2018), so this appears a plausible level to consider. In practice such costs for GGR may only prove possible in specific, limited, applications which might not 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, exacerbating the risk of Type 3 effects.

Under an RCP6.0 baseline, 50% of mitigation (or a median of 543Gt-C), would cost above the \$100/t-CO_2 threshold (IPCC 2007) (see Supplementary material and Supplementary table 1 for calculations) However, of this amount, 80-176 Gt-C is the remaining permitted unabated cumulative emission, and (assuming that GGR substitutes only for more expensive mitigation), a further 71-281 Gt-C would be removed by GGR. This leaves a residual of expensive mitigation required of 182-297 Gt-C to achieve a 1.5°C outcome. This amount (or 17-27% of all mitigation) is considered to be at risk of imagined offsetting or Type 3 mitigation deterrence (MD_3 in the Supplementary material).

By contrast, with a counterfactual of a 1613 Gt-C RCP 8.5 emissions baseline (recalculated for 2020-2100) – still not entirely inconceivable given current political trends in countries such as the US, Brazil and Australia - the risk from imagined offsetting would reach 709-823 Gt-C (see Supplementary table 3). Once again this calculation assumes that all expensive mitigation is at risk. In practice one would expect some cultures, governments and sectors to be more susceptible to the appeal of Type 3 deterrence, and others less so. Therefore the RCP8.5 counterfactual is excluded from the figures consider further.

4. Summarising the risks of mitigation deterrence

This section brings together the preliminary estimates for the three types of mitigation deterrence considered in this paper. Table 1 summarises the carbon at risk from all three mitigation deterrence types when set against a 1.5°C target, presenting a plausible 'worst-case' exceedance of the carbon budget for 1.5°C by 371-545 Gt-C. The range drops slightly to 371-513 Gt-C if using only the IPCC summary of GGR expectations, but would rise substantially if a counterfactual of RCP8.5 were used to estimate baseline emissions rather than RCP6.0. Higher figures would also be generated if the modelling synthesized here has underestimated direct land-use change implications of GGR, or if policy design generated a detectable Keynesian multiplier effect from GGR investment. In any case, it would appear that mitigation deterrence must be taken seriously and directly addressed by both researchers and policy makers concerned with GGR. Amongst other responses, it is hoped that modellers will seek to validate or improve these quantitative estimates of the scale of the risks, and interrogate the assumptions presented regarding the inter-relations between the three types.

Table 1: Summary calculations of carbon 'at risk' from mitigation deterrence (Gt-C)

	Low estimate	Central estimate	High Estimate
Carbon at risk from GGR substitution & failure (Type 1)	50	156	229
Carbon at risk from rebounds & other side-effects (Type 2)	25	71	134
Carbon at risk from mitigation foregone in imagined offsetting (Type 3)	297	216	182
Total carbon at risk	**371**	**444**	**545**

Note: the low estimate for Type 1 is based on IPPC figures alone, the high estimate also relies on Realmonte et al 2019 (see methodology), the central estimate is a median of the two approaches. All the estimates of Type 3 reflect only an RCP6.0 counterfactual, and assume that in scenarios with high promised GGR, there will be less residual expensive mitigation at risk from type 3, and vice versa).

In terms of implications for temperatures, the exceedance of carbon budgets resulting from the substitution effects of GGR alone would be significant. 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 1.9°C; and Realmonte et al (2019) suggest up to a 0.8°C overshoot if GGR were to fail to deliver as forecast after 2050. This analysis suggests that the overall effect of overoptimistic reliance on GGRs could be even more significant, for illustration, with unfavourable climate sensitivity, leading to an overshoot to 2.9°C, despite policies aiming at 1.5°C.

This estimate is based on the IPCC's transient sensitivity range of 0.73-2.57°C per trillion tonnes of carbon (IPCC, 2018). At the median value of 1.65°C, the additional cumulative emissions shown in Table 1 equate to an additional 0.6-0.9°C of warming (Table 2). At the upper bound of 2.57°C they equate to 0.9-1.4°C extra warming. It should be noted that these figures relate only to the CO_2 forcing. If the mechanisms here were to lead to additional emissions or rebounds of other greenhouse gases alongside CO_2, the temperature effects would be proportionately higher. Matthews, Zickfeld et al. (2018) report a lower observationally constrained range of 0.7-2.0°C which would imply slightly lower figures.

A scenario in which all three forms of mitigation deterrence arise to the maximum extent estimated above may be unlikely, but still merits consideration. 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. Experience with nuclear fission and with CCS on fossil energy also suggest that significant underperformance is possible, and perhaps even predictable (Markusson, Dahl Gjefsen et al. 2017). Even in the event of complete failure, GGRs could continue to stimulate reduced mitigation even while delivering zero withdrawals, because of the critical issue of timing. 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). If GGRs were to promise but *never* materialise (which makes types 1 and 3 deterrence significant), they would be unlikely to generate any type 2 effects (such as economic rebounds). Yet a 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.

Table 2: Temperature implications of estimated carbon budget exceedances (°C)

	Estimated exceedance		
TCRE (IPCC, 2018)	**Low (367 Gt-C)**	**Central (441 Gt-C)**	**High (544 Gt-C)**
0.73 (low)	0.27	0.32	0.40
1.65 (median)	0.60	0.73	0.90
2.57 (high)	0.94	1.13	1.40

This analysis implies that the delivery of GGR requires policy and incentives which are robustly designed to avoid mitigation deterrence. It supports the view that GGR will be needed to offset some level of recalcitrant emissions, and most likely, to reverse a carbon budget overshoot. However, this analysis suggests that both such requirements might be 'reconstructed' in unhelpful ways – adjusting both their definition and scale - in the light of promises of GGR. For example, in the presence of modelled GGR the implied overshoot grows, as more expensive mitigation is postponed. In a similar way, GGR promises might enable continued use of otherwise stranded assets, or to argue that expensive zero-carbon technologies for industrial processes or air-travel are (economically) impractical or unnecessary.

5. Conclusions

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

These effects could be additive, not just alternative ways in which emissions reductions might be delayed or deterred. Moreover, the problem is a matter for concern in part because of the temporal dimension – GGRs offer promises of 'future retrospective fixing' in which the GGR compensates for past emissions. By contrast, other future action taken in response to failures, limitations or side-effects of GGR could not prevent or reverse emissions that had already happened because mitigation ambitions had not increased to the levels otherwise needed. The impacts of techno-fix promises of GGR may therefore be more pernicious than those of past climate techno-fixes such as nuclear power or fossil-CCS.

A plausible worst-case total level of cumulative 'carbon at risk' from the three types of mitigation deterrence has been calculated. Type 1 risks might constitute about 70% of promised removals, or 50-229 Gt-C. The Type 2 risks quantified here account for an additional 25-134 Gt-C, and Type 3 risk could reduce remaining emissions cuts 18-32% (182-297 Gt-C). Added together the cumulative carbon at risk to 2100 is 371-545 Gt-C (in the order of two to three times the amount of carbon removals promised).

The implications of this for global temperatures are that the committed temperature rise could be up to 1.4°C higher than anticipated (in pathways otherwise expected to limit rises to 1.5°C). This assumes all other impacts on climate forcings remain equal and that climate responses remain consistent even if emissions rates become net negative. Here the non-climate implications of different pathways have not been considered, but the replacement of mitigation with GGR might also have implications for inequality for example, depending on the nature of the techniques and the distribution of the increased residual emissions. More air travel, offset by BECCS based on annexation of cropland for bioenergy production, for example, could be expected to increase injustice in both respects.

These findings carry serious implications for research and policy. They do not, however, constitute an argument to halt or reduce research into GGR. This analysis rather confirms the great difficulty of meeting climate goals without deployment of GGR in some form(s). However, if the nature and scale of these risks is as portrayed here, it is incumbent upon both policy makers and researchers to consider and develop governance approaches for research and development which minimise the risks of deterrence. To facilitate this will require greater disaggregation of the risks, and more detailed analysis of the potential political and psychosocial mechanisms by which they may emerge.

The 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, and this is especially true for imaginaries of GGR (Minx, Lamb et al. 2017). Modellers tend to understand that models should be experimental sandpits, yet policy tends to treat them as truth-machines (McLaren 2018). Developing responsible and deliberative ways to deploy and interpret models in politically charged climate debates where misinterpretation is rife, and multiple decision makers face conflicting incentives, is a key challenge for preventing mitigation deterrence. Consistently constraining models to avoid overshoots would be one helpful approach (Rogelj, Huppmann et al. 2019). More generally, when developing governance of GGRs in the face of mitigation deterrence, interventions are needed that not only support the material delivery of functioning GGR, but also minimise the offsets, substitution, and rebounds that constitute mitigation deterrence. Elsewhere the present author has argued for a clear separation in target setting and incentives for emissions reduction and negative emissions, analogous to the 'chinese walls' used in financial policy (McLaren, Tyfield et al. 2019). Measures that enhance the monitoring and verification of negative emissions would also help limit some forms of mitigation deterrence, as would measures which specifically incentivise or progressively mandate removal to storage, rather than just capture. Supporting portfolios of GGR rather than single technologies may also reduce risks, and enable planning for some redundancy in delivery. Overall, and critically, there will remain a need for a reflexive framework that raises emissions reduction ambitions in advance of emerging deterrence effects.

References

Allen, M. R., D. J. Frame, C. Huntingford, C. D. Jones, J. A. Lowe, M. Meinshausen and N. Meinshausen (2009). "Warming caused by cumulative carbon emissions towards the trillionth tonne." Nature **458**: 1163.

Alvarez, R. A., D. Zavala-Araiza, D. R. Lyon, D. T. Allen, Z. R. Barkley, A. R. Brandt, K. J. Davis, S. C. Herndon, D. J. Jacob, A. Karion, E. A. Kort, B. K. Lamb, T. Lauvaux, J. D. Maasakkers, A. J. Marchese, M. Omara, S. W. Pacala, J. Peischl, A. L. Robinson, P. B. Shepson, C. Sweeney, A. Townsend-Small, S. C. Wofsy and S. P. Hamburg (2018). "Assessment of methane emissions from the U.S. oil and gas supply chain." Science **361**(6398): 186-188.

Anderson, K. and A. Bows (2008). "Reframing the climate change challenge in light of post-2000 emission trends." Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences **366**(1882): 3863.

Anderson, K. and G. Peters (2016). "The trouble with negative emissions." Science **354**(6309): 182.

Armstrong, K. and P. Styring (2015). "Assessing the potential of utilization and storage strategies for post-combustion CO2 emissions reduction." Frontiers in Energy Research **3**(8): 1-9.

Azar, C., D. J. A. Johansson and N. Mattsson (2013). "Meeting global temperature targets—the role of bioenergy with carbon capture and storage." Environmental Research Letters **8**(3): 034004.

Beck, S. and M. Mahony (2018). "The politics of anticipation: the IPCC and the negative emissions technologies experience." Global Sustainability **1**: e8.

Bednar, J., M. Obersteiner and F. Wagner (2019). "On the financial viability of negative emissions." Nature Communications **10**(1): 1783.

Bennett, S. and T. Stanley. (2018). "Commentary: US budget bill may help carbon capture get back on track, 12 March

2018." Retrieved 22/02/2019, from https://www.iea.org/newsroom/news/2018/march/commentary-us-budget-bill-may-help-carbon-capture-get-back-on-track.html.

Fuss, S., J. G. Canadell, G. P. Peters, M. Tavoni and others (2014). "Betting on negative emissions." Nature Climate Change **4**: 850-853.

Fuss, S., W. F. Lamb, M. W. Callaghan, J. Hilaire, F. Creutzig, T. Amann, T. Beringer, W. d. O. Garcia, J. Hartmann, T. Khanna, G. Luderer, G. F. Nemet, J. Rogelj, P. Smith, J. L. Vicente, J. Wilcox, M. d. M. Z. Dominguez and J. C. Minx (2018). "Negative emissions—Part 2: Costs, potentials and side effects." Environmental Research Letters **13**(6): 063002.

Godec, M., S. Carpenter and K. Coddington (2017). "Evaluation of Technology and Policy Issues Associated with the Storage of Carbon Dioxide via Enhanced Oil Recovery in Determining the Potential for Carbon Negative Oil." Energy Procedia **114**: 6563-6578.

Godec, M., V. Kuuskraa, T. Van Leeuwen, L. Stephen Melzer and N. Wildgust (2011). "CO2 storage in depleted oil fields: The worldwide potential for carbon dioxide enhanced oil recovery." Energy Procedia **4**: 2162-2169.

Goulder, L. H. and R. C. Williams (2012). "The choice of discount rate for climate change policy evaluation." Climate Change Economics **03**(04): 1250024.

Grubler, A., C. Wilson, N. Bento, B. Boza-Kiss, V. Krey, D. L. McCollum, N. D. Rao, K. Riahi, J. Rogelj, S. De Stercke, J. Cullen, S. Frank, O. Fricko, F. Guo, M. Gidden, P. Havlík, D. Huppmann, G. Kiesewetter, P. Rafaj, W. Schoepp and H. Valin (2018). "A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies." Nature Energy **3**(6): 515-527.

IPCC (2007). Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA, Cambridge University Press.

IPCC (2018). Global Warming of 1.5°C. Switzerland, Intergovernmental Panel on Climate Change.

Jouini, E., J.-M. Marin and C. Napp (2010). "Discounting and divergence of opinion." Journal of Economic Theory **145**(2): 830-859.

Keith, D. W., G. Holmes, D. St. Angelo and K. Heidel (2018). "A Process for Capturing CO2 from the Atmosphere." Joule.

Larkin, A., J. Kuriakose, M. Sharmina and K. Anderson (2017). "What if negative emission technologies fail at scale? Implications of the Paris Agreement for big emitting nations. ." Climate Policy.

Luderer, G., Z. Vrontisi, C. Bertram, O. Y. Edelenbosch, R. C. Pietzcker, J. Rogelj, H. S. De Boer, L. Drouet, J. Emmerling, O. Fricko, S. Fujimori, P. Havlík, G. Iyer, K. Keramidas, A. Kitous, M. Pehl, V. Krey, K. Riahi, B. Saveyn, M. Tavoni, D. P. Van Vuuren and E. Kriegler (2018). "Residual fossil CO2 emissions in 1.5–2 °C pathways." Nature Climate Change **8**(7): 626-633.

Markusson, N., M. Dahl Gjefsen, J. C. Stephens and D. Tyfield (2017). "The political economy of technical fixes: The (mis)alignment of clean fossil and political regimes." Energy Research & Social Science **23**: 1-10.

Markusson, N., D. McLaren and D. Tyfield (2018). "Towards a cultural political economy of mitigation deterrence by negative emissions technologies (NETs)." Global Sustainability **1**: e10.

Masnadi, M. S. and A. R. Brandt (2017). "Climate impacts of oil extraction increase significantly with oilfield age." Nature Climate Change **7**(8): 551-556.

Material Economics (2019). Industrial Transformation 2050 - Pathways to Net-Zero Emissions from EU Heavy Industry. Cambridge, University of Cambridge Institute for Sustainability Leadership (CISL).

Matthews, H. D., K. Zickfeld, R. Knutti and M. R. Allen (2018). "Focus on cumulative emissions, global carbon budgets and the implications for climate mitigation targets." Environmental Research Letters **13**(1): 010201.

McLaren, D. (2012). "A comparative global assessment of potential negative emissions technologies." Process Safety and Environmental Protection **90**(6): 489-500.

McLaren, D. (2016). "Mitigation Deterrence and the 'Moral Hazard' in Solar Radiation Management." Earth's Future **4**(12): 596-602.

McLaren, D. P. (2018). "Whose climate and whose ethics? Conceptions of justice in solar geoengineering modelling." Energy Research & Social Science **44**: 209-221.

McLaren, D. P., D. P. Tyfield, R. Willis, B. Szerszynski and N. O. Markusson (2019). "Beyond "Net-Zero": A Case for

Separate Targets for Emissions Reduction and Negative Emissions." Frontiers in Climate **1**: 4.

Millar, R. J., J. S. Fuglestvedt, P. Friedlingstein, J. Rogelj, M. J. Grubb, H. D. Matthews, R. B. Skeie, P. M. Forster, D. J. Frame and M. R. Allen (2017). "Emission budgets and pathways consistent with limiting warming to 1.5 °C." Nature Geoscience **10**: 741.

Minx, J. C., W. F. Lamb, M. W. Callaghan, L. Bornmann and S. Fuss (2017). "Fast growing research on negative emissions." Environmental Research Letters **12**(3): 035007.

Minx, J. C., W. F. Lamb, M. W. Callaghan, S. Fuss, J. Hilaire, F. Creutzig, T. Amann, T. Beringer, W. d. O. Garcia, J. Hartmann, T. Khanna, D. Lenzi, G. Luderer, G. F. Nemet, J. Rogelj, P. Smith, J. L. Vicente, J. Wilcox and M. d. M. Z. Dominguez (2018). "Negative emissions—Part 1: Research landscape and synthesis." Environmental Research Letters **13**(6): 063001.

Oreskes, N. and E. M. Conway (2011). Merchants of Doubt: How a Handful of Scientists Obscured the Truth on Issues from Tobacco Smoke to Global Warming. London, Bloomsbury Press.

Peters, G. P. (2018). "Beyond carbon budgets." Nature Geoscience **11**(6): 378-380.

Peters, G. P., R. M. Andrew, S. Solomon and P. Friedlingstein (2015). "Measuring a fair and ambitious climate agreement using cumulative emissions." Environmental Research Letters **10**(10): 105004.

Realmonte, G., L. Drouet, A. Gambhir, J. Glynn, A. Hawkes, A. C. Köberle and M. Tavoni (2019). "An inter-model assessment of the role of direct air capture in deep mitigation pathways." Nature Communications **10**(1): 3277.

Riahi, K., E. Kriegler, N. Johnson, C. Bertram, M. den Elzen, J. Eom, M. Schaeffer, J. Edmonds, M. Isaac, V. Krey, T. Longden, G. Luderer, A. Méjean, D. L. McCollum, S. Mima, H. Turton, D. P. van Vuuren, K. Wada, V. Bosetti, P. Capros, P. Criqui, M. Hamdi-Cherif, M. Kainuma and O. Edenhofer (2015). "Locked into Copenhagen pledges — Implications of short-term emission targets for the cost and feasibility of long-term climate goals." Technological Forecasting and Social Change **90**: 8-23.

Rogelj, J., P. M. Forster, E. Kriegler, C. J. Smith and R. Séférian (2019). "Estimating and tracking the remaining carbon budget for stringent climate targets." Nature **571**(7765): 335-342.

Rogelj, J., D. Huppmann, V. Krey, K. Riahi, L. Clarke, M. Gidden, Z. Nicholls and M. Meinshausen (2019). "A new scenario logic for the Paris Agreement long-term temperature goal." Nature **573**(7774): 357-363.

Rogelj, J., A. Popp, K. V. Calvin, G. Luderer, J. Emmerling, D. Gernaat, S. Fujimori, J. Strefler, T. Hasegawa, G. Marangoni, V. Krey, E. Kriegler, K. Riahi, D. P. van Vuuren, J. Doelman, L. Drouet, J. Edmonds, O. Fricko, M. Harmsen, P. Havlík, F. Humpenöder, E. Stehfest and M. Tavoni (2018). "Scenarios towards limiting global mean temperature increase below 1.5 °C." Nature Climate Change **8**(4): 325-332.

Rogelj, J., M. Schaeffer, P. Friedlingstein, N. P. Gillett, D. P. van Vuuren, K. Riahi, M. Allen and R. Knutti (2016). "Differences between carbon budget estimates unravelled." Nature Climate Change **6**: 245.

Rosen, J. (2018). "The Carbon Harvest." Science **359**(6377): 733-737.

Souza, G. M., R. L. Victoria, C. A. Joly and L. M. Verdade (2013). Bioenergy & Sustainability: bridging the gaps. Sao Paulo, SCOPE. **72**.

van Vuuren, D. P., E. Stehfest, D. E. H. J. Gernaat, M. van den Berg, D. L. Bijl, H. S. de Boer, V. Daioglou, J. C. Doelman, O. Y. Edelenbosch, M. Harmsen, A. F. Hof and M. A. E. van Sluisveld (2018). "Alternative pathways to the 1.5 °C target reduce the need for negative emission technologies." Nature Climate Change **8**(5): 391-397.

Vaughan, N. E. and C. Gough (2016). "Expert assessment concludes negative emissions scenarios may not deliver." Environmental Research Letters **11**(9): 095003.

Wilcox, J., P. C. Psarras and S. Liguori (2017). "Assessment of reasonable opportunities for direct air capture." Environmental Research Letters **12**(6): 065001.

Wiltshire, A. and T. Davies-Barnard (2015). Planetary limits to BECCS negative emissions AVOID Working Paper.

Quantifying Mitigation Deterrence: Supplementary material

Methodology and background calculations

This Supplementary material details the methodology and the background calculations required to estimate mitigation deterrence from GGRs. The paper seeks primarily to quantify the potential scale of mitigation deterrence, not to quantify the likelihood of its incidence. To do this it makes use of figures produced from published and peer-reviewed carbon budget analysis and integrated assessment modelling. Where possible estimates are based on the synthesis figures published in SR1.5 (IPCC 2018).

Supplementary Table 1 summarises the estimates, derivations and sources described below.

Supplementary table 1: The methodology, estimates and data sources used for Type 1, 2 and 3 mitigation deterrence

Identity	Description	Estimate (Gt-C)	Method or Source(s)
MD_{total}	Total carbon at risk from mitigation deterrence	213-780	$MD_1 + MD_2 + MD_3$ (using GGR_{dac} this rises to 278-812 Gt-C)
MD_1	Type 1 mitigation deterrence at risk (substitution and failure)	**50-197**	MD1 = GGR_{sub} (using GGR_{dac} rather than GGR_{req} to calculate GGR_{sub} gives 115-229 Gt-C)
GGR_{req}	Modelled GGR requirement in 1.5°C scenarios	71-281	5th-95th percentile range (median 199 Gt-C) as provided by IPCC (2018).
GGR_{dac}	Modelled GGR requirement for 1.5°C scenarios including both BECCS and DAC	164-327	Realmonte et al (2019)
GGR_{sub}	Modelled GGR deployment that (temporally) substitutes for emissions reduction.	50-197	GGR_{req} x SUB_{rate}
SUB_{rate}	Central estimate of the proportion of modelled GGR that substitutes for emissions reduction	70%	(a) (GGR_{req}-GGR_{min})/GGR_{req} (gives 77% on central GGR_{req}) (b) Calculated from Azar et al (2013), and Riahi et al (2105) (gives 66%)
GGR_{min}	Modelled minimum GGR to deliver 1.5°C scenario	46	Grubler et al (2018)
MD_2	Type 2 mitigation deterrence (Rebound effects and other indirect sources of additional emissions from GGR efforts)	**20-135**	RE_{luc} + RE_{eor}
RE_{luc}	Carbon rebound from land-use change for BECCS	0-55	GGR_{beccs} x $RE(LUC)_{rate}$
$RE(LUC)_{rate}$	Carbon rebound from land-use change as fraction of carbon mitigated by bioenergy.	10-20%	Estimate for indirect land-use change effects of well managed bioenergy (Souza et al 2013)
GGR_{beccs}	Modelled range of BECCS contribution to 1.5C scenarios	0-273	IPCC (2018)
RE_{eor}	Rebound effects from use of captured carbon in enhanced oil recovery	25-79	RE_{eor} = EOR_{com} - EOR_{stor}
EOR_{em}	Carbon released by combustion of additional oil and co-products recovered through EOR, and associated upstream emissions.	63-166	EOR potential 470-1070 billion barrels of oil (Godec et al 2011) at 134-155kg-C per barrel (USEPA Undated; Masnadi et al 2016; Gordon et al 2015)
EOR_{stor}	Carbon stored in EOR processes	38-87	Global potential for EOR related CO_2 storage of 38-87 Gt-C (Godec et al 2011).
MD_3	Type 3 mitigation deterrence (mitigation foregone, or imaginary offsets)	**182-297**	MIT_{100} – ($CBUD_{1.5}$ - GGR_{req}), (= residual emissions reduction costing over \$100/t-CO_2)
MIT_{100}	Amount of emissions that would cost over \$100/t-CO_2 to mitigate in an RCP6.0 baseline scenario.	543	EM_{base} x $PROP_{100}$
EM_{base}	Baseline remaining cumulative emissions in RCP6.0 (2020-2100)	1087	IPCC (2014) – 987-1360 Gt-C (2011-2100), less cumulative emissions from 2011-2019 (87Gt-C): median 1087 Gt-C.
$CBUD_{1.5}$	Permitted unabated emissions (2020-2100) compatible with 1.5°C scenarios	80-176	IPCC (2018) adjusted for estimated emissions from 2017-2019.
$PROP_{100}$	The proportion of total emissions mitigation costing more than \$100/t-CO_2 given an RCP6.0 baseline	50%	IPCC (2007) estimate of economic mitigation at 2030

Type 1

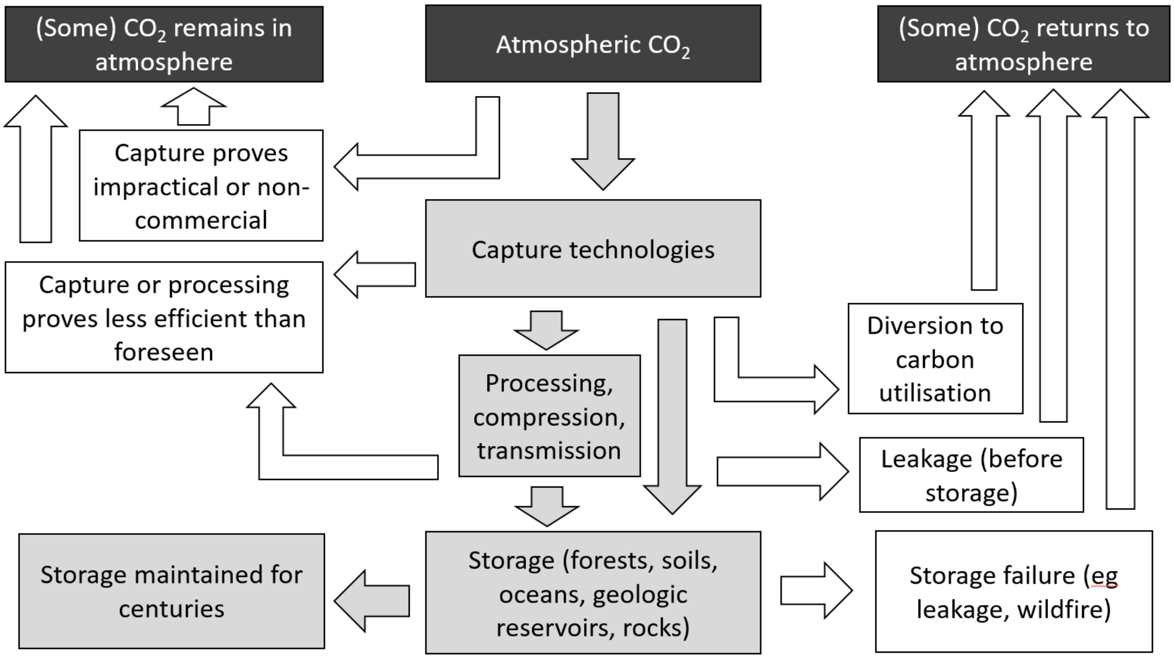
The estimates of mitigation deterrence begin in Section 3.1 using the modelled requirements for GGR in 1.5°C compliant pathways (GGR_{req}), treating this as a reasonable synthesis estimate of the likely requirement (see Supplementary Table 2). Higher initial estimates of GGR deployment in more recent modelling including both BECCS and DAC technologies (GGR_{dac}) are also noted, because the modelling work synthesized in SR1.5 relied almost entirely on the single (constrained) GGR technology of BECCS. Modelling which also includes DAC (and promises of DAC) may therefore provide a more realistic estimate of current expectations.

Supplementary table 2: Estimates of the scale of GGR required to 2100

Source	Cumulative GGR (Gt-C, to 2100)	Target	Role in this paper
IPCC (2018)	71-281	1.5°C ('zero and no overshoot' pathways)	Used as baseline for calculations in this paper
Wiltshire and Davies-Barnard (2015)	166 372	2°C (median 'compatible') 2°C (90% chance)	Used to illustrate 2°C target GGR requirements
Realmonte et al (2019)	164-327	1.5°C	Used for upper bound, to illustrate implications of multiple technological GGRs
Rogelj et al (2018)	38-262 44-327	2.0°C 1.5°C	Used to note the implications of shift between 2°C & 1.5°C targets
Luderer et al (2018)	98-210 175-259	2.0°C (67% chance) 1.5°C (50% chance)	
Grubler et al (2018)	46	1.5°C	Used to illustrate GGR-minimising scenarios to calculate substitution

The modelled deployment is separated into two elements: first that which does not substitute for otherwise abateable emissions (basically GGR deployed to compensate for genuinely recalcitrant residual emissions); and second, that which does substitute (typically but not exclusively GGR which reverses excess emissions after a temporal delay (GGR_{sub})). In the models such later GGR removals are largely matched by net increases in emissions in the near term, and thus failure to deliver GGR would mean that an additional amount of emissions equal to GGR_{sub} would go unabated.

Estimates of the proportion of GGR which does substitute (the factor SUB_{rate}) are derived from two sources. First a minimum GGR requirement (GGR_{min}) derived from recent work exploring extremely ambitious mitigation (Grubler, Wilson et al. 2018, van Vuuren, Stehfest et al. 2018) is compared with the GGR deployment in the IPCC (GGR_{req}). Grubler et al reduce cumulative GGR requirements (in the form of re- or afforestation) to as little as 46Gt-C, or just 23% of the central GGR requirement in SR1.5 (199 Gt-C). This implies the remaining 77% of GGR substitutes for otherwise feasible mitigation. Comparing GGR_{min} with the extremes of the IPCC GGR range would suggest substitution of 35% and 84% respectively. Second, a supplementary SUB_{rate} estimate is extracted from previous 2°C scenario modelling which explicitly calculates the decrement in emissions reduction arising from the introduction of GGR in the same model. Reviewing findings from five IAMs, Tavoni and Socolow (2015) report that in all cases GGR *"availability reduces conventional mitigation early in the [current] century, relative to base cases where no [GGR] is available"* (p6). Two studies (Azar, Johansson et al. 2013, Riahi, Kriegler et al. 2015) provide direct comparative figures. These studies forecast emissions reductions to be 1.7-2.45 Gt-C pa lower in 2°C pathways with substantial deployment of GGR. Shortfalls at these rates continued over the rest of the century (with a constantly receding promise of GGR[1]) would aggregate to 153-196Gt-C, or a median of 166 Gt-C, equivalent to 66% of the median 273 Gt-C removals by GGR in 2°C pathways found by Wiltshire and Davies-Barnard (2015). Combining these two approaches, suggests that treating 70% of cumulative GGR as a substitute is a reasonable approximation. This approximate central figure of 70% (SUB_{rate}), based on the two sources, is therefore applied to both GGR_{req} and GGR_{dac} to calculate the *amount* of GGR that substitutes (GGR_{sub}). This provides an estimated range for Type 1 mitigation deterrence (MD_1, Supplementary Table 1). The potential for subsequent failure to achieve long-term removal of the whole of this substituted amount is discussed in the main text (see sections 2.1, 3.1.1 and 4). Possible failure routes are illustrated here in Supplementary Figure 1.



Supplementary Figure 1: A flow diagram showing the steps required for successful long-term carbon storage by GGRs. Possible failures are shown by white arrows and boxes. Success requires negotiating the grey track.

Type 2

In section 3.2, to estimate MD_2, two possible rebound effects are estimated and combined. These are illustrative of different ways in which additional emissions, not accounted in the models, might arise from the actual or attempted deployment of GGR. These relate to land use change and enhanced oil recovery, two phenomena which have already been identified as risks associated with the most widely modelled form of GGR (BECCS). A range for BECCS deployment (GGR_{beccs}) is taken from IPCC (2018). A ratio for indirect land-use rebound emissions ($RE(LUC)_{rate}$) and an estimate for EOR related emissions in excess of storage (RE_{eor}) are derived from relevant literatures (see also Supplementary Table 1).

For $RE(LUC)_{rate}$ the estimate relies on the central range of a 10-20% emissions rebound estimated for well-managed bioenergy systems (Souza, Victoria et al. 2013). The GGR_{beccs} figure is multiplied by the $RE(LUC)_{rate}$ to estimate the land-use rebound emissions RE_{luc}. Attribution of this rebound to GGR may be contentious, as non-GGR pathways also include substantial increases in land use for biomass energy. Nor is it simple to

[1] In Azar et al's pathways 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) (Azar, C., D. J. A. Johansson and N. Mattsson (2013). "Meeting global temperature targets—the role of bioenergy with carbon capture and storage." Environmental Research Letters **8**(3): 034004.)

unpick the extent to which models already include these effects in their land-use calculations. Wiltshire and Davies-Barnard (2015) highlight that early modelling of BECCS often overlooked even direct land-use change, which for certain deployments could eliminate any carbon benefit of the technology. If this is not fully accounted for in the models considered here the rebound effects would be higher than estimated here.

The EOR rebound (RE_{eor}) is based on a global potential for EOR to recover an additional 470-1070 billion barrels of oil and store 38-87 Gt-C (140-320 Gt-CO2) (EOR_{stor}) at an average rate of 300kg-CO_2 (82kg-C) (Godec, Kuuskraa et al. 2011). The oil recovered is assumed to have an embodied average CO_2 content on combustion of 430kg-CO_2 (117 kg-C) ((USEPA Undated), to which is added 63kg-CO2 per barrel for global average upstream emissions (based on 6120 MJ per barrel and 10.3g/MJ (Masnadi, El-Houjeiri et al. 2018)) for a low estimate of per barrel emissions of 493kg CO2 (134 kg-C). A high estimate for per barrel emissions is derived from Gordon, Brandt et al. (2015) who calculate a weighted average of 570kg-CO_2 (155kg-C) per barrel including all upstream and processing emissions and coproducts. Gross emissions associated with the additional oil (EOR_{em}) are therefore 63-166 Gt-C (470-1070 barrels at 134-155kg per barrel). The net additional emissions from EOR (RE_{eor}) can be calculated by subtracting EOR_{stor} from EOR_{em}, or by subtracting the storage per barrel from the emissions per barrel, giving a range from 193-270 kg-CO_2 (53-74 kg-C) per barrel, which, multiplied by 470-1070 billion barrels, gives 24.7-79.8 Gt-C (RE_{eor}).

The two effects are potentially additive and co-correlated (in that the amounts of CO_2 available for EOR will grow with higher rates of BECCS and or DAC; while the scale and potential severity of land-use rebounds can also be expected to grow with higher deployment of BECCS). Therefore the low and high extremes of the ranges of each of the two rebounds are summed to give a range for Type 2 mitigation deterrence (MD_2, Supplementary Table 1). Because this only covers two possible rebounds, it remains a partial estimate.

Type 3

Section 3.3 (and Supplementary table 3) present an estimate of the potential scale of mitigation foregone through imaginary offsetting (or Type 3 mitigation deterrence – MD_3). There are no empirical estimates of this effect, so a novel approach is applied, based on the tendency of promises of future GGR to embody claims about cost. This assumes that actors (governments, businesses, individuals) faced with difficult or expensive mitigation actions will be more likely to seek to avoid them if the promised cost of future GGR is lower than the immediate anticipated cost of mitigation.

Supplementary table 3: Carbon at risk through mitigation foregone in imagined offsetting

	Counterfactual	
	RCP6.0	**RCP 8.5**
Median anticipated emissions (2020-2100) (Gt-C)	1087	1613
Emissions abated for less than \$100/t-CO_2 (Gt-C)	543	543
Emissions costing over \$100/t-CO_2 to mitigate	543	1087
Residual budget for 1.5°C (Gt-C) (Based on IPCC, 2018)	80-176	80-176
GGR removals (Gt-C)	71-281	71-281
Remaining 'at risk' mitigation at over \$100/t-CO_2 (Gt-C)	182-297	709-823

To derive a quantitative estimate, figures for baseline emissions in RCP6.0 (EM_{base}) are used to calculate the quantity of emissions reduction that would be expected to cost more than \$100/t-CO_2 (\$367/t-C) (MIT_{100}). This cost threshold is selected to represent emissions reductions costing more than the typically promised cost of GGR (Fuss, Lamb et al. 2018, Keith, Holmes et al. 2018). All emissions reduction activities costing in excess of the $100 threshold level are considered to be vulnerable to imagined offsetting or Type 3 mitigation deterrence (MD_3, Supplementary Table 1), because the relevant emitters might – in isolation - reasonably expect that paying for future carbon removal would cost them less than cutting emissions.

To calculate the amount of carbon involved, the most recent available IPCC estimate for the proportion of mitigation costing over this threshold ($PROP_{100}$) (IPCC 2007): (50%), is applied to baseline RCP6.0 emissions from IPCC (2014), adjusted downwards for emissions from 2011-2020). From MIT_{100} the permissible cumulative unabated emissions ($CBUD_{1.5}$) and the contribution of GGR (GGR_{req}) are both subtracted, to produce figures for the residual amount of anticipated mitigation costing over $100/t-$CO_2$.

According to the IPCC's Fourth Assessment Report (IPCC 2007), in 2030, mitigation of between 50 and 70% of total emissions would cost more than $100/t-$CO_2$ (and thus 30-50% would cost less than $100 per tonne).[2] The lower figure (50%) is based on baseline emissions from an RCP6.0 path, while the upper figure of 70% applies to RCP8.5 (IPCC, 2007). In RCP6.0 (see Supplementary table 3) 900-1273 Gt-C (median 1087 Gt-C) cumulative emissions are anticipated between 2020 and 2100.[3] Half of this, or 543 Gt-C is therefore the median estimate of MIT_{100} in the RCP6.0 baseline. However, of this amount, 80-176 Gt-C is the permitted unabated cumulative emission, and (assuming that all the substitution described in section 3.1 was of more expensive mitigation), a further 71-281 Gt-C would be removed by GGR.[4] This leaves a residual of mitigation (costing above the $100 threshold, and required to achieve a 1.5°C outcome) of 182-297 Gt-C (MD_3). One can assume that higher anticipated emissions would stimulate higher GGR deployment, but that a large permitted residual emissions budget would stimulate lower GGR deployment. To calculate the range of MD_3 therefore the sum of high GGR and low remaining budget (361 Gt-C) or the sum of low GGR and high remaining budget (247 Gt-C) respectively, were subtracted from the figure for residual expensive emissions (see Supplementary Table 3). Supplementary table 3 also illustrates the effects of a RCP 8.5 counterfactual on Type 3 mitigation deterrence.

Summary and temperature implications

This gives quantitative estimates of the carbon at risk for the three types of mitigation deterrence. In Section 4 and Table 1 these are summed. Because Types 1 and 2 are both positively correlated with the underlying GGR requirement, but Type 3 is inversely correlated with the underlying GGR requirement, the low estimates of Types 1 and 2 are added to the high estimate of Type 3 and vice versa to construct the range of carbon at risk from mitigation deterrence. Finally, a range of transient climate response to cumulative carbon emissions (TCRE) estimates derived from IPCC (2018), are used to calculate the additional temperature rise that could result from this 'at risk' carbon (Table 2).

Supplementary material references

Azar, C., D. J. A. Johansson and N. Mattsson (2013). "Meeting global temperature targets—the role of bioenergy with carbon capture and storage." Environmental Research Letters **8**(3): 034004.

Fuss, S., W. F. Lamb, M. W. Callaghan, J. Hilaire, F. Creutzig, T. Amann, T. Beringer, W. d. O. Garcia, J. Hartmann, T. Khanna, G. Luderer, G. F. Nemet, J. Rogelj, P. Smith, J. L. Vicente, J. Wilcox, M. d. M. Z. Dominguez and J. C. Minx (2018). "Negative emissions—Part 2: Costs, potentials and side effects." Environmental Research Letters **13**(6): 063002.

Gordon, D., A. Brandt, J. Bergerson and J. Koomey (2015). Know Your Oil: Creating an Global Oil-Climate Index. Washington DC, Carnegie Endowment for International Peace.

Grubler, A., C. Wilson, N. Bento, B. Boza-Kiss, V. Krey, D. L. McCollum, N. D. Rao, K. Riahi, J. Rogelj, S. De Stercke, J. Cullen, S. Frank, O. Fricko, F. Guo, M. Gidden, P. Havlík, D. Huppmann, G. Kiesewetter, P. Rafaj, W. Schoepp and H. Valin (2018). "A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies." Nature Energy **3**(6): 515-527.

[2] See Chapter 11 in https://www.ipcc.ch/site/assets/uploads/2018/03/ar4_wg3_full_report-1.pdf

[3] RCP6.0 involves 987-1360 Gt-C cumulative emissions over 2011-2100, here reduced by 87 Gt-C to account for emissions from 2011-2019.

[4] The whole amount of GGR deployed is used here, as the total in RCP6.0 includes recalcitrant emissions.

IPCC (2007). Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA, Cambridge University Press.

IPCC (2014). Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva, IPCC.

IPCC (2018). Global Warming of 1.5ºC. Switzerland, Intergovernmental Panel on Climate Change.

Keith, D. W., G. Holmes, D. St. Angelo and K. Heidel (2018). "A Process for Capturing CO2 from the Atmosphere." Joule.

Masnadi, M. S., H. M. El-Houjeiri, D. Schunack, Y. Li, J. G. Englander, A. Badahdah, J.-C. Monfort, J. E. Anderson, T. J. Wallington, J. A. Bergerson, D. Gordon, J. Koomey, S. Przesmitzki, I. L. Azevedo, X. T. Bi, J. E. Duffy, G. A. Heath, G. A. Keoleian, C. McGlade, D. N. Meehan, S. Yeh, F. You, M. Wang and A. R. Brandt (2018). "Global carbon intensity of crude oil production." Science **361**(6405): 851.

Riahi, K., E. Kriegler, N. Johnson, C. Bertram, M. den Elzen, J. Eom, M. Schaeffer, J. Edmonds, M. Isaac, V. Krey, T. Longden, G. Luderer, A. Méjean, D. L. McCollum, S. Mima, H. Turton, D. P. van Vuuren, K. Wada, V. Bosetti, P. Capros, P. Criqui, M. Hamdi-Cherif, M. Kainuma and O. Edenhofer (2015). "Locked into Copenhagen pledges — Implications of short-term emission targets for the cost and feasibility of long-term climate goals." Technological Forecasting and Social Change **90**: 8-23.

Souza, G. M., R. L. Victoria, C. A. Joly and L. M. Verdade (2013). Bioenergy & Sustainability: bridging the gaps. Sao Paulo, SCOPE. **72**.

USEPA. (Undated). "Greenhouse Gases Equivalencies Calculator - Calculations and References." from https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references.

van Vuuren, D. P., E. Stehfest, D. E. H. J. Gernaat, M. van den Berg, D. L. Bijl, H. S. de Boer, V. Daioglou, J. C. Doelman, O. Y. Edelenbosch, M. Harmsen, A. F. Hof and M. A. E. van Sluisveld (2018). "Alternative pathways to the 1.5 °C target reduce the need for negative emission technologies." Nature Climate Change **8**(5): 391-397.

Wiltshire, A. and T. Davies-Barnard (2015). Planetary limits to BECCS negative emissions AVOID Working Paper.