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

Sivan Kartha and Kate Dooley

Stockholm Environment Institute - U.S. Center
11 Curtis Avenue
Somerville, MA 02144
USA

Tel: +1 617 627 3786
Web: www.sei-international.org

Author contact:
Sivan Kartha, Stockholm Environment Institute, U.S. Center
sivan.kartha@sei-international.org
Kate Dooley, University of Melbourne
katedooley0@gmail.com

Director of Communications: Robert Watt
Editor: Marion Davis

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Sivan Kartha

Stockholm Environment Institute – U.S. Center

Kate Dooley

University of Melbourne

ABSTRACT

This paper focuses on the risks associated with "negative emission" techniques for drawing carbon dioxide from the atmosphere through photosynthesis and storing it in land-based sinks or underground. It examines what these risks may imply for near-term actions to limit warming to 1.5°C or 2°C above pre-industrial levels. Negative emission techniques increasingly appear – explicitly or implicitly – in discussions of options for meeting climate goals, such as those of the Paris Agreement. Negative emissions could allow society to "undo" earlier emissions, enabling us to stay within a given carbon budget in the long run, even if we exceed it early in the century. We identify three types of risks in counting on negative emissions: (i) that negative emission options will not ultimately prove feasible; (ii) that their large-scale deployment involves unacceptable ecological and social impacts; and, (iii) that negative emissions activities prove less effective than hoped, either because they are subsequently reversed by human or natural forces, or because climate change impacts prove irreversible. We examine four main land-based negative emissions options in light of those risks: ecosystem restoration, mosaic-landscape restoration, reforestation, and bioenergy with carbon capture and sequestration (BECCS). Many mitigation pathways aiming to keep warming below 1.5°C or 2°C assume negative emissions as high as 1,000 Gt CO_2. We find that negative emission options cannot be safely relied upon to fill such a large gap. Embarking on such pathways could lead societies to do too little to decarbonize, and greatly exceed their carbon budgets without a way to undo the damage. Pathways that rely on much smaller amounts of negative emissions, however, could prove viable, with ecosystem restoration and reforestation providing close to 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.

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1. INTRODUCTION

"Negative emission" mitigation techniques have increasingly appeared – sometimes transparently and sometimes only implicitly – in analyses and discussions of options for addressing climate change. "Negative emissions" refers to carbon dioxide (CO_2) removal from the atmosphere. The Paris Agreement on climate change approved last December (UNFCCC 2015) calls for holding global average temperature increase to "well below" 2°C, and to "pursue efforts" to limit the temperature increase to 1.5°C. Such an ambitious objective raises questions about the extent to which removing emissions from the atmosphere may be necessary to achieve this.

Some negative emission technologies are still considered speculative – such as direct air capture (an "immature" technology with "high technical and environmental risk" (National Research Council 2015) and ocean fertilization (immature, energy-intensive, and cost-prohibitive (ibid.). Thus, they are not considered in this report, as they do not figure prominently in current discussions of mitigation strategies. Instead we focus on options that aim to remove CO_2 from the atmosphere through photosynthesis and sequester it in plants and other organic material in land-based sinks or underground (geological) storage. These land-based options are increasingly looked to as cost-effective and feasible components of climate 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 restoration 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 carbon removal via land-based sinks and via negative emission technologies, and what these risks mean for near-term actions and long-term mitigation strategies, including for respecting 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 accepting them may lock us into much higher levels of warming than intended. Indeed, taking on such risks may substantially undermine society's overall mitigation efforts.

Section 2 outlines 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 relative to those risks. Section 4 discusses the implications of these findings for the objective of limiting warming to below 1.5°C and 2°C in light of the Paris outcome on a global mitigation goal, and the choice of mitigation pathways generally.

2. RISKS OF NEGATIVE EMISSION OPTIONS

2.1 Three types of risks that affect current mitigation strategies

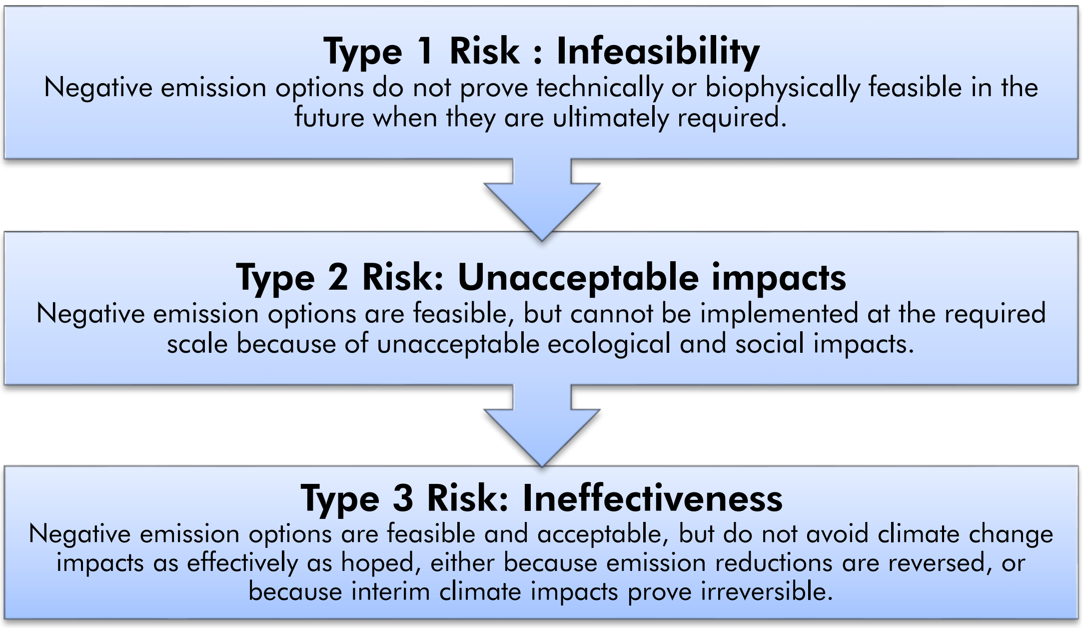
All mitigation options come with risks that they might be less effective than expected. Energy efficiency investments might lead to unanticipated rebound in consumption. Solar panels might decline in power output more quickly than their manufacturers predicted. Wind resources might not be optimally usable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

Negative emission techniques pose a very different class of risks, however – one from which there may be no way to recover if things go wrong. This is because they are typically discussed as options to be deployed later in the century, to "undo" emissions that occurred earlier. This, the logic goes, would enable us to stay within a given carbon budget – such as the extremely strict 1,000 Gt CO_2 limit presented in the latest Intergovernmental Panel on Climate Change assessment (IPCC 2014) as a "likely" 2°C budget – in the long run, even after having greatly 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 seems eminently sensible. It buys time and allows for a slower and more orderly transition to a low-carbon energy system. It allows societies to avoid near-term mitigation costs and rely instead on negative-carbon options that are deferred to the comfortably distant future. It takes the pressure off sectors where mitigation is difficult, such as aviation. Tavoni and Socolow (2013), noting that negative emissions have increasingly been incorporated into modelled assessments of mitigation pathways, 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 echoed several times in the recent literature (Anderson 2015; Fuss et al. 2014; Geden 2015; Smith et al. 2015; Williamson 2016; Peters 2016).

In the real world, this "easier and less expensive" strategy poses fundamental risks due to uncertainties about whether society will ultimately be able to realize the benefits of negative emission techniques when they are needed. We highlight three sequential risks, shown in Figure 1, and discussed below.

Figure 1: Three types of risks posed by negative emission measures



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 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 eventually prove to be 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. This means they would take up large amounts of land that might otherwise be used for agriculture, or be left wild. There is thus no guarantee that it will be possible to deploy them at large enough scales without major adverse impacts on biodiversity, food security, water resources, and human rights. It might be feasible if several conditions align favourably: agricultural yields continue to rise steadily, so societies need less land to grow food; water and the other necessary resources are plentiful in the selected locations; biomass production avoids common problems associated with agriculture, such as fertilizer runoff; good governance helps ensure that there are no food price shocks or land grabs that dispossess indigenous peoples and local communities (Type 2 risk in Figure 1).

Third, even if negative emission options prove feasible, and can be undertaken at large scale without adverse ecological and social consequences, they could still prove less effective than expected at reducing climate impacts (Type 3 risk in Figure 1). 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 sink 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. And, even if carbon is sequestered successfully, irreversible climatic changes could occur due to the period of concentration overshoot. Impacts that could be wholly or partially irreversible include species extinction, coral reef death, ocean acidification, and loss of sea or land ice, some of which themselves lead to positive feedbacks or tipping points. The likelihood of irreversible impacts increases with the amount and duration of concentration overshoot – i.e. with the amount of negative emissions (ICCI 2015).

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 and effective. As expressed by 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." This is especially so given that it is increasingly the case that policy-oriented documents (for example, UNEP 2015) and policy decisions (for example, UNFCCC 2015 see Section 4) assume the availability of negative emissions.

For society to proceed now as if future large-scale deployment of negative emissions will assuredly work is therefore a very risky course. If we overshoot the available carbon budget with the intention of balancing it with negative emissions in the future, and later learn this is not possible, we will be faced with a much more disruptive transition and greater climate change impacts than we had intended.

2.2 Assessing land-based negative emission options

This section presents an overview of factors that arise in assessing land-based negative emission options, organized along the three types of risk outlined above: feasibility, social and ecological impacts, and effectiveness. These categories are interrelated; for example, biodiversity impacts could be seen as an ecological constraint or as a component of biophysical limits, and 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.

Risk type 1: Technological and biophysical feasibility

The main technological uncertainties apply to BECCS, which is also most heavily relied on in mitigation scenarios for negative emissions,[1] even though it 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 for power production or – at lower sequestration rates – as a synthesis gas for biofuel production, allowing for a stream of CO_2 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 CO_2 released from an ethanol production process), which captures only 11–13% of the carbon in the feedstock (Gough and Vaughan 2015), 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 sufficient and spatially appropriate CCS capture, pipeline, storage infrastructure and reservoir capacity (Smith et al. 2014).

Land-based negative emission options are also limited by fundamental biophysical constraints. Sink saturation sets an upper 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 the biosphere to sequester additional 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, one study (Mackey et al. 2013) estimates an upper theoretical limit to cumulative terrestrial sequestration of 187 Gt C before ecosystem sinks would be saturated (equal to loss of terrestrial carbon since pre-industrial revolution though past land-use change). The practical limit is lower, however, because current land uses, including settlements and agriculture, preclude restoring carbon stocks to their previous levels. In addition, the practical limit will ultimately be influenced, and quite possibly diminished, by climate change.

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 limited by net primary production, which is discussed further in Section 4.

Risk type 2: Unacceptable 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 million to almost 3,000 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 – and competition for productive land is already a global concern (Nilsson 2012; Searchinger and Heimlich 2015).

[1] Note that carbon capture and storage combined with fossil fuels cannot lead to net negative emissions – only CCS combined with bioenergy that removes more carbon from the atmosphere during growth than is released by the associated land conversion, production, harvest, and processing.

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 a large-scale increase in land use from mitigation activities may conflict with these objectives (Smith et al. 2014). These 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). Below we consider risks related to social and ecological impacts in turn.

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 has long been a global development priority, with the 1996 World Food Summit declaration aiming to halve food insecurity by 2015. The Sustainable Development Goals (under SDG2) include a target to end hunger and achieve food security for all by 2030. Land availability is not the only component of food insecurity, but how land is used and who can access it is a critical factor in achieving global food security objectives.

Some negative emissions options can displace natural ecosystems and existing land uses that are important for subsistence production and local livelihoods in smallholder farming communities and among indigenous peoples. About two thirds of the world's land area is under customary or traditional ownership, but only a small fraction is legally recognized, so indigenous peoples and local communities already face dispossession (Rights and Resources Initiative 2015). The lack of clear legal 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. Research has shown that community-owned and -managed forests, incorporating local knowledge and decentralized decision-making, can yield not only livelihood benefits but high carbon storage as well (Chhatre and Agrawal 2009). Securing local land rights is recognized as an urgent global priority (Rights and Resources Initiative 2014), contributing to protecting livelihoods, food security, and climate mitigation.

Ecological impacts

Some land-based mitigation activities, such as extensive monoculture plantations, including bioenergy crops, can degrade land, altering ecosystem function. This contributes to food insecurity, undermines livelihoods, and can diminish biodiversity and deplete scarce resources.

Biodiversity is now a critical global issue, with species extinction rates at 100 to 1,000 times natural background rates. Rockström et al. (2009) assess the rate of species extinction as an indicator of human interference is transgressing planetary boundaries that define the safe operating space within which human civilization can thrive, and which relies on 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; SDG15.2 to halt global deforestation by 2020 and substantially increase afforestation and reforestation; and SDG15.5 to halt biodiversity loss. Other high-level political goals relating to forests exist, such as the Bonn Challenge and the New York Declaration on Forests (see Section 3.2), which could have positive impacts for biodiversity if mixed species regeneration and other methods that enhance biodiversity are pursued. In contrast, because land-intensive negative emissions activities could conflict with biodiversity objectives, such activities are covered by a

A plantation of eucalyptus, a fast-growing species, in Hawaii. Forest & Kim Starr / Flickr

moratorium on geoengineering adopted by the Convention on Biodiversity (CBD), which includes "increasing carbon sequestration from the atmosphere on a large scale that may affect biodiversity".[2]

Land and water resources are already stressed and becoming more so (Alexandratos and Bruinsma 2012), largely due to the pressures of industrialized agriculture. Large-scale deployment of land-based mitigation measures could add to this stress, with energy crops entailing significant consumption of the world's fertilizer supply, impacting 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, widespread and large-scale ocean anoxic events that compromise marine ecosystems – Rockström et al. (2009) estimate that current human fixation of nitrogen from the atmosphere would need to be reduced by 75% to keep within planetary boundaries.

Risk type 3: Negative emissions are not as effective as expected

One reason that negative emissions might not yield the expected climate benefit is that carbon stored in the terrestrial biosphere is vulnerable to disturbance. Such storage is thus inherently non-permanent. An ecosystem can serve as a reservoir of carbon, but it must remain undisturbed

[2] CBD COP 10 Decision X33, Biodiversity and Climate Change, paragraph 8w. Available at: https://www.cbd.int/decision/cop/?id=12299.

over time-scales relevant to climate change. Negative emissions options that rely on sequestering carbon in the terrestrial biosphere inherently entail a risk that those carbon stocks will be re-released to the atmosphere. 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 there would be a 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 fossil fuel emissions does not present the same risk of reversal as is posed by sequestration of carbon into the terrestrial biosphere.

Terrestrial 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 (and, to a lesser extent, oceans) will take up carbon at lower levels than historically, and possibly become a net source of carbon emissions (IPCC 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 strengthens the resilience of forest ecosystems to external stressors, including climate change (Thompson et al. 2014).

A second reason why negative emissions might be less effective than expected is the risk that climate impacts occurring during the period of concentration overshoot may prove irreversible. It is known that, for a given amount of total cumulative emissions, peak warming is higher for a pathway that overshoots before negative emissions begin to reduce concentrations. The peak warming is driven by time-integrated radiative forcing, and is a function of maximum cumulative emissions (before negative emissions start), rather than total cumulative emissions (including negative emissions) (Zickfeld et al. 2012). The higher peak warming causes greater climate impacts, and "increases the likelihood of crossing thresholds for 'dangerous' warming" (Tokarska and Zickfeld 2015). Of particular concern is the potential to pass thresholds relating to sea ice, glaciers, ice sheets and permafrost (ICCI 2015), which can themselves create a positive feedback that causes additional warming (for example, through albedo effects or methane emissions).

3. EVALUATING LAND-BASED NEGATIVE EMISSION OPTIONS

In this section we assess four types of land-based negative emissions – forest ecosystem restoration, reforestation, mosaic landscape restoration and BECCS – in light of the risks outlined above. We begin by assessing the mitigation potential of avoiding emissions from forest loss, recognizing that society's ability to halt and reverse the global decline in forest carbon stocks depends on its ability to reduce deforestation and forest degradation.

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 around half of this (about 10% of global emissions) coming from land use change: deforestation, forest degradation and drained peatland in tropical regions (Smith et al. 2014). Reducing emissions from land use change represents significant potential for permanent mitigation benefits. Although this does not constitute a form of negative emissions, in terms of removing carbon from the atmosphere, we briefly discuss deforestation and forest degradation here because they are a significant source of emissions and are driven largely by demand for agricultural land (Hoare 2015; Lawson et al. 2014), and because forest regeneration can only be used to store carbon if first we stop and reverse forest loss.

Net global carbon emissions from deforestation and forest degradation average 1.1 ± 0.5 Gt C for the period 1990–2010 (Houghton 2013), although emissions from forest degradation are poorly quantified globally, with estimates ranging from 15% to 50% of emissions from deforestation alone (Asner et al. 2010), with disproportionately large impacts on biodiversity (Barlow et al. 2016). There are also significant emissions from drained peatlands (organic soils), of approximately 0.3 Gt C/year, an estimate that is likely to be conservative due to the unmapped extent and depth of peat. This brings the total emissions from land use change, excluding agricultural soils, to 1.4 ± 0.5 Gt C/year (Baccini et al. 2012; Houghton 2013).

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

Global initiatives and efforts to reduce and halt forest loss have scaled up significantly in the past decade, with renewed impetus from the recognition of the large potential for emission reductions from this sector to contribute to climate mitigation. A large number of countries have taken on international obligations relating to preventing forest loss. In 2008 the European Union put forward a goal of at least halving tropical deforestation by 2020 and halting global forest loss by 2030 at the latest, which was embraced by a larger constituency in the 2014 New York Declaration on Forests.[3] More recently, the Sustainable Development Goals included a target to halt global deforestation by 2020, and Norway has become the first country to commit to zero deforestation in all public procurement (Norwegian Parliament 2016).

While such goals are ambitious, failure to achieve them would make the 1.5°C and 2°C targets much more challenging to meet. Furthermore, slowing and halting forest loss brings significant benefits aside from carbon, including biodiversity protection, watershed protection and rural livelihoods. One of the key ways to tackle deforestation is through secure collective tenure rights: research shows that legally recognized tenure rights for communities leads to reduced deforestation and lower CO_2 emissions when compared with 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 and ecological function – forest ecosystem restoration refers to the regeneration of degraded forests, while reforestation happens on land that was forested in the past, but is no longer forested.

Forest ecosystem restoration

Degraded forests recover naturally over time; forest ecosystem restoration can be defined as enabling or accelerating that recovery. The mitigation potential is significant, because degraded forests store significantly less carbon in the trees and the soil than natural forest ecosystems (Mackey 2008). Ecosystem restoration also boosts biodiversity, helps maintain watersheds, and

[3] See: http://forestdeclaration.org.

can improve livelihoods. Degraded forests vary in the degree of fragmentation and the extent to which biodiversity has been lost, so the potential for restoration will vary. Some areas can recover unaided if protected from further disturbance. This is likelier if forest loss is recent (months to years), residual trees and soil seed stores remain, and biodiversity-rich native forests are still present in the surrounding landscape (Lamb et al. 2005). Natural recovery of degraded forests is less feasible where the ecosystem has lost its 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 also possible, but it is highly resource-intensive, and success often depends on the proximity of nearby native forests to aid recolonization (Lamb et al. 2005). This highlights the immense difficulty of reversing the loss of biodiversity-rich native forests.

Houghton (2013) suggests that ecosystem restoration, by protecting and enabling the regrowth of forests, could remove as much as 1–3 Gt C/year from the atmosphere. However, achieving this large rate of carbon sequestration would require that certain lands that are currently in use – such as secondary forests and the fallows of swidden (or shifting) cultivation – are permitted to regrow, with no further harvest or clearing for agriculture or other purposes. This would increase competition over the remaining land, potentially threatening food security – even more so if forest restoration is done as a commercial enterprise, without engaging local communities.

Restricting swidden agriculture could have significant impacts on local and subsistence livelihoods, and potentially undermine customary access and ownership rights to land. Moreover, research suggests that shifting cultivation can often be climate-neutral rather than emissive (Baccini et al. 2012), and Ziegler et al. (2012) further suggest that when the fallow periods are long, existing swidden systems can produce substantial carbon benefits. There are also mitigation benefits to sustainable harvest of secondary forests – for example, substitution of timber for materials associated with high greenhouse gas emissions, such as steel and cement, and ongoing storage of carbon in harvested wood products. Hence, there are limits to the benefits of ecosystem restoration, relating mostly to competition with existing land uses.

Given these considerations, it might be most reasonable to use the lower end of Houghton's range in estimating the potential for future carbon sequestration from ecosystem restoration. This might be increased over time if warranted by improved scientific understanding (such as the feasibility of restoring highly degraded ecosystems) or resolution of socio-institutional barriers (such as ensuring food security). Achieving this rate of carbon sequestration would still be extremely challenging, requiring forests to switch from a net carbon source of 1 Gt C/year to a net sink of at least the same magnitude. This requires both reversing forest loss and facilitating the effective long-term, stable regeneration of degraded forests.

Houghton et al. (2015) note that changing land management practices to enable ecosystem restoration provides a carbon sink that would be in addition to "other natural processes on land (that) remove approximately 25% of the carbon emitted each year" (p.1023). Beyond the benefits of carbon sequestration and storage, regeneration of degraded forests with increased biodiversity makes forest landscapes more resilient (Hicks et al. 2014), thereby 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.

Volunteers at a mass tree planting on Cerro Zapotecas in Mexico, part of a reforestation effort. Gobierno Cholula / Flickr

Reforestation

Reforestation refers to the re-establishment through human intervention (planting, seeding, etc.) of forest on lands that were forest at some time in the past.[4] This differs from ecosystem restoration in that the land's capacity for natural regeneration has been lost or severely impaired, due to far more intense tree and biodiversity loss. When these areas are replanted, the resulting forests generally have lower biodiversity than a natural forest (Brockerhoff et al. 2008; Lamb et al. 2005), and thus lower carbon storage capacity (Hicks et al. 2014; Strassburg et al. 2010). As a result, the cumulative mitigation potential is lower from planting new forests than from restoring degraded forests (Mackey 2008).

Houghton (2013) suggests that reforesting an area of 500 Mha would provide a global sink of approximately 1 Gt C/year (assuming an annual accumulation of carbon in trees and soil of 2 t C ha/year). This is toward the upper end of the roughly 0.5– 1.15 Gt C/year range reported in the IPCC (both the Fourth and Fifth Assessment Report give the same data range; see Smith et al. 2014). While Houghton does not specify where such lands are and whether they are available for reforestation, his land requirement is consistent with the mapping of forest landscape restoration possibilities produced by the Global Partnership on Forests and Landscape Restoration[5] (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 closed-canopy reforestation is possible. Across both of these categories, two billion hectares are estimated to

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[4] Reforestation here refers to reforesting historically deforested lands, while afforestation refers to establishing forests on landscapes that do not naturally support forests. The CBD moratorium on geoengineering (see footnote 2) can be interpreted as applying to afforestation with non-native species.
[5] See: http://www.forestlandscaperestoration.org.

be available for restoration in tropical and temperate areas,[6] three quarters of which are 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.

The latter work informs the "Bonn Challenge", a high-level global goal to restore 150 Mha of degraded and deforested lands by 2020, with 96 Mha of land pledged by mid-2016 toward this target – 64% of the 2020 goal.[7] The New York Declaration on Forests includes a target to restore an additional 200 Mha of forests by 2030. Other estimates from the literature of the land required for 1Gt C/year 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). However, there is significant uncertainty in global mapping estimates, particularly regarding the spatial extent of degraded forests, and thus the degree to which estimates for reforestation potential overlap with estimates for restoring degraded forest ecosystems.

The ecological and social implications of reforestation on such as large scale would depend on how well the projects are planned and implemented, including the choice of sites, how projects are structured (commercial vs. community-based), and the extent to which local stakeholders are engaged and given a strong say. The biodiversity potential also varies enormously depending on methods of reforestation (Lamb et al. 2005). For example, Smith and Torn (2013) estimate that achieving 1 Gt C/year carbon drawdown through fast-growing commercial plantation species would require significant inputs of nitrogen and phosphorus and alter local hydrological patterns. The impacts of reforestation on biodiversity can be positive, but not when natural ecosystems, such as grasslands, are converted into secondary forests. 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). In addition, the climate effects of reforestation can vary significantly by geography; at high latitudes, warming due to reduced albedo can potentially outweigh the benefits of carbon sequestration (Arora and Montenegro 2011).

This points to scale, spatial location and species type as key considerations for reforestation. In light of uncertainty around land availability (Gibbs and Salmon 2015), it would be risky to overestimate the land available in the future for reforestation. In light of these considerations, it may be reasonable to assume that achieving the existing targets in the Bonn Challenge and the New York Declaration 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 et al. (2011), allowing some buffer for uncertainty in availability of suitable land. It is also important to note that these global targets for reforestation are not solely focused on maximizing carbon sequestration, but also on broader social and ecological benefits when reforestation is done in the right manner, with localized decision-making to reduce the risk of adverse impacts. The benefits of community-managed and -owned forests are increasingly well documented. Reforestation programmes which place communities at the centre of efforts can help to secure livelihoods, conserve biodiversity and reduce conflict, while also storing carbon (Stevens et al. 2014).

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[6] These estimates are based on low accuracy (1 km 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).

[7] See: http://www.bonnchallenge.org.

Sink saturation is another key determinant of the potential carbon benefits from reforestation. It is generally understood that 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), although some studies show mature forests continue to sequester carbon (Smith et al. 2014). As the forest biome matures, while some low levels of sequestration may continue, its primary mitigation benefit is now as a carbon stock that needs to be protected in order to prevent the sequestered carbon from being re-emitted to the atmosphere. Hence ecosystem restoration and reforestation represent a one-off opportunity to partially restore the land carbon debt, replacing some of the historically depleted terrestrial carbon sink (see Mackey et al. 2013).

Mosaic landscape restoration and soil carbon sequestration

Mosaic-type landscape restoration accommodates multiple land uses, such as agriculture, protected reserves, managed plantations and agroforestry systems. The risks and potential carbon benefits of activities such as agroforestry, biochar[8] 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 activities. 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 restoration 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. Indeed, in practice, the key motivation for implementing practices such as agroforestry to date has been their adaptation, health and livelihood benefits.

3.3 Bioenergy with CCS (BECCS)

This section reviews the potential for negative emissions from bioenergy combined with carbon capture and storage (BECCS). As outlined in Section 2.2, a key constraint on BECCS is the uncertainty of CCS technologies. This section focuses on a second limiting factor – 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 determinant of bioenergy potential is the maximum biospheric capacity of net primary production (NPP) of plant growth, which is estimated to be around 30 Gt C/year, with an energy value of ≈ 1,100 EJ/year (Haberl et al. 2013). Humans currently harvest approximately 230 EJ/year for food, feed, fibre and energy, with the remainder locked up in natural and protected areas, cultivated areas, or already 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 (Haberl et al. 2013; Kolby Smith et al. 2012). The bioenergy potential from available residues (agricultural and forest harvest residues, municipal waste and biogas from animal manures) adds about 60 EJ/year (Kolby Smith et al. 2012; Smith et al. 2014), putting the upper biophysical limit for bioenergy potential at ≈250 EJ/year (Haberl et al. 2013). Note, this estimated biophysical limit is not an estimate of what could be considered

[8] Biochar is charcoal that is added to the soil. For an explanation of how it is made and how it might improve soil carbon storage, as well as a synthesis of research on its effectiveness, see Box 11.3 in Smith et al. (2014).

sustainable primary bioenergy potential. Rather, it provides an upper limit based on current understanding of constraints posed by ecological systems on potential agricultural output.

In practice, reaching 250 EJ/year in 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 mitigation scenarios are well within this upper limit (Erb et al. 2012; Kraxner et al. 2013), many 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 1,000 EJ/year (Smith et al. 2014). This sanguine outlook on future bioenergy availability has been adopted by many widely cited mitigation scenario integrated assessment models (Wiltshire and Davies-Barnard 2015). Creutzig et al. (2015) note that beyond 100 EJ/year, there is decreasing agreement on the sustainable technical potential of bioenergy.

These estimates for bioenergy are typically based on two sources of biomass: energy crops (such as woody biomass) grown on dedicated cropland, and bioenergy sourced from residues and wastes. Bioenergy from residues and wastes can use materials from many different sources, including forest and agricultural residues, and household and urban waste. Current production of bioenergy, which is mostly from residues and traditional biomass uses, is around 55 EJ/year – equivalent to 12% of current energy production from fossil fuels (Erb et al. 2012; Haberl et al. 2013; Smith et al. 2014). Yet the availability of residues and wastes for bioenergy 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 estimated potential for 60 EJ/year of bioenergy feedstocks to be sourced from waste and residues comes with trade-offs. In terms of contributing to negative emissions, bioenergy from wastes and residues is not likely to be suitable for BECCS due to logistical constraints associated with dispersed feedstock (Smith et al. 2014).

Key uncertainties in total bioenergy potential therefore lie 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 fertilization 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 and Bruinsma 2012). Dramatic yield increases in the past were mainly achieved by increasing the "harvest index", i.e., shifting biomass production to the grain portion of the plant at the expense of the stem portion, hardly changing total biomass production. This does not benefit bioenergy feedstock production, in which the whole plant is used. Improving bioenergy feedstock production would rely on other strategies, such as improving basic photosynthetic efficiency or overcoming stubborn yield gaps, which cannot be taken for granted (Kemp-Benedict et al. 2012). Potential for yield increase has commonly been overestimated 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 and Bruinsma 2012).

Land availability at the global aggregate level is highly uncertain, with large disagreements in the literature in both the scale and spatial location of degraded lands (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 et al. 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 presuppose that this will occur and rely on such land availability for climate mitigation, 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 directly causes or indirectly leads to conversion of wilderness areas (Haberl et al., 2013; Kolby Smith et al., 2012). Bioenergy at a large scale would also increase the demand for key resources such as fertilizer and freshwater irrigation, which could result in increased GHG emissions, nutrient loading, watershed stress, and environmental degradation (Erb et al. 2012; Smith and Torn 2013; Wiltshire and Davies-Barnard 2015). Research by Wiltshire and Davies-Barnard (2015) has found that land use emissions associated with BECCS can be large, reducing the overall mitigation potential of BECCS. In worst-case scenarios, land use emissions (from associated deforestation) exceed the potential climate mitigation value of BECCS.

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/year from dedicated land use) have contributed to rising 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 the development of integrated land-use policies to ensure sustainable land-use (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, concerned that society already faces a deficit of cultivable land (Searchinger and Heimlich 2015), and arguing that society cannot afford to divert land for bioenergy feedstock production. In the face of uncertain land availability and the possible negative impacts of large-scale expansion of bioenergy production on food security and the environment, it is highly risky to rely on the future availability of significant amounts of land for producing bioenergy feedstock for BECCS. In a carbon-constrained world, the effective use of wastes and residues should be prioritized; this would enable bioenergy at fairly limited scales, and likely with no CCS (Miyake et al. 2012). Confidence that bioenergy can be deployed at significant scale as a negative emissions measure would be warranted only after the feasibility of the required technologies is proven and robust institutions and practices for scaling up bioenergy feedstock production without posing unacceptable ecological and social costs are developed. Until then, it is risky to base current mitigation strategies on the presumed future availability of large-scale bioenergy with CCS.

Cattle graze on a pasture in an agricultural extension farm in Texas. AgriLife Today / Flickr

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 over growth in 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. It found that in 2050, a shift to healthier diets (reduced sugars and saturated fats, including livestock products, while providing a minimum of 2,500 kcal per person as well as sufficient protein), could reduce net GHG emissions from agriculture and land use by about 45% (about 6 Gt CO_2e/year). It could also reduce 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 unneeded 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 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_2e/year, vs. 7.8 Gt CO_2e/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 made available 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.*

Table 1: Risks of negative emission activities

Risk type	**Type 1: Infeasible technology deployment**		**Type 2: Unacceptable social and ecological impacts**		**Type 3: Ineffectiveness**	
Key problem	**Technological development**	**Biophysical limits**	**Social impacts**	**Ecological impacts**	**Irreversible climate impacts**	**Reversal of negative emissions**
Risk factors	Biomass gasification CCS Geological storage Yield increases	Net primary productivity (NPP) Biospheric carbon sink saturation	Food security Livelihoods Customary land rights	Biodiversity Resource input requirements Watershed protection	Climate system thresholds or tipping points Positive climate feedbacks	Reversals caused by climatic disturbance or human disturbance
Forest ecosystem restoration	N/A	Risk of lower-than-expected feasible scale due to NPP/saturation limits Risk that continued deforestation and degradation will pre-empt ecosystem restoration	Risk reduced if community-owned and -managed; can create food security, livelihood benefits and potentially greater carbon benefits	Minimal risk	Risks increase with duration and extent of temperature overshoot	Risk of reversal significantly reduced by improving ecosystem resilience
Reforestation	N/A	As above	Risk reduced if community owned and managed forestry risks to livelihoods and food security if scale of land demand adversely affects land and food access	Biodiversity can be protected or threatened, depending on the manner of reforestation. Commercial plantations require high nutrient and water inputs	As above	Risk of reversal higher in commercial plantations
Mosaic landscape restoration	N/A	As above	Risk reduced if community-owned and -managed	Minimal risk	As above	Risk of reversal reduced by improving ecosystem resilience
Bioenergy from dedicated land use	BECCS not available at commercial scale Continuing yield increases may not materialize Geological storage may be limited, geographically constrained	As above (estimates of future bioenergy potentials are often well above maximum biophysical limits)	Risks to livelihoods and food security if scale of land demand adversely impacts land and food access	Risks to biodiversity if natural ecosystems converted to energy crops or due to indirect land use change Risk of exacerbating already significant overconsumption of nutrients and water	As above	Minimal risk

4. IMPLICATIONS FOR THE IMPLEMENTATION OF THE PARIS AGREEMENT

Based on the outline of risks presented in Section 2, and the review of negative emissions options and potentials in Section 3, we discuss here the implications for achieving the stated temperature objective of the Paris Agreement to limit temperature to "well below 2°C", and to "pursue efforts to limit temperature increase to 1.5°C", along with its long-term mitigation objective to "balance" anthropogenic emissions with removals, which is to be achieved "in the context of sustainable development and efforts to eradicate poverty" (UNFCCC 2015).

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). It reviews results from some 200 modelled "low stabilization scenarios," providing a fairly comprehensive meta-analysis of scenarios available at the time of its writing. That said, it is important to note that scenarios are actively being developed, as models are refined and assumptions are updated. In particular, there is much research in progress for publication as inputs to the upcoming IPCC Special Report on the Impacts of Global Warming of 1.5 °C Above Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathways, being prepared at the invitation of the Conference of the Parties in Paris last December.

Because Rogelj et al. consider many scenarios with even lower emissions than those in the IPCC scenario database, they 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 the global mean surface temperature has a greater than 50% chance of returning to less than 1.5°C above pre-industrial levels by 2100. They note that these scenarios are "temperature overshoot" scenarios, as they typically have a poorer than 50% chance of keeping warming 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" at the time of publication. 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 1,000 Gt CO_2 is required, and for the 2°C scenarios, between 0 and 900 Gt CO_2. In these scenarios, negative-emissions measures are adopted widely in the second half of the century to reverse a large fraction of fossil-fuel 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 specific models, find a range of roughly 500 to 1,600 Gt CO_2. Fuss et al. (2014) note that the upper end of the range of assumed negative emissions is comparable in magnitude to the natural ocean sink and the natural terrestrial sink, giving rise to considerable uncertainties with regard to their impacts on carbon cycle dynamics.

Our analysis here suggests that the upper end of the stated range of negative emissions must be called out as improbably high, given biophysical limits and the risks of social and economic impacts. As discussed in detail in Section 3, negative emissions on the order of 1,000 Gt CO_2 may be simply unachievable owing to biophysical constraints.

However, a large number of the modelled 1.5°C and 2°C pathways at the other end of the range require significantly lower levels of negative emissions. Specifically, Rogelj et al. show that a total of 480 Gt CO_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 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 even less on negative emissions and more on renewables and energy efficiency if the negative emission options were further constrained by socio-ecological limits.

Table 2 estimates the land-based carbon sequestration potential based solely on options that have a reasonable 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 (of technological infeasibility, as in Figure 1), they still pose risks – and potentially substantial risks – of Type 2 (risk of adverse social and ecological impacts) and Type 3 (risk of ineffectiveness). Moreover, these risks increase with the scale of deployment.

The estimated range – from 370 to 480 Gt CO_2 cumulative carbon sequestration – overlaps the range of negative emissions in the modelled 1.5°C pathways assessed by Rogelj et al. This suggests, tentatively at least, that "1.5°C" pathways might be achievable relying only on negative emissions options for which there is less Type 1 risk that they will ultimately fail to materialize. That said, potentially significant Type 2 and Type 3 risks remain.

With respect to "2°C" pathways, the range of scenarios reviewed by Rogelj et al. includes several that do not rely on negative emissions at all; the authors also note that "2°C scenarios with a significantly lower or even zero contribution of negative emissions are available in the literature". All of these pathways still require a prompt, rapid and dramatic transformation of the economy to shift away from fossil fuels and minimize land use-related emissions.

This set of options presented in Table 2 for achieving 370 to 480 Gt CO_2 negative emissions does not exceed biophysical constraints, but it would still be extremely 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.

Table 2: Options for achieving 370–480 Gt CO_2 negative emissions

Negative emission category		**Cumulative sequestration** (21st century)
Avoided deforestation/ degradation	Forest loss halted by 2020, in line with Sustainable Development Goal 15.2	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 Gt C/year, 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 Gt C (≈ 150 Gt CO_2).	150 Gt CO_2
Ecosystem Restoration	Extensive ecosystem restoration, sufficient to enhance the natural sinks at an average rate of 1 to 1.5 Gt C/year for 60 years until saturation, would yield a cumulative total of 60 to 90 Gt C (= 220 to 330 Gt CO_2)	220–330 Gt CO_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 are 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 bioenergy production, and/or a technological breakthrough in bioenergy production that reduces land requirements.	0 Gt CO_2
Total		**370–480 Gt CO_2**

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

Throughout the recent international climate negotiations, and within the broader climate policy discourse, many parties have advocated for a goal of "net zero" global emissions by a certain date. This is essentially what the Paris Agreement formalized, referring to achieving a "balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century" (UNFCCC 2015). Other parties and stakeholders, including many civil society organizations, have advocated for a goal that would focus on full decarbonization – or "zero fossil carbon" – from the energy system.[9]

The "zero fossil carbon" formulation is not in itself a complete or comprehensive approach to mitigation. For example, it does not set a limit for non-fossil CO_2 emissions, such as those from land-related activities (such as deforestation and landscape degradation). Nor does it set a specific limit for non-CO_2 emissions such as the other "Kyoto-gases" – methane, nitrous oxide,

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

and the industrial "F-gases". As such, it accounts directly for somewhat less than two-thirds of current global greenhouse gas emissions (IPCC 2014, p.9).

The net-zero formulation is also incomplete, as it implies only that all emissions (if formulated as "net-zero greenhouse gas emissions" or "climate neutrality") or at least all CO_2 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 emission of fossil CO_2 to the extent that it is balanced by negative emissions.

As we have argued in this paper, any strategy based on future carbon removals leaves society at risk of insufficient decarbonization by counting on negative emissions 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. It offers no promise of future absolution based on negative emissions from still unproven land-based options, but neither does it exclude the use of them, should they be developed and proven effective to enhance the benefits of emission reductions.

Moreover, a "zero fossil carbon" target could also 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 to substantial climate change mitigation, 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. Indeed, the second half of the mitigation goal states that the "balance" must be achieved "in the context of sustainable development and efforts to eradicate poverty". Achieving these dual outcomes of climate mitigation and environmental and development goals requires approaches which promote localized decision-making over natural resources, such as community forest management, as key elements of enhancing and maintaining biospheric carbon stocks. Thus, a zero fossil carbon target, coupled with these other distinct goals, may constitute the most robust approach for a comprehensive mitigation strategy.

5. CONCLUSION

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 negative emissions prove less effective than hoped, either because of the reversal of emission reductions (due to human or natural forces, including climate change), or because of climate change impacts irreversibly committed during the period of emissions overshoot (for instance, due to thresholds being crossed or tipping points triggered).

It is a bad strategy to rely on the future large-scale deployment of negative emissions without reasonable confidence that there will be ways to achieve those negative emissions through options that are technically feasible and ecologically and socially acceptable at the required scale, and effective. Such a strategy could leave us – and future generations – stranded with an insufficiently transformed energy economy and a carbon debt that cannot be repaid.

That is the heart of the matter: scientists have been warning for decades about the urgency of climate action. Increasingly, civil society and political and business leaders are echoing their calls. The Paris Agreement recognizes the urgency and commits world leaders to doing what it takes to keep warming well below 2°C and, if possible, 1.5°C. If the promise of future negative emissions leads them to grossly underestimate the effort needed in the near term, the results would be disastrous. The decades during which society had allowed itself a slower, softer transition would eventually be revealed as an unaffordable loss of time during which the only effective strategy would have been rapid emission reductions. Saddled still with a fossil fuel-dependent energy infrastructure, society would face a much more abrupt and disruptive transition than the one it had sought to avoid. Having exceeded its available carbon budget, and unable to compensate with negative emissions, society could ultimately be faced with much greater warming than it had prepared for. An inadequate response to the climate crisis, based on the illusion that BECCS or other measures can be used to "undo" emissions at a later date, would be woefully irresponsible and dangerous.

Prudence demands that climate change mitigation strategies rely on measures that can be deployed with confidence on a large scale, and that we know we can count on. To the extent that negative emissions options become feasible at significant scales, we can make use of them then – after carefully choosing how and where to deploy them, to avoid any negative social or ecological impacts. But first, we will have done everything in our power to reduce emissions, promptly and aggressively, and to build low-carbon, more sustainable economies.

This is particularly important for policy-makers trying to determine what near- and medium-term climate actions are needed to keep warming below 1.5°C or 2°C. Because the models all take the long view – usually to 2100, if not later – the expectations for the first few decades can vary drastically depending on the expected role of negative emissions in the second half of the century. Any pathway that relies heavily on negative emissions will allow for considerably higher emissions in the next few decades, requiring far less aggressive mitigation efforts. If those negative emissions fail to materialize, or they cannot undo the damage already done, a strategy aimed at keeping warming below 1.5°C or 2°C might easily result in 3°C or more warming. So, policy-makers would be well advised to be sceptical of any "1.5°C" or "2°C" pathway labelled as "likely" to keep warming below "1.5°C" or "2°C" if it relies on negative emission options that themselves do not have a "likely" chance of proving feasible and providing reliably permanent and effective reductions at the needed scale. At this point, the evidence simply does not support reliance on these options to provide permanent, effective emission reductions on the large scale often taken for granted.

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SEI - Headquarters
Stockholm
Sweden
Tel: +46 8 30 80 44
Executive Director: Johan L. Kuylenstierna
info@sei-international.org

Visitors and packages:
Linnégatan 87D
115 23 Stockholm, Sweden
Letters:
Box 24218
104 51 Stockholm, Sweden

SEI - Africa
World Agroforestry Centre
United Nations Avenue, Gigiri
P.O. Box 30677
Nairobi 00100
Kenya
Tel: +254 20 722 4886
Centre Director: Stacey Noel
info-Africa@sei-international.org

SEI - Asia
15th Floor
Witthyakit Building
254 Chulalongkorn University
Chulalongkorn Soi 64
Phyathai Road, Pathumwan
Bangkok 10330
Thailand
Tel: +(66) 2 251 4415
Centre Director: Niall O'Connor
info-Asia@sei-international.org

SEI - Oxford
Florence House
29 Grove Street
Summertown
Oxford, OX2 7JT
UK
Tel: +44 1865 42 6316
Centre Director: Ruth Butterfield
info-Oxford@sei-international.org

SEI - Stockholm
Linnégatan 87D, 115 23 Stockholm
(See HQ, above, for mailing address)
Sweden
Tel: +46 8 30 80 44
Centre Director: Jakob Granit
info-Stockholm@sei-international.org

SEI - Tallinn
Lai str 34
10133 Tallinn
Estonia
Tel: +372 627 6100
Centre Director: Tea Nõmmann
info-Tallinn@sei-international.org

SEI - U.S.
Main Office
11 Curtis Avenue
Somerville, MA 02144
USA
Tel: +1 617 627 3786

Davis Office
400 F Street
Davis, CA 95616
USA
Tel: +1 530 753 3035

Seattle Office
1402 Third Avenue, Suite 900
Seattle, WA 98101
USA
Tel: +1 206 547 4000

Centre Director: Michael Lazarus
info-US@sei-international.org

SEI - York
University of York
Heslington
York, YO10 5DD
UK
Tel: +44 1904 32 2897
Centre Director: Lisa Emberson
info-York@sei-international.org

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