The risks of relying on tomorrow's "negative emissions" to guide today's mitigation ambition

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Contents

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Abstract

This paper focuses on the risks associated with "negative emission" options for drawing carbon dioxide from the atmosphere through photosynthesis and storing it in land-based sinks. It examines what these risks mean for near-term actions and long-term mitigation strategies, including the 1.5°C and 2°C temperature limits. Negative emissions options have increasingly appeared – sometimes transparently and sometimes only implicitly – in analyses and discussions of society's options for addressing the challenge of climate change. Deployed later in the century, negative emissions could allow society to "undo" emissions that occurred earlier, enabling us to honor a given carbon budget in the long run, even after having grossly exceeded it in prior decades.

We identify three types of risks associated with using negative emissions in such strategies: (i) the risk that negative emission options do not prove feasible in the future when they are ultimately required; (ii) the risk that unacceptable ecological and social impacts are unavoidable for large-scale deployment; and, (iii) the risk that the reversal of emission reductions is caused by human or natural forces, including climate change.

In light of these three types of risks, we examine four main land-based negative emissions options: ecosystem restoration, mosaic-landscape restoration, reforestation, and bioenergy with carbon capture and sequestration (BECCS).

Of the mitigation pathways presented in the literature as "likely" to comply with a 1.5°C or 2°C goal, many assume the future availability of a very high volume of negative emissions (e.g., 1000 $GtCO_2$), despite the absence of reasonable confidence that negative emissions at the required scale will be available from options that are technically and biophysically feasible, ecologically and socially acceptable, and reliably permanent. It is necessary to question whether a pathway can be considered "likely" to comply with a specified goal if it relies on negative emission options that themselves may not have a "likely" chance of proving feasible and providing reliable reductions at the needed scale. Embarking on such pathways could strand us at a later date with an insufficiently transformed energy economy, an exceeded carbon budget, and a carbon debt that cannot be repaid.

However, the literature also presents pathways (those that most rapidly reduce emissions from fossil fuels and deforestation) that rely on a significantly lower level of negative emissions for the 1.5°c pathways, or none at all for 2°c pathways. At this lower level, it is possible for ecosystem restoration and reforestation to provide the required volume of negative emissions. This avoids the need to rely on other options (BECCS, in particular) that pose higher risks of technical infeasibility and unacceptable ecological and social impacts.

1 Introduction

“Negative emission” mitigation options have increasingly appeared – sometimes transparently and sometimes only implicitly – in analyses and discussions of society’s options for addressing the challenge of climate change. Negative emissions refers to carbon dioxide removal (CDR) from the atmosphere.

Some negative emission technologies are still considered speculative – such as direct air capture [ref] and ocean-fertilization [ref] and are not considered in this report as they do not tend to figure strongly in current discussions of mitigation strategies. Here we focus on those negative emissions based on drawing carbon dioxide out of the atmosphere through photosynthesis and sequestering it in plants and other organic material in land-based sinks. These land-based negative emissions options are increasingly looked to as cost-effective and feasible components of a mitigation strategy. The key options being widely considered are large-scale afforestation and bioenergy in combination with carbon capture and storage (BECCS). Less commonly assessed is the potential for landscape restoration, both of closed canopy forests and mosaic-restoration of more intensively used landscapes, to contribute to climate mitigation.

This paper focuses on the risks associated with negative emission options, and what they mean for near-term actions and long-term mitigation strategies, including the 1.5°C and 2°C limits. We argue that the risks are of a different nature than those posed by conventional mitigation options, because they may lock us into much higher levels of warming than intended. Indeed, by doing so, they may undermine society’s mitigation efforts altogether.

Section 2 outlines the three types of risks posed by negative emission options and discusses the factors that contribute to those risks. Section 3 reviews the various land-based negative emissions options in light of those risk considerations. Section 4 discusses the implications of these findings for global 1.5°C and 2°C goals, for “zero carbon” vs “net zero carbon” formulations of global goals, and the choice of mitigation pathways generally.

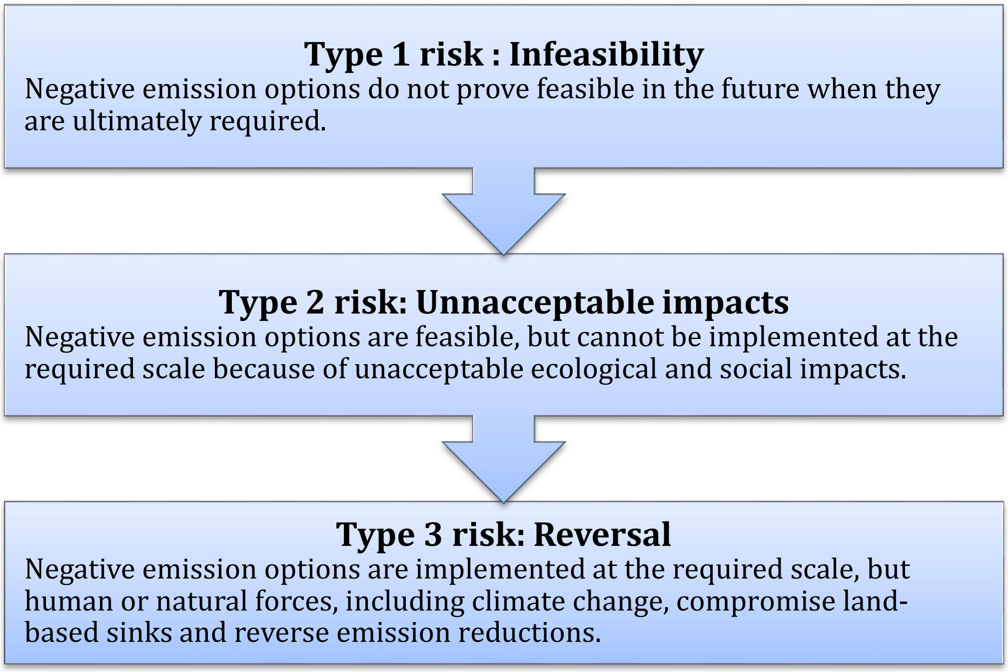
2 Risks of negative emission options

2.1 Three types of risks that affect current mitigation strategies

All mitigation options come with risks that they might be less effective than expected. Energy efficiency investments might lead to unanticipated rebound in consumption; solar panels might decline in power output quicker than their manufacturers predicted; wind resources might not be optimally usable because of the need to avoid interfering with bird migration corridors. Naturally, as global society endeavours to reduce emissions, it will need to assess how effective its ongoing mitigation efforts are and what adverse impacts they impose, and to continually adapt strategies accordingly.

Negative emission options pose a very different class of risks, however, from which there may be no way to recover if things go wrong. This is because they are assessed and discussed as options to be deployed later in the century to "undo" emissions that occurred earlier. This would, the logic goes, enable us to honor a given carbon budget – such as the extremely strict 1,000 GtCO$_2$ limit presented in the IPCC AR5 as a "likely" 2°C budget – in the long run, even after having grossly exceeded it in prior decades. In their comprehensive study of a large set of modelled techno-economic pathways Rogelj *et al* (2015), for example, highlight that 1.5°C and 2°C scenarios generally rely on precisely this strategy. (See Section 3.)

In the idealized world of techno-economic models with perfect-foresight and confident projections of costs and potentials, this strategy appears eminently sensible. It buys time and allows for a slower and more orderly transition to a low-carbon energy system. It avoids low-carbon energy options in favour of negative-carbon land options that are projected to be less costly. It takes the pressure off of hard-to-mitigate end-uses such as air travel. Tavoni and Socolow (2013), noting that negative emissions have increasingly been incorporated into modelled assessments of mitigation options, point out the ironic trend in recent years: "Thus, paradoxically, despite little progress in international climate policy and increasing emissions, long-term climate stabilization through the lens of IAM [Integrated Assessment Modelling] appears easier and less expensive." This concern has been reflected more recently in the literature (Anderson, 2015; Fuss et al., 2014; Geden, 2015)



Type 1 risk : Infeasibility
Negative emission options do not prove feasible in the future when they are ultimately required.

Type 2 risk: Unnacceptable impacts
Negative emission options are feasible, but cannot be implemented at the required scale because of unacceptable ecological and social impacts.

Type 3 risk: Reversal
Negative emission options are implemented at the required scale, but human or natural forces, including climate change, compromise land-based sinks and reverse emission reductions.

FIGURE 1. THREE TYPES OF RISKS POSED BY NEGATIVE EMISSION MEASURES.

In the real world, this "easier and less expensive" strategy poses fundamental risks due to the uncertainty that society will ultimately prove able to realize the negative emission options when they are needed. We highlight three sequential risks. First, the measures on which negative emission strategies tend to rely most heavily are as yet unproven. What happens if the necessary negative emission measures – such as large-scale centralized biomass-fuelled power plants coupled with carbon capture and sequestration – ultimately prove technologically infeasible, or cannot be deployed at the necessary scale because of fundamental biophysical constraints? (Type 1 risk in Figure 1.)

Second, even if the necessary negative emission options ultimately prove technically feasible, society may find the ecological and social costs to be unacceptably high. Negative emissions options, insofar as they rely on biological carbon fixation, are inherently land-intensive. Requiring large amounts of agriculturally productive land, there is presently no guarantee that it will be possible to deploy negative emission measures at a large-scale and avoid major adverse impacts on biodiversity, food security, water resources, and human rights. Perhaps it will be doable, providing several further conditions align favourably: agricultural yields continue inexorably to rise so as to limit the productive land that society will need to devote to food; water, fertilizer, and other necessary resources are available in sufficient quantities in the locations they are needed; ecological damage such as anoxic dead zones caused by fertilizer run-off are avoided; institutions are put in place to avoid food price shocks or land grabs that dispossess indigenous peoples and local communities. (Type 2 risk in Figure 1.)

And, third, even if negative emission options prove feasible, and can be undertaken at large scale without adverse ecological and social consequences, the risk remains that any climate mitigation benefits will be fleeting. Land-based carbon stocks are inherently insecure. A labile pool of carbon, they are vulnerable to release either through human action (e.g., land clearing) or natural forces outside of human control (drought, fire, pests, and other factors). Climate change itself compounds the risk that land-based carbon will be released, and evidence suggests that a weakening of the land-based sinks has already started in some regions, such as the Arctic (Rawlins et al., 2015). Ultimately, it is fallacious to assume that negative emissions that sequester carbon insecurely in the land can substitute for avoided fossil carbon emissions, which maintain carbon stocks in permanent secure underground fossil reserves. (Type 3 risk in Figure 1.)

In light of these risks, it is critical to assess carefully any strategy that relies on negative emissions, even if such strategies only rely on the use of negative emission options in the distant future (say, the latter half of the 21st century). Serious risks are associated with relying on the future large-scale deployment of negative emissions before we have high confidence that such options will be technically feasible, ecologically and socially acceptable, and reliably permanent. As expressed by Fuss et al. (Fuss et al., 2014), "Determining how safe it is to bet on negative emissions in the second half of this century to avoid dangerous climate change should be among our top priorities."

If society proceeds with confidence that large-scale deployment of negative emissions options will be available in the future, and consequently invests in less ambitious mitigation in the near-term, the costs could be high if that confidence proves unfounded. The decades during which society had allowed itself a slower, softer transition might ultimately be revealed as an unaffordable loss of time during which the only effective strategy would have been a more rapid decarbonisation. Saddled still with a fossil fuel-dependent energy infrastructure, society would confront a much more rapid and disruptive transition than the one it had sought to avoid. Having exceeded its available carbon budget, and unable to repay the carbon debt through negative emissions, society could ultimately be faced with much greater warming than it had prepared for.

2.2 Assessing land-based negative emission options

This section presents an overview of the factors that arise in assessing land-based negative emission options with regard to the three types of risk outlined in the preceding section. The section is organized along those same three themes: feasibility, social and ecological impacts, and risk of reversals. These categories are inter-related: biodiversity impacts could as much be seen as an ecological constraint as a component of biophysical limits, while demand for land associated here with food security is also the cause of ecological constraints. However, these categories allow us to organize a set of relevant global objectives, and to evaluate negative emissions options against these objectives.

Technological and biophysical feasibility

The main technological uncertainties apply to BECCS, which has not yet been proven at a commercial scale. The primary technology upon which large-scale negative emissions from BECCS would be based is industrial-scale thermochemical gasification of biomass to produce a gaseous fuel. This gaseous fuel is then used either power production or – at lower sequestration rates – for use as a synthesis gas for biofuel production, allowing for a stream of carbon dioxide to be extracted, compressed, and sequestered in a geological reservoir. The single BECCS pilot plant operating at scale is based on a different technology (using carbon dioxide released from an ethanol production process), which captures only 11-13% (Gough and Vaughan, 2015) of the carbon in the feedstock, and thus can be the basis of only very limited scale BECCS deployment. Challenges are posed by the logistics associated with the long-term, reliable supply of biomass feedstock to a large-scale industrial facility, integration of disparate technological systems, and the establishment of spatially appropriate CCS capture, pipeline, and storage infrastructure (Smith et al., 2014).

Land-based negative emission options are also limited by fundamental biophysical constraints. Sink saturation sets a limit on the total cumulative amount of carbon that can be removed from the atmosphere and stored in the biosphere, while net primary production (NPP) from plant growth sets a limit on the rate of removal of carbon from the atmosphere. The capacity of land carbon stocks to sequester carbon before reaching saturation is finite, and limited by the extent of depletion due to past land use. Based on an assessment of past land-use, (Mackey et al., 2013) estimate an upper theoretical limit to cumulative terrestrial sequestration of 187 GtC before ecosystem sinks would be saturated. The practical limit is lower, however, because current land uses including settlements and agriculture preclude restoring carbon stocks to their previous level. The practical limit will also ultimately be influenced by climate change.

Bioenergy with carbon capture and storage (BECCS) is not subject to limits of sink saturation, because the carbon is sequestered in geological reservoirs. However, BECCS is reliant on large-scale biomass feedstock supply, which is ultimately limited by net primary production, which is discussed further in Section 4, below.

Social and Ecological Impacts

Land-based negative emission options on a scale typically considered in long-term mitigation assessments require large areas of productive land, with estimates in the literature ranging from 100 to almost 3000 million hectares (Mha) (Humpenöder et al., 2014; Popp et al., 2014; Powell and Lenton, 2012; Smith et al., 2014). The upper end of this range is equivalent to twice the world's currently cultivated land, yet competition for productive land is already a global concern (Nilsson, 2012; Searchinger and Heimlich, 2015).

The scale of the land requirement alone suggests serious social and ecological risks, since land plays a crucial role in achieving multiple global sustainability objectives, in particular those related to food security, the rights and livelihoods of indigenous peoples and local communities, and biodiversity protection. The IPCC has concluded that large-scale increase in land use from mitigation activities may conflict with these objectives (Smith et al., 2014). The risks need to be well understood before society can be confident that the future large-scale deployment of negative emissions options will be possible (Smith and Torn, 2013).

Social Impacts

Dedicated use of land for negative emissions options, whether bioenergy, reforestation, or other land-based sinks can compromise food security by reducing the availability of land for food production (Smith et al., 2014). Food security goals have long been on the global development agenda, starting with the 1996 World Food Summit declaration to halve food in-security by 2015. The post-2015 development agenda recognizes the importance of food security, with Sustainable Development Goal 2 (SDG2) including a target to end hunger and achieve food security for all by 2030. Land availability is not the only component of food insecurity, yet how land is used and who is able to access land will play a critical role in achieving global food security objectives, as well as many of the other SDGs.

Natural ecosystems play an important role in subsistence production and livelihoods for local and smallholder farming communities and indigenous peoples. Indigenous peoples and local communities are estimated to hold up to 65% of the world's land area under customary or traditional ownership, although the area legally recognized by governments is a small fraction of this (Rights and Resources Initiative, 2015). The lack of clear rights to land is a major driver of illegal logging and forest loss, and enables large-scale land transfers and displacement that can exacerbate poverty, food insecurity and conflicts. Some land-based mitigation activities such as extensive monoculture plantations including bioenergy crops can undermine customary land-use, resulting in displacement and environmental degradation. Research has shown that community owned and managed forests, incorporating localized knowledge and decentralized decision making, result in high carbon storage and livelihood benefits (Chhatre and Agrawal, 2009). Securing local land rights is recognized as an urgent global priority (Rights and Resources Initiative, 2014), protecting livelihoods and food security as well as contributing to climate mitigation, but presenting a social constraint on some types of mitigation activities.

Ecological impacts

Any land-intensive undertaking can give rise to ecological impacts on biodiversity and resource use, including water and fertilizer needs. Biodiversity is now a critical global issue, with species extinction rates at 100 to 1000 times natural background rates. Rockström (2009) assess the rate of species extinction as an indicator that biodiversity loss is crossing planetary boundaries – which includes the role of biodiversity in regulating the resilience of earth systems. Global goals related to biodiversity include the Convention on Biological Diversity's Aichi Targets, to restore 15% of degraded ecosystems and halve the rate of natural habitat loss by 2020; and the SDG15 target to halt global deforestation by 2020 and substantially increase afforestation and reforestation. Other high-level political goals related to reforestation exist, such as the Bonn Challenge and the New York Declaration on Forests. (See Section 3.2). These could have positive impacts for biodiversity if mixed species regeneration and other methods are pursued that enhance biodiversity.

Land and water resources are already stressed and becoming more so (Alexandratos et al., 2012), largely due to the pressures of industrialized agriculture. Large-scale deployment of land-based mitigation measures would add to this stress, entailing significant consumption of the world's fertilizer supply, with consequences for waterways and ecosystems (Smith and Torn 2013). Human perturbation of the nitrogen and phosphorus cycles is causing significant environmental pollution, as well as contributing to greenhouse gas emissions. Due to the detrimental effect of nitrogen and phosphorus flows on lakes and coastal zones, including increasingly frequent and wide-spread large-scale ocean anoxic events that compromise marine ecosystems, Rockström et al (2009) estimate that current use of nitrogen would need to be reduced by 75% to keep within planetary boundaries.

Risk of Reversals

Carbon stored in the terrestrial biosphere is vulnerable to disturbance and therefore inherently non-permanent. An ecosystem can serve as a reservoir of carbon, but it must remain undisturbed over timescales relevant to climate change. Negative emissions options that rely on sequestering carbon in the terrestrial biosphere inherently entail a risk of reversal of those carbon stocks. Reversals of previously sequestered carbon stocks will negate the mitigation benefit to an extent that depends on the scale of the reversal and the ability of the carbon stock to recover (Smith et al., 2014). Meadowcraft (2013) suggest the need for mechanisms for remediation and compensation and associated liability regimes if stocks are reversed, although major large-scale reversals might strain any such provisions. Since stocks of carbon in natural fossil fuel deposits are stable on geological timescales and not vulnerable to unintended disturbance, avoiding emissions does not present the same risk of reversal as is posed by land-based negative emissions options.

Land carbon stocks can be lost through both human-induced and climatic factors (land clearing, as well as the sensitivity of terrestrial carbon stocks to drought, pests, fire and other factors). Climate change itself increases the risk of reversals, with projections consistently estimating a weakening of the land carbon sink (Smith et al., 2014). It is anticipated that as climate change progresses and temperatures rise, land will take up carbon at lower levels than historically, and possibly become a net source of carbon emissions (Stocker et al., 2013). Forests in particular are at risk of die-off due to increasing drought conditions, raising the distinct threat of a tipping point in which large swathes of the world's forests become a net source of carbon emissions by the end of this century (Choat et al., 2012). Restoring degraded forests and maintaining intact forest ecosystems also strengthens the resilience of forest ecosystems to external stressors, including climate change (Thompson et al., 2014).

3 Evaluating land-based negative emission options: potential and risks

3.1 Avoided emissions in the land sector

Just under a quarter of global emissions are from the land sector (largely agriculture and land-use change), with approximately 10% of these emissions from land use change: deforestation, forest degradation and drained peatland in tropical regions (Smith et al., 2014), representing a significant potential for permanent mitigation benefits through avoided emissions. We briefly discuss avoided emissions from deforestation and degradation, though they do not constitute a negative emissions option, because they are a significant source of emissions from the land sector; they are driven largely by demand for agricultural land (Hoare, 2015; Lawson, 2014); and because sequestration in regenerating forests is reliant on reversing forest loss.

Global carbon emissions from deforestation and forest degradation average 1.1 ± 0.5 GtC for the period 1990–2010 (Houghton, 2013), although emissions from forest degradation are poorly quantified globally, with estimates ranging from as much as 15% to 50% of emissions from deforestation alone (Asner et al., 2010). There are also significant losses from drained peatlands (organic soils), of 0.3 GtC/yr, an estimate that is likely to be conservative due to unmapped extent and depth of peat (Baccini et al., 2012; Houghton, 2013). This brings the total emissions from land use change, excluding agricultural soils, to 1.4 ± 0.5 GtC/yr (Baccini et al., 2012; (Houghton, 2013).

Hence, the potential for avoided emissions from the land sector lies in preventing forest loss – both deforestation and forest degradation, and in re-wetting degraded peatlands, preventing further emissions from organic soils, with the maximum potential for this equivalent to current emissions from land use change, at ≈1.4 GtC/yr (Houghton, 2013).

Global initiatives and efforts to reduce and halt forest loss have scaled up significantly in the past decade, with recognition of the contribution of deforestation and forest degradation to climate change providing renewed impetus and a large number of countries taking on international obligations relating to preventing forest loss. In 2008 the EU put forward a goal of at least halving tropical deforestation by 2020 and halting global forest loss by 2030 at the latest, which was reflected in the 2014 New York Declaration on Forests. More recently, the Sustainable Development Goals included a target to halt global deforestation by 2020. While ambitious, failure to achieve these goals makes the 1.5°C and 2°C targets much more challenging. Furthermore, slowing and halting forest loss brings significant benefits aside from carbon, including biodiversity protection, watershed protection, rural livelihoods and the rights of forest dependent peoples. It is increasingly well accepted that legal tenure rights for communities leads to reduced deforestation and lower CO_2 emissions when compared to forest areas with unclear tenure rights (Stevens et al., 2014).

3.2 Potential for enhanced sinks in the land sector

There are a variety of options for increasing the carbon sequestration of land-based sinks, with differing potential impacts on food security, biodiversity, local livelihoods and climate benefits. Here we consider the challenges and potential of forest ecosystem restoration and reforestation. We distinguish these two terms by way of current land-use – forest ecosystem restoration refers to the regeneration of degraded (logged) forests, while reforestation happens on land that was forested in the past, but is no longer forested.

Ecosystem restoration

The mitigation potential from the restoration of natural forest ecosystems is significant, and can potentially bring additional benefits such as biodiversity, watershed maintenance and improved livelihoods. Ecosystem restoration can be defined as accelerating the natural recovery of degraded forests. Degraded forests vary in the degree of fragmentation and the extent to which biodiversity has been lost, hence the potential for restoration will vary. Some areas can recover unaided if protected from further disturbance. This usually requires that the forest loss is recent (months to years), residual trees and soil seed stores remain, and biodiversity rich native forests are still present in the landscape (Lamb et al., 2005). Natural recovery of degraded forests is difficult where the ecosystem has lost further biodiversity and soils are depleted, making it difficult for plants to recolonize. Enhanced restoration, aimed at re-establishing the original forest ecosystem through cover trees or mixed seeding is possible, but highly resource intensive, and success often depends on the proximity of nearby native forests to aid recolonization (Lamb et al., 2005). The difficulty of successful ecosystem restoration highlights the irreversibility of the loss of biodiversity rich native forests.

Houghton (2013) suggests that ecosystem restoration, through the protection of regrowing forests, could remove as much as 1–3 GtC/yr from the atmosphere. However, sequestering such a large amount of carbon would require allowing secondary forests and the fallows of shifting cultivation to continue growing, with no further harvest or clearing. Halting forest harvest in secondary forests could have impacts on other land uses, potentially causing an expansion of commercial forest plantation areas and competing for arable land, with negative impacts on food security. In addition, sustainable forest harvest in itself can have climate mitigation benefits; for example, substitution of timber for materials associated with high greenhouse gas emissions, such as steel and cement, or ongoing storage of carbon in harvested wood products. Restricting swidden agriculture would have significant impacts on local and subsistence livelihoods, and would be inconsistent with customary access and ownership rights to land. The climate impacts of shifting cultivation can in fact often be climate neutral rather than emissive (Baccini et al., 2012). (Ziegler et al., 2012) suggest that under traditional land use practices, with lengthy fallow periods, existing swidden systems can produce substantial carbon benefits, offering alternatives that respect land and tenure rights. Hence, despite the apparent biodiversity and livelihood benefits of ecosystem restoration, there are still potential adverse effects, relating mostly to existing land uses, which restricts the ultimate sequestration potential of allowing forests to regrow.

For these reasons a cautious assumption about the negative emissions potential from ecosystem restoration might assume perhaps no more than half of the upper end of Houghton's range could be achieved. This in itself would be extremely challenging, being dependent on both reversing forest loss, and effective long-term, stable and permanent regeneration of degraded forests. Beyond the benefits of carbon sequestration and storage, regeneration of degraded forests also makes forest landscapes less susceptible to drought (Malhi et al., 2008), therefore decreasing the risk of reversal of forest carbon stocks, while also increasing biodiversity. If done in a way that strengthens customary rights and traditional land uses, forest regeneration can also greatly contribute to secure livelihoods.

Reforestation

Reforestation refers to the re-establishment of forests on lands that were forests at some time in the past.[1] This differs from ecosystem restoration in that it applies to land whose capacity for natural regeneration has been lost, due to there being a greater intensity and a greater elapsed time since forest clearance.

Houghton (2013) suggests that an area of 500 Mha would provide a global sink of approximately 1 GtC/yr assuming an annual accumulation of carbon in trees and soil of 2 MgC ha/yr. This is toward the upper end of the roughly 0.5 - 1.15 GtC/yr range reported in the IPCC (both IPCC AR4 and AR5 report the same data range, see: (Smith et al., 2014). While Houghton does not specify where such lands are and if they would be available for reforestation, his land requirement is

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[1] We use the term reforestation rather than afforestation, as afforestation can refer to converting areas to forests that were not forests in the past. Reforesting historically deforested lands makes more sense for local ecosystem impacts. We do not distinguish between the terms reforestation and afforestation as used in the land-use accounting context – where afforestation refers to establishing forests on land that was deforested before 1990.

consistent with the mapping of forest landscape restoration possibilities produced by the Global Partnership on Forests and Landscape Restoration[2] (Laestadius et al., 2011). This mapping considers two types of landscape restoration opportunity: "mosaic-type restoration", in more populated and higher land-use areas, and "broad-scale restoration", in areas where the land-use pressure is low and reforestation is possible. Across both of these categories, two billion hectares of land is estimated to be available for restoration in tropical and temperate areas,[3] three quarters of which is considered suitable only for mosaic restoration – multiple land use where forests and trees are combined with other land uses, such as agroforestry, smallholder agriculture, and settlements (discussed below). The remaining 500 Mha, consisting of degraded forests and deforested lands, is considered available for the broad-scale restoration of closed forests. This work informs the "Bonn Challenge", a high-level global goal to restore 150 Mha of degraded and deforested lands by 2020, with 59.2 Mha of land currently pledged toward this target.[4] The New York Declaration on Forests includes a target to restore an additional 200 Mha of forests by 2030.[5] Other estimates from the literature of the land required for 1GtC/yr sequestration range from around 300 to 750 Mha (Smith and Torn, 2013), bracketing the 500 Mha figure from Houghton (2013) and Laestadius et al., (2011).

Reforestation on this large a scale could have significant ecological and social impacts if pursued as commercial plantations or in inappropriate locations. The biodiversity potential varies enormously depending on methods of reforestation (Lamb et al., 2005), and commercial plantations can have negative impacts on biodiversity, water and other resources (Smith et al., 2014). For example, Smith and Torn (2013) estimate that achieving 1 GtC/yr carbon drawdown through fast-growing commercial plantation species would require significant inputs of nitrogen and phosphorus and alter local hydrology patterns. Reforestation of mixed species and in carefully chosen sites, on the other hand, could increase biodiversity and restore waterways, reducing run-off and erosion (Lamb et al., 2005). However, the climate effects of reforestation show significant geographical variation, with reduced albedo potentially outweighing carbon sequestration at high latitudes (Arora and Montenegro, 2011).

This points to scale and spatial location as key considerations for reforestation. In light of uncertainty around land availability (Gibbs and Salmon, 2015), it would seem prudent to make conservative assumptions about the total amount of land available for reforestation so as to limit competition for land, which could

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[2] http://www.forestlandscaperestoration.org

[3] These estimates are based on low accuracy (1km resolution) satellite mapping as well as reported data on land cover and land use and other factors (although land tenure was not considered due to lack of data, and land areas are estimates rather than confirmed sites) (Laestadius et al., 2011).

[4] http://www.forestlandscaperestoration.org/resource/iucn-press-release-world-track-meet-ambitious-forest-restoration-goal

[5] http://www.un.org/climatechange/summit/wp-content/uploads/sites/2/2014/07/New-York-Declaration-on-Forest-%E2%80%93-Action-Statement-and-Action-Plan.pdf

lead to land conversion and further carbon loss. The impacts of reforestation on biodiversity can be positive, but not when natural ecosystems, such as grasslands, are converted into secondary forests. In light of these considerations, achieving the existing targets in the Bonn Challenge and the New York Deceleration combined – to reforest 350 Mha by 2030 - would keep reforestation targets under the limit of potentially available land (as estimated by Houghton (2013) and Laestadius (2011)), allowing some buffer for uncertainty in land availability. These global targets for reforestation are not solely focused on carbon sequestration, recognizing the potential for broader social and ecological benefits when reforestation is done in the right manner, emphasising localized decision-making. The benefits of community managed and owned forests are increasingly well documented. Reforestation programs which place communities at the centre of efforts can help to secure livelihoods, conserve biodiversity and reduce conflict, in addition carbon sequestration (Stevens et al., 2014).

Sink saturation is another important consideration for estimating carbon benefits from reforestation – as forest biomes reach a steady state, the net carbon uptake rate declines, peaking at around 50 years, with little additional sequestration (plateauing) after 70 years (Nilsson and Schopfhauser, 1995). Hence there is a one-off benefit from reforestation. As the forest biome matures and reaches steady state, it becomes a carbon stock to be protected to prevent the sequestered carbon from being re-emitted to the atmosphere. Harvested wood products continue to store carbon in addition to sink sequestration limits, but are limited in scale as by harvest rates of commercial forest plantations and competing uses for forest products.

Mosaic landscape restoration and soil carbon

The opportunity for mosaic-type restoration within the concept of landscape restoration accommodates a multiplicity of land uses such as agriculture, protected reserves, managed plantations and agroforestry systems. From the standpoint of assessing the risks and potential of negative emissions options, the carbon benefits of activities such as agroforestry, biochar and soil carbon improvement are still being explored. At present, however, due to the lack of data, measurement uncertainty, and problems of non-permanence, particularly in the case of soil carbon (Lal, 2004; Meadowcroft, 2013), it would not be prudent to assume the future availability of large amounts of negative emissions benefits from these options. As scientists and practitioners obtain further information about the scale of the potential carbon sink, the nature of risks and measures for alleviating them, and permanence of sequestered carbon, some landscape restorations measures may come to be seen as a reliable climate mitigation option. In the meantime, many landscape restoration measures should be pursued on account of their multiple other benefits, and indeed the adaptation, health and livelihood benefits of improved agricultural practices such as agroforestry should remain key drivers for their implementation.

3.3 Bioenergy with CCS

This section reviews the potential for negative emissions from bioenergy combined with carbon capture and storage (BECCS). As outlined in section 3.1, BECCS is constrained in the first order by the uncertainty of the technology. The purpose of this section is to examine the second limiting factor to BECCS – the availability of bioenergy supply - and the potential social and ecological impacts, to examine the risks associated with current assumptions of future bioenergy use in mitigation pathways.

Bioenergy supply

A key consideration in determining bioenergy potential is the maximum biospheric capacity of net primary production (NPP) of plant growth, which is estimated to be around 30 GtC/yr, with an energy value of ≈ 1,100 EJ/yr (Haberl et al., 2013). Humans currently harvest approximately 230 EJ/yr for food, feed, fiber and energy, with the remainder locked up in natural and protected areas, cultivated areas, or destroyed (Haberl et al., 2013). Based on the remaining NPP in land ecosystems, an upper biophysical limit in primary bioenergy supply has been estimated at approximately 190 EJ/year (Kolby Smith et al., 2012; Haberl et al., 2013). The bioenergy potential from available residues (agricultural and forest harvest residues, municipal waste and biogas from animal manures) adds approximately 60 EJ/yr (Kolby Smith et al., 2012; Smith et al., 2014), putting the upper biophysical limit for bioenergy potential at ≈250 EJ/yr (Haberl et al., 2013). Note, this estimated biophysical limit of ≈250 EJ/yr is not an estimate of what could be considered *sustainable* primary bioenergy potential. Rather, it provides an upper limit based on current understanding constraints posed by ecological systems on potential agricultural output.

Reaching this 250 EJ/yr upper biophysical limit of bioenergy output would require a doubling of current human biomass harvest (all crops, feedstock, and other materials), which suggests the potential for serious social, economic and ecological constraints on the maximum feasible bioenergy feedstock (Haberl et al., 2013; Searchinger and Heimlich 2015). Nevertheless, while some estimates of bioenergy potential in the mitigation scenario literature are well within this upper limit (Erb et al., 2012; Kraxner et al., 2013), many estimates are close to or exceed it (GEA, 2012; Humpenöder et al., 2014; Kriegler et al., 2013), with some prominent studies estimating as much as double this amount (IPCC, 2000; Smeets et al., 2007), and the overall range of projections reaching as high as 1000 EJ/yr (Smith et al., 2014). Creutzig et al. (2015) note that beyond 100EJ/year there is decreasing agreement on the sustainable technical potential of bioenergy.

These estimates for bioenergy are typically based on two types of sources – biomass grown on dedicated crop land (such as energy crops including woody biomass), and bioenergy sourced from residues and wastes. Bioenergy from wastes and residues includes the utilization of many different products, such as forest and agricultural residues and organic wastes. Current production of bioenergy, mostly from residues and traditional biomass uses, is around 55 EJ/yr, which is 12% as much as current energy production from fossil fuels (Erb et al., 2012; Haberl et al., 2013; Smith et al., 2014), and its availability is limited by competing uses. For example, agricultural residues are key to retaining soil carbon in many areas, and forest residues left in place improve biodiversity, soil health and carbon storage. Thus, even the 60 EJ/yr contribution to bioenergy feedstocks sourced from waste and residues comes with trade-offs. In terms of assessing its potential as a negative emission option, bioenergy from wastes and residues is not likely to be suitable for BECCS due to logistical constraints associated with dispersed feedstocks (Smith et al., 2014)

Key uncertainties in total bioenergy potential therefore lies in the availability of land for dedicated energy crops, the potential for yield increase, and trade-offs with other land uses such as food production and biodiversity (Haberl et al., 2010). Climate change itself also introduces further uncertainty into bioenergy potential (Smith et al., 2014), with Wiltshire and Davies-Barnard (2015) noting that "response of bio-energy crops to climate and CO_2 fertilisation is a leading order uncertainty in the feasibility of BECCS".

Land availability problems often do not arise in models because of the assumed continued growth in crop yields, delivering greater bioenergy productivity or freeing up agricultural land for energy crops. However, the growth of crop yields has slowed down considerably in recent years (Alexandratos et al., 2012). Dramatic yield increases in the past were mainly due to shifting biomass from the stem to the grain portion of the plant – which does not improve bioenergy production where the whole plant is used (Kemp-Benedict et al., 2012). Potential for yield increase has commonly been over-estimated in assessments of future bioenergy potential due to extrapolation of plot-based samples (Kolby Smith et al., 2012). It is also possible that any yield increase would be needed to help meet growing demand for food (Alexandratos et al., 2012).

Land availability at the global aggregate level is highly uncertain, with large disagreements in both the scale and spatial location of degraded lands in the literature (Gibbs and Salmon, 2015). Overestimating land availability, particularly of degraded lands, risks diverting attention from demand side measures, such as diet change or reduced demand for land-based commodities (Nilsson, 2012). Although in recent decades diets have shifted toward more land-intensive meat-rich diets as incomes have risen, diets could shift in the future in a manner that frees up agricultural land. For a discussion of these issues see Box 1. While it could happen that a combination of yield improvements and diet changes could make more land available for bioenergy feedstock production, it would not be prudent to assume this will happen given the high level of uncertainty.

Bioenergy production from forest harvesting has been shown to lead to increased emissions (Holtsmark, 2015), as could bioenergy at a scale that leads to conversion of wilderness areas (Haberl et al., 2013; Kolby Smith et al., 2012). Bioenergy at a large scale would also compete for key resources such as fertilizer and increased irrigation, which could result in increased GHG emissions, watershed stress, and environmental degradation (Erb et al., 2014; Smith and Torn, 2013; Wiltshire and Davies-Barnard, 2015). Modelling by Wiltshire and Davies-Barnard (2015) has found that land use emissions embedded in BECCS scenarios can be large and reduce the overall mitigation potential of BECCS, with land-use emissions exceeding the potential carbon sequestration from BECCS in worst-case scenarios.

Bioenergy has already been identified as an emergent global risk to food security and ecosystems due to indirect land use change (Oppenheimer et al., 2014). Evidence suggests that even comparatively low levels of bioenergy production (currently at around 5 EJ/yr from dedicated land use), has contributed to raising food prices (Hochman et al., 2014). Deploying bioenergy on any scale, well below the estimates in many climate models, would require effective global governance networks to manage trade-offs and develop integrated land-use policies (Nilsson, 2012; WGBU, 2008).

While some maintain that land availability will not be a constraint to bioenergy expansion (Osseweijer et al., 2015), others advise a 'food first' approach, assuming we may already be facing a deficit of cultivable land (Searchinger and Heimlich, 2015) and implying zero availability of land for bioenergy feedstocks. In the face of uncertainty of land availability and the possible negative impacts of large-scale expansion of bioenergy production on food security and the environment, it is prudent to take a cautious approach. The effective use of wastes and residues should be prioritized (which would enable bioenergy at fairly limited scales, and likely with no CCS) (Miyake et al., 2012). However, confidence that bioenergy will be deployed at significant scale as a negative emissions measure relies heavily on future technology development and a means for scaling up bioenergy feedstock production without posing unacceptable ecological and social costs. Unless bioenergy with CCS is proven feasible at commercial scale, along with bioenergy feedstocks that are limited to sustainable levels and produced in socially and ecologically acceptable ways, it would be risky to base current mitigation strategies on the presumed future availability of biomass energy with CCS.

Box 1

Impact of healthier diets on land use. *Contributed by Doug Boucher, Union of Concerned Scientists**

Estimates of future land requirements for food are highly uncertain. In addition to uncertainty in future crop yields, there is great uncertainty in how diets will change, especially with respect to consumption of meat, a particularly land-intensive food product. An important recent study by Bajzelj et al. (2014) highlighted the benefits with respect to emissions and land use of shifting towards healthier diets. They found that in 2050, the implications of a healthier diet (reduced sugars and saturated fats, including livestock products, while providing a minimum of 2500 kcals per person as well as sufficient protein), could reduce net GHG emissions by 45% (about 6 Gt CO_2eq/year) as well as reducing the land needed for pasture by 25% and for cropping by 5%. Nearly all the reductions in emissions came from the livestock sector: from the combination of lower emissions of methane from ruminants; and increased sequestration from the return of un-needed pasture and cropland to natural vegetation.

The importance of the livestock sector is not surprising, as currently, 80% of the world's 3.9 billion hectares of agricultural and pasture lands are used for livestock, mostly in low-productivity grazing systems which account for less than 1% of the edible energy that humans can eat (Herrero et al., 2015). This land is mostly used for beef cattle production, which produces high methane and nitrous oxide emissions (Persson et al., 2014) as well as nitrogen and phosphorus pollution (Bouwman et al., 2013). These impacts suggest that significant environmental benefits would derive from shifts in diets away from beef and towards other kinds of foods, particularly in developed countries, where consumption is already above levels associated with health impacts such as heart disease, cancer and diabetes (Boucher et al., 2013; Pan et al., 2012). This would not require a large-scale shift to vegetarianism, because the climate and other environmental impacts of alternative animal-based foods are much lower than for beef (FAO, 2015). For example, Stehfest et al. (2009) estimated that eliminating only food from ruminants (mostly cattle) from the global diet would reduce emissions in 2050 by 5.8 Gt CO_2eq/year, vs. 7.8 Gt CO_2eq/year if foods from all animal sources were eliminated. The differences in efficiency and productivity of edible food thus make it possible for diet shifts to actually increase food security while substantially reducing land use (Herrero et al., 2015).

Land “freed up” by such shifts could be used in a variety of ways, with different kinds of climate and social benefits. It is important that plans for such potential changes respect traditional land tenure patterns, and take into account other values of cattle such as dairy production, traction, transport, their role as a store of wealth and their potential value in maintaining grassland biodiversity.

* UCS does not necessarily endorse the full report

Risk type	**Type 1** **Infeasibility**		**Type 2** **Unacceptable social and ecological costs**		**Type 3** **Non-permanence of carbon stock**
Risk factors	**Technological development**	**Biophysical limits**	**Social**	**Ecological**	**sink degradation**
	Biomass gasification CCS Geological storage Yield increases	NPP Sink saturation	Food security Customary land rights	Biodiversity Resource input requirements	Climatic disturbance Human disturbance
Avoided deforestation /degradation	n/a	n/a	Secure land rights results in greater forest protection	Immediate and permanent emission reductions Enhanced biodiversity from decreasing forest loss	Avoiding emissions from forest loss represent permanent emission reductions
Forest ecosystem restoration	n/a	Sequestration is a one-off opportunity to replenish lost terrestrial carbon stocks	Community owned and managed forestry creates food security, livelihood benefits and greater carbon stocks	Increased biodiversity	Restoration improves ecosystem resilience, decreasing risk of reversal
Reforestation	n/a	As above	Risks to food security if scale of land demand impacts food production Community owned and managed forests yield higher carbon benefits	Biodiversity can be protected or threatened, depending on the manner of reforestation. Commercial plantations require high nitrogen and water inputs	Not permanent
Mosaic Landscape restoration	n/a	As above	Benefits to food security, rural livelihoods and customary land rights	Biodiversity improved compared to degraded landscapes Efficiency of resource use improved	Enhanced resilience

Bioenergy from dedicated land-use	CCS technology not developed Continuing yield increases often assumed Geological storage limited, geographically constrained	Estimated bioenergy potentials are generally at or above maximum biospheric capacity for production (NPP)	Risks to food security if food crops diverted to energy Risk to customary land rights and local livelihoods if energy crops present a high-value alternative use of land	Risks to biodiversity if natural ecosystems converted to energy crops Risk of exacerbating already significant overconsumption of nitrogen and water	Permanent

4 Implications for the formulation of long-term global goals

Based on the outline of risks presented in Section 2 above, the review of negative emissions options and potentials presented in Section 3, we discuss here the implications for long-term global goals.

4.1 Feasibility of "1.5°C and 2°C targets, given negative emission constraints.

As a convenient reference point for the state of scientific knowledge and Integrated Assessment Model results on temperature targets and global mitigation pathways, and the corresponding analysis on the role of negative emission mitigation measures, we draw upon the recent analysis by Rogelj *et al* (2015). The authors provide in this paper results from some 200 modelled "low stabilization scenarios." Because this set of scenarios includes many with emissions below the lower bound of emissions in the IPCC scenario database, Rogelj et al. are able to draw conclusions about 1.5°C pathways, which the IPCC could not do. They present results for a set of "1.5°C scenarios", in which temperature has a greater than 50% chance of returning below 1.5 °C by 2100. They note that these scenarios are "temperature overshoot" scenarios, as they typically have a poorer than 50% chance of staying below 1.5°C during the 21st century, and explain that "no scenarios that have a high probability of limiting warming to below the 1.5°C limit during the entire twenty-first century exist in the literature." Rogelj *et al.* also present results for a set of "likely 2°C" scenarios", which have a greater than 66% chance of keeping warming in the twenty-first century below 2 °C, and are typically not temperature overshoot scenarios.

Drawing upon these modelled scenarios, Rogelj *et al.* draw conclusions about the required cumulative global negative emissions over the remainder of the 21st century. For the 1.5°C scenarios, they find that between 450 and 1000 $GtCO_2$ is required, and for the 2°C scenarios between 0 and 900 $GtCO_2$ is required. In these scenarios, negative emissions are adopted widely in the 2nd half of the century so as to reverse a large fraction of fossil emissions (up to 60% in the 2°C scenarios, and as much as 100% in the 1.5°C scenarios). Tavoni and Socolow (2013), polling five models, find a range of roughly 500 to 1600 $GtCO_2$. Fuss et al. (2014) note that the upper end of the range of required negative emissions is comparable in magnitude to the natural ocean sink and the natural terrestrial sink, and raise uncertainties relating to the effect on carbon cycle dynamics.

The upper end of the stated range of negative emissions must be called out as extremely high, given biophysical limits and the risks of social and economic impacts. As discussed in detail in Section 3, negative emissions in the order of 1000 $GtCO_2$ may be simply unachievable owing to biophysical constraints.

Toward the lower end of the stated range, however, a significantly lower level of negative emissions is shown to still be adequate to meet the needs of a large number of the modelled 1.5°C and 2°C pathways. Specifically, Rogelj *et al.* show that a total of 480 $GtCO_2$, would be sufficient to meet the negative emission needs of more than one-third of the modelled 1.5°C scenarios and more than one-half of the modelled 2°C scenarios in their study. Insofar as these models generate least-cost pathways (according to their own techno-economic assumptions) for a specified target, they would in principle generate pathways that relied on less negative emissions and more renewables and efficiency if the negative emission options were further constrained by socio-ecological limits. The study also makes clear (see fig. 4 in Rogelj *et al*), that many of the modelled scenarios in the nominal "1.5°C" set actually reduce median warming in 2100 to even lower temperatures, as low as 1.25°C. These, presumably, tend to require negative emissions toward the upper end of the stated ranges.

Table 2 outlines a case that could in principle meet the lower-end requirement of 480 $GtCO_2$ based solely on options that have a decent probability of being technically feasible, in that they rely on known, available measures. It is important to stress that, although these may not be greatly susceptible to risks of type 1 (as in Fig. 1), they still pose risks – and potentially substantial risks – of type 2 and 3.

This case allows one to conclude, tentatively at least, that "1.5°C" pathways could be achieved relying only on negative emissions options for which there is less Type 1 risk that they will ultimately fail to materialize. That said, there remains the Type 2 risk of adverse ecological and social impacts, and Type 3 risk of non-permanence. Further, these pathways still require a rapid and dramatic transformation of the economy to shift away from fossil sources, and they do not allow for any delay.

Negative emission category		**Cumulative sequestration (21st c.)**
Avoided deforestation /degradation	Forest loss halted by 2020, in line with New York Declaration on Forests target	Avoided emissions
Reforestation	This case assumes optimistic levels of reforestation consistent with meeting the Bonn Challenge to reforest 150 Mha by 2020 and expanding efforts to meet the New York Declaration on Forests goal to reforest an additional 200 MHa by 2030. Assuming a per hectare sequestration rate consistent with Houghton (2013) yields an average negative emission rate of 0.7 GtC/yr, which accords well with the middle of the IPCC range. Over a period of 60 years until saturation, this would yield a cumulative total negative emission of approximately 40 GtC (≈ 150 $GtCO_2$).	150 $GtCO_2$
Ecosystem Restoration	Extensive ecosystem restoration, sufficient to enhance the natural sinks at an average rate of 1.5 GtC/yr for 60 years until saturation, would yield a cumulative total of 90 GtC (≈ 330 $GtCO_2$)	330 $GtCO_2$
Mosaic landscape restoration	While landscape restoration (agroforestry, soil carbon, biochar, etc) includes promising measures with multiple benefits, this case does not take account for any quantified negative emission contribution from these activities. While it may prove eventually, as information improves and experience is gained, that there are emission benefits, the uncertainty (especially with soil carbon) is presently too great to justify reliance on any such benefit.	Not quantified
Bioenergy with CCS	Negative emissions from BECCS is also excluded from this case, on the basis that the technology is not yet proven, and that it would be able contribute at a significant scale only if other challenging conditions are also met, which would primarily involve decreased consumption in the agricultural sector, leaving land and other resource inputs available for primary bio-energy production, and / or a technological breakthrough in bioenergy production not dependent on land.	0 $GtCO_2$

With respect to “2°C” pathways, the Rogelj *et al* scenarios include several that do not rely on negative emissions at all, and also note that “2°C scenarios with a significantly lower or even zero contribution of negative emissions are available in the literature”.

This set of options for achieving 480 $GtCO_2$ negative emissions does not exceed basic biophysical constraints, but it would still be challenging to achieve, and would impose a demand for land that could jeopardize other critical land uses such as food production, habitat, and biodiversity, and thus present serious risks. It is conceivable – though by no means guaranteed – that measures such as ecosystem restoration and reforestation could be implemented in a manner that achieves the required amount of negative emissions without jeopardizing other critical land uses.

Especially with respect to long-term strategies that rely on much larger amounts of negative emissions, we wish to highlight a caution. Any nominal “1.5°C” or “2°C” pathway that relies on large amounts of negative emissions will have locked us into much higher temperature rise than advertised if these negative emission options do not ultimately prove feasible when they are called upon in the second half of the 21st century. In this regard, is highly questionable to label a “1.5°C” or “2°C” pathway as “likely” if it relies on negative emission options that themselves do not have a “likely” chance of proving feasible and providing reliably permanent reductions at the needed scale.

4.2 “Zero fossil carbon” versus “net zero” formulations of a global goal

Long-term global goals are squarely on the international climate agenda, and are a specific focus of negotiations toward the Paris Conference of Parties to the UNFCCC. Many countries are advocating for a goal of “net zero” global emissions to be formally adopted and included in the post-2020 agreement. Meanwhile, many civil society organizations are advocating for a goal that would more narrowly focus on full decarbonisation – or “zero fossil carbon” – from the energy system[6].

The “zero fossil carbon” formulation does not explicitly set a limit for any carbon dioxide emissions that are not from fossil fuel sources. That is, it does not set a limit for land-related sources (such as deforestation and landscape degradation), nor for non-carbon dioxide sources such as the other “Kyoto-gases” – methane, nitrous oxide, and the industrial “F-gases”. As such, it accounts for somewhat less than two-thirds of current global greenhouse gas emissions (IPCC, WG3]. The net-zero formulation, on the other hand, implies that all emissions (if formulated as “net-zero *greenhouse gas* emissions” or “climate neutrality”) or at least all carbon dioxide emissions (if formulated as “net-zero *carbon* emissions” or “carbon neutrality”) reach zero in aggregate. Critically, however, the “net-zero” position, though covering a broader range of gases, allows for the continued emissions of fossil carbon dioxide to the extent they are balanced by negative emissions.

However, as we’ve argued in this paper, a strategy based on future negative emissions leaves society at risk of insufficient decarbonisation while anticipating negative emissions options that may not materialize. A global goal based on “zero fossil carbon” does not pose that risk. It sends an unambiguous signal regarding the rate at which carbon emissions must be ceased, with no illusory

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[6] See Climate Action Network’s position here: http://climatenetwork.org/publication/can-position-long-term-global-goals-2050-june-2014

promise of future absolution based on negative emissions from still unproven land-based options.

Certainly, a “zero fossil carbon” target could be part of an even more robust global goal. It could be coupled with distinct goals for protecting and restoring ecosystems through measures focused on halting and reversing forest loss, and the restoration of forest ecosystems. In addition to contributing towards climate mitigation goals, such options contribute to a multitude of sustainability objectives, including preserving critical ecosystem services such as biodiversity and watershed protection, and development goals of protecting food security, human rights, and local livelihoods. Achieving these dual outcomes of climate mitigation and environmental and development goals requires approaches which promote localised decision–making over natural resources, such as community forest management, as key elements of enhancing and maintaining biospheric carbon stocks.

5 Summary

We defined three layers of risk associated with strategies that rely on future negative emissions. Type 1 is the risk that negative emission options do not prove feasible in the future when they are ultimately required. Type 2 is the risk that unacceptable ecological and social impacts are unavoidable for large-scale deployment. Type 3 is the risk that the reversal of emission reductions is caused by human or natural forces, including climate change. It is poor strategy to rely on the future large-scale deployment of negative emissions without reasonable confidence that there will be negative emissions available at the required scale from options that are technically feasible, ecologically and socially acceptable, and reliably permanent. Such a strategy could strand us at a late date with an insufficiently transformed energy economy, an exceeded carbon budget, and a carbon debt that cannot be repaid.

Drawing on results of modelled pathways from Integrated Assessment Models, we conclude, tentatively at least, that “1.5°C” pathways can be achieved relying only on negative emissions options for which there is comparatively little Type 1 risk. Type 2 and Type 3 risks remain, however. Importantly, these pathways still require a rapid and dramatic transformation of the economy to shift away from fossil sources, and they do not allow for any delay.

A “net-zero” goal could motivate an excessively risky reliance on future negative emissions options. On the other hand, a “zero fossil carbon” goal could provide an unambiguous impetus for a transformation of the energy economy. Coupling it with distinct goals related to protecting and restoring ecosystems could make for a comprehensive global goal.

References

Alexandratos, N., Bruinsma, J., others, 2012. World agriculture towards 2030/2050: the 2012 revision (ESA Working Paper No. 12-03). FAO.

Anderson, K., 2015. Duality in climate science. Nat. Geosci.

Arora, V.K., Montenegro, A., 2011. Small temperature benefits provided by realistic afforestation efforts. Nat. Geosci. 4, 514–518. doi:10.1038/ngeo1182

Asner, G.P., Powell, G.V.N., Mascaro, J., Knapp, D.E., Clark, J.K., Jacobson, J., Kennedy-Bowdoin, T., Balaji, A., Paez-Acosta, G., Victoria, E., Secada, L., Valqui, M., Hughes, R.F., 2010. High-resolution forest carbon stocks and emissions in the Amazon. Proc. Natl. Acad. Sci. 107, 16738–16742. doi:10.1073/pnas.1004875107

Bajželj, B., Richards, K.S., Allwood, J.M., Smith, P., Dennis, J.S., Curmi, E., Gilligan, C.A., 2014. Importance of food-demand management for climate mitigation. Nat. Clim. Change 4, 924–929. doi:10.1038/nclimate2353

Boucher, D., Elias, P., Mulik, K., Davis, E., 2013. Climate-Friendly Land Use: Paths and policies toward a less wasteful planet. Union of Concerned Scientists.

Bouwman, L., Goldewijk, K.K., Hoek, K.W.V.D., Beusen, A.H.W., Vuuren, D.P.V., Willems, J., Rufino, M.C., Stehfest, E., 2013. Exploring global changes in nitrogen and phosphorus cycles in agriculture induced by livestock production over the 1900–2050 period. Proc. Natl. Acad. Sci. 110, 20882–20887. doi:10.1073/pnas.1012878108

Chhatre, A., Agrawal, A., 2009. Trade-offs and synergies between carbon storage and livelihood benefits from forest commons. Proc. Natl. Acad. Sci. 106, 17667–17670.

Choat, B., Jansen, S., Brodribb, T.J., Cochard, H., Delzon, S., Bhaskar, R., Bucci, S.J., Feild, T.S., Gleason, S.M., Hacke, U.G., Jacobsen, A.L., Lens, F., Maherali, H., Martínez-Vilalta, J., Mayr, S., Mencuccini, M., Mitchell, P.J., Nardini, A., Pittermann, J., Pratt, R.B., Sperry, J.S., Westoby, M., Wright, I.J., Zanne, A.E., 2012. Global convergence in the vulnerability of forests to drought. Nature. doi:10.1038/nature11688

Creutzig, F., Ravindranath, N.H., Berndes, G., Bolwig, S., Bright, R., Cherubini, F., Chum, H., Corbera, E., Delucchi, M., Faaij, A., Fargione, J., Haberl, H., Heath, G., Lucon, O., Plevin, R., Popp, A., Robledo-Abad, C., Rose, S., Smith, P., Stromman, A., Suh, S., Masera, O., 2015. Bioenergy and climate change mitigation: an assessment. GCB Bioenergy 7, 916–944. doi:10.1111/gcbb.12205

Erb, K.-H., Haberl, H., Plutzar, C., 2012. Dependency of global primary bioenergy crop potentials in 2050 on food systems, yields, biodiversity conservation and political stability. Energy Policy 47, 260–269. doi:10.1016/j.enpol.2012.04.066

FAO, 2015. Natural Capital Impacts in Agriculture: Supporting Better Business Decision-Making. Food and Agricultural Organization of the United Nations, Rome.

Fuss, S., Canadell, J.G., Peters, G.P., Tavoni, M., Andrew, R.M., Ciais, P., Jackson, R.B., Jones, C.D., Kraxner, F., Nakicenovic, N., others, 2014. Betting on negative emissions. Nat. Clim. Change 4, 850–853.

GEA, 2012. Global Energy Assessment - Toward a Sustainable Future. Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria.

Geden, O., 2015. Policy: Climate advisers must maintain integrity. Nature 521, 27.

Gibbs, H.K., Salmon, J.M., 2015. Mapping the world's degraded lands. Appl. Geogr. 57, 12–21. doi:10.1016/j.apgeog.2014.11.024

Gough, C., Vaughan, N.E., 2015. Synthesising existing knowledge on the feasibility of BECCS (D1a) | AVOID 2 climate change research programme (No. WPD1a), AVOID2.

Haberl, H., Erb, K.-H., Krausmann, F., Running, S., Searchinger, T.D., Kolby Smith, W., 2013. Bioenergy: how much can we expect for 2050? Environ. Res. Lett. 8, 031004. doi:10.1088/1748-9326/8/3/031004

Herrero, M., Wirsenius, S., Henderson, B., Rigolot, C., Thornton, P., Havlík, P., Boer, I. de, Gerber, P.J., 2015. Livestock and the Environment: What Have We Learned in the Past Decade? Annu. Rev. Environ. Resour. 40, 177–202. doi:10.1146/annurev-environ-031113-093503

Hoare, A., 2015. 20150715IllegalLoggingHoare.pdf. Chatham House, London.

Hochman, G., Rajagopal, D., Timilsina, G.R., Zilberman, D., 2014. Impacts of Biofuels on Food Prices, in: Timilsina, G.R., Zilberman, D. (Eds.), The Impacts of Biofuels on the Economy, Environment, and Poverty, Natural Resource Management and Policy. Springer New York, pp. 47–64.

Holtsmark, B., 2015. Quantifying the global warming potential of CO $_2$ emissions from wood fuels. GCB Bioenergy 7, 195–206. doi:10.1111/gcbb.12110

Houghton, R.A., 2013. The emissions of carbon from deforestation and degradation in the tropics: past trends and future potential. Carbon Manag. 4, 539–546. doi:10.4155/cmt.13.41

Humpenöder, F., Popp, A., Dietrich, J.P., Klein, D., Lotze-Campen, H., Bonsch, M., Bodirsky, B.L., Weindl, I., Stevanovic, M., Müller, C., 2014. Investigating afforestation and bioenergy CCS as climate change mitigation strategies. Environ. Res. Lett. 9, 064029. doi:10.1088/1748-9326/9/6/064029

IPCC, 2000. Special report on emissions scenarios: a special report of working group III of the intergovernmental panel on climate change. Cambridge University Press.

Kemp-Benedict, E., Kartha, S., Fencl, A., 2012. Biomass in a Low-Carbon Economy: Resource Scarcity, Climate Change, and Business in a Finite World.

Kolby Smith, W., Zaho, M., Running, S., 2012. Global Bioenergy Capacity as Constrained by Observed Biospheric Productivity Rates. BioScience 62, 911–922. doi:10.1525/bio.2012.62.10.11

Kraxner, F., Nordström, E.-M., Havlík, P., Gusti, M., Mosnier, A., Frank, S., Valin, H., Fritz, S., Fuss, S., Kindermann, G., McCallum, I., Khabarov, N., Böttcher, H., See, L., Aoki, K., Schmid, E., Máthé, L., Obersteiner, M., 2013. Global bioenergy scenarios – Future forest development, land-use implications, and trade-offs. Biomass Bioenergy 57, 86–96. doi:10.1016/j.biombioe.2013.02.003

Kriegler, E., Edenhofer, O., Reuster, L., Luderer, G., Klein, D., 2013. Is atmospheric carbon dioxide removal a game changer for climate change mitigation? Clim. Change 118, 45–57. doi:10.1007/s10584-012-0681-4

Laestadius, L, Maginnis, S, Minnemeyer, S, Potapov, P, Saint-Laurent, C, Sizer, N, 2011. Mapping opportunities for forest landscape restoration. Unasylva 238 62, 47–48.

Lal, R., 2004. Soil carbon sequestration to mitigate climate change. Geoderma 123, 1–22. doi:10.1016/j.geoderma.2004.01.032

Lamb, D., Erskine, P.D., Parrotta, J.A., 2005. Restoration of degraded tropical forest landscapes. Science 310, 1628–1632.

Lawson, S., 2014. Consumer Goods and Deforestation: An Analysis of the Extent and Nature of Illegality in Forest Conversion for Agriculture and Timber Plantations, Forest Trade and Finance. Forest Trends, Washington DC.

Mackey, B., Prentice, I.C., Steffen, W., House, J.I., Lindenmayer, D., Keith, H., Berry, S., 2013. Untangling the confusion around land carbon science and climate change mitigation policy. Nat. Clim. Change 3, 552–557. doi:10.1038/nclimate1804

Meadowcroft, J., 2013. Exploring negative territory Carbon dioxide removal and climate policy initiatives. Clim. Change 118, 137–149. doi:10.1007/s10584-012-0684-1

Miyake, S., Renouf, M., Peterson, A., McAlpine, C., Smith, C., 2012. Land-use and environmental pressures resulting from current and future bioenergy crop expansion: A review. J. Rural Stud. 28, 650–658. doi:10.1016/j.jrurstud.2012.09.002

Nilsson, S., 2012. Availability of cultivable land to meet expected demand in food, fibre and fuel, in: The Global Need for Food, Fibre and Fuel: Land Use Perspectives on Constraints and Opportunities in Meeting Future Demand, 4. Royal Swedish Academy of Agriculture and Forestry, Stockholm, p. 37–.

Nilsson, S., Schopfhauser, W., 1995. The carbon-sequestration potential of a global afforestation program. Clim. Change 30, 267–293.

Oppenheimer, M., Campos, M., Warren, R., 2014. Chapter 19: Emergent Risks and Key Vulnerabilities, in: Climate Change 2014 Mitigation of Climate Change Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Osseweijer, P., Watson, H.K., Johnson, F.X., Batistella, M., Cortez, L., Lynd, L., Kaffka, S., Long, S., Meijl, H., Nassar, A., Woods, J., 2015. Bioenergy and Food Security, in: Bioenergy and Sustainability. Bioenergy: bridging the gaps. Paris. France: SCOPE, pp. 91–136.

Pan, A., Sun, Q., Bernstein, A.M., Schulze, M.B., Manson, J.E., Stampfer, M.J., Willett, W.C., Hu, F.B., 2012. Red Meat Consumption and Mortality: Results From 2 Prospective Cohort Studies. Arch. Intern. Med. 172, 555–563. doi:10.1001/archinternmed.2011.2287

Persson, U.M., Henders, S., Cederberg, C., 2014. A method for calculating a land-use change carbon footprint (LUC-CFP) for agricultural commodities – applications to Brazilian beef and soy, Indonesian palm oil. Glob. Change Biol. 20, 3482–3491. doi:10.1111/gcb.12635

Popp, A., Rose, S.K., Calvin, K., Van Vuuren, D.P., Dietrich, J.P., Wise, M., Stehfest, E., Humpenöder, F., Kyle, P., Van Vliet, J., Bauer, N., Lotze-Campen, H., Klein, D., Kriegler, E., 2014. Land-use transition for bioenergy and climate stabilization: model comparison of drivers, impacts and interactions with other land use based mitigation options. Clim. Change 123, 495–509. doi:10.1007/s10584-013-0926-x

Powell, T.W.R., Lenton, T.M., 2012. Future carbon dioxide removal via biomass energy constrained by agricultural efficiency and dietary trends. Energy Environ. Sci. 5, 8116. doi:10.1039/c2ee21592f

Rawlins, M.A., McGuire, A.D., Kimball, J.S., Dass, P., Lawrence, D., Burke, E., Chen, X., Delire, C., Koven, C., MacDougall, A., Peng, S., Rinke, A., Saito, K., Zhang, W., Alkama, R., Bohn, T.J., Ciais, P., Decharme, B., Gouttevin, I., Hajima, T., Ji, D., Krinner, G., Lettenmaier, D.P., Miller, P., Moore, J.C., Smith, B., Sueyoshi, T., 2015. Assessment of model estimates of land-atmosphere CO<sub>2</sub> exchange across Northern Eurasia. Biogeosciences 12, 4385–4405. doi:10.5194/bg-12-4385-2015

Rights and Resources Initiative, 2015. Who Owns the World's Land? A global baseline of formally recognized indigenous and community land rights. Washington, DC: RRI.

Rights and Resources Initiative, 2014. Recognizing Indigenous and Community Rights: Priority Steps to Advance Development and Mitigate Climate Change, Supporting forest tenure, policy and market reforms. Rights and Resources Initiative, Washington DC.

Rockström, J., Steffen, W., Noone, K., Persson, \AAsa, Chapin, F.S., Lambin, E.F., Lenton, T.M., Scheffer, M., Folke, C., Schellnhuber, H.J., others, 2009. A safe operating space for humanity. Nature 461, 472–475.

Rogelj, J., Luderer, G., Pietzcker, R.C., Kriegler, E., Schaeffer, M., Krey, V., Riahi, K., 2015. Energy system transformations for limiting end-of-century warming to below 1.5 °C. Nat. Clim. Change 5, 519–527. doi:10.1038/nclimate2572

Searchinger, T., Heimlich, R., 2015. Avoiding bioenergy competition for food crops and land (Working Paper), Installment 9, Creating a Sustainable Food Future. World Resources Institute, Washington DC.

Smeets, E., Faaij, A., Lewandowski, I., Turkenburg, W., 2007. A bottom-up assessment and review of global bio-energy potentials to 2050. Prog. Energy Combust. Sci. 33, 56–106. doi:10.1016/j.pecs.2006.08.001

Smith, L.J., Torn, M.S., 2013. Ecological limits to terrestrial biological carbon dioxide removal. Clim. Change 118, 89–103. doi:10.1007/s10584-012-0682-3

Smith, P., Bustamante, M., Ahammad, H., Clark, H., Dong, H., Elsiddig, E.A., Haberl, H., Harper, R., House, J., Jafari, M., others, 2014. Chapter 11: Agriculture, forestry and other land use (AFOLU), in: IPCC, 2014: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. pp. 811–922.

Stehfest, E., Bouwman, L., Vuuren, D.P. van, Elzen, M.G.J. den, Eickhout, B., Kabat, P., 2009. Climate benefits of changing diet. Clim. Change 95, 83–102. doi:10.1007/s10584-008-9534-6

Stevens, C., Winterbottom, R., Springer, J., Reytar, K., 2014. Securing Rights, Combating Climate Change: How Strengthening Community Forest Rights Mitigates Climate Change. World Resources Institute, Washington DC.

Stocker, T.F., Qin, D., Plattner, G.-K., Alexander, L.V., Allen, S.K., Bindoff, N.L., Bréon, F.-M., Church, J.A., Cubasch, U., Emori, S., others, 2013. Technical summary, in: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, pp. 33–115.

Tavoni, M., Socolow, R., 2013. Modeling meets science and technology: an introduction to a special issue on negative emissions. Clim. Change 118, 1–14. doi:10.1007/s10584-013-0757-9

Thompson, I., Mackey, B., McNulty, S., Mosseler, A., Secretariat of the convention on the biological diversity, 2014. Forest resilience, biodiversity, and climate change: a synthesis of the biodiversity, resilience, stabiblity relationship in forest ecosystems.

WGBU, 2008. Future bioenergy and sustainable land use. Earthscan, London.

Wiltshire, Davies-Barnard, 2015. Planetary Limits to BECCS Negative Emissions (No. V1.1), 1104872 / AVOID 2 WPD.2a Report 1. AVOID 2 programme.

Ziegler, A.D., Phelps, J., Yuen, J.Q., Webb, E.L., Lawrence, D., Fox, J.M., Bruun, T.B., Leisz, S.J., Ryan, C.M., Dressler, W., Mertz, O., Pascual, U., Padoch, C., Koh, L.P., 2012. Carbon outcomes of major land-cover transitions in SE Asia: great uncertainties and REDD+ policy implications. Glob. Change Biol. 18, 3087–3099. doi:10.1111/j.1365-2486.2012.02747.x