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Land-based negative emissions: risks for climate mitigation and impacts on sustainable development

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Abstract This paper focuses on the risks associated with "negative emissions" technologies (NETs) for drawing carbon dioxide from the atmosphere through photosynthesis and storing it in land-based sinks or underground. Modelled mitigation pathways for 1.5 °C assume NETs that range as high as 1000 Gt CO_2. We argue that this is two to three times greater than the amount of land-based NETs that can be realistically assumed, given critical social objectives and ecological constraints. Embarking on a pathway that assumes unrealistically large amounts of future NETs could lead society to set near-term targets that are too lenient and thus greatly overshoot the carbon budget, without a way to undo the damage. Pathways consistent with 1.5 °C that rely on smaller amounts of NETs, however, could prove viable. This paper presents a framework for assessing the risks associated with negative emissions in the context of equity and sustainable development. To do this, we identify three types of risks in counting on NETs: (1) that NETs will not ultimately prove feasible; (2) that their large-scale deployment involves unacceptable ecological and social impacts; and (3) that NETs prove less effective than hoped, due to irreversible climate impacts, or reversal of stored carbon. We highlight the technical issues that need to be resolved and—more importantly—the value judgements that need to be made, to identify the realistic potential for land-based NETs consistent with social and environmental goals. Given the critical normative issues at stake, these are decisions that should be made within an open, transparent, democratic process. As input, we offer here an indicative assessment of the realistic potential for land-based NETs, based on a precautionary assessment of the risks to their future effectiveness and a provisional assessment of the extent to which they are in conflict with sustainable development goals related to land, food and climate.

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Abbreviations

BECCS	Bioenergy with carbon capture and storage
GHG	Greenhouse gasses
HANPP	Human appropriation of net primary production
HWP	Harvested wood products
IAM	Integrated assessment modelling
NETs	Negative emissions technologies
NPP	Net primary production
SDGs	Sustainable development goals

1 Introduction

The Paris Agreement on climate change (UNFCCC 2015) has thrown the spotlight on very low emissions scenarios, with its call to hold global average temperature increase to “well below” 2 °C, and to “pursue efforts” to limit 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, and the equity implications of doing so. One result of the focus on low emissions scenarios is that “negative emissions technologies” (NETs), referring to the removal of carbon dioxide from the atmosphere, have increasingly appeared—explicitly or implicitly—in analyses and discussions of options for addressing climate change.

There is a wide range of proposed negative emissions options (Williamson 2016). In this paper, we focus on those most commonly included in modelled scenarios for 2 °C and lower pathways, to assess the risks posed by such mitigation options. Proposals for NETs are currently dominated by land-based options, which are increasingly seen as cost-effective and feasible components of climate mitigation strategies. The two options being widely considered are large-scale reforestation and bioenergy in combination with carbon capture and storage (BECCS).[1] 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.

The Paris Agreement states that efforts to achieve the long-term temperature goal must be carried out “on the basis of equity, and in the context of sustainable development and efforts to eradicate poverty” (UNFCCC 2015). This outlines an obligation for climate mitigation action to be in line with the sustainable development agenda, including the right to development. Gupta and Arts (2017) have elaborated on the links between Agenda 2030 and the principle of equity within the Paris Agreement as requiring a “just” approach to climate action—necessitating reduced inequality between states, and international cooperation for sustainable development. Yet, proposals for large-scale reliance on land-based mitigation for negative emissions pose clear and significant risks to sustainable development. At the same time, there is unexplored potential for synergies between climate

[1] Note that soil carbon sequestration is excluded from modelled pathways due to scientific uncertainties, and so we do not include it here as a common NET option.

mitigation in the land sector and the achievement of sustainable development goals (SDGs[2]).

We argue that extending the near-term carbon budget by presupposing the future availability of NETs poses risks that are of a different nature than those posed by conventional mitigation options. Accepting these risks may lock us into much higher levels of future warming than intended, and/or force us to confront considerably higher social and ecological costs. Indeed, taking on such risks may substantially undermine society's overall mitigation efforts.

As part of this special issue on *Achieving 1.5 °C and Climate Justice*, the aim of this paper[3] is to highlight those risks, and to identify—and very roughly quantify—sustainable NETS potential in terms of both the magnitude and the type of land-based mitigation options that could contribute. Section 2 introduces three categories of risks to the future effectiveness of NETs and develops a framework to evaluate these risks in the context of land-based NETs. Section 3 evaluates land-based NETs by identifying mitigation estimates found in the literature and reviews potential impacts on key SDGs reliant on land. It then tentatively suggests an estimated potential for those negative emissions options that pose less risk of conflicts with sustainable development objectives. Section 4 discusses the implications of these findings for the objective of limiting warming to below 1.5 °C in the light of the Paris outcome on a global mitigation goal. Section 5 concludes.

2 Risks to achieving land-based negative emissions

This section identifies three sequential levels of risks posed to the future effectiveness of NETs generally and uses these to examine land-based NETs specifically.

2.1 Risk evaluation framework

All mitigation options come with risks that they might be less effective than expected. As global society seeks to reduce emissions, it will need to assess the effectiveness of its mitigation efforts and their adverse impacts, and continually adapt strategies accordingly.

Negative emissions 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 in the long run, even after having greatly exceeded it in prior decades.

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, allowing societies to avoid near-term mitigation costs by relying on 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

[2] The United Nations SDGs are explained here: http://www.un.org/sustainabledevelopment/sustainable-development-goals/.

[3] This paper is based on research originally presented in a working paper, available here: https://www.sei-international.org/mediamanager/documents/Publications/Climate/SEI-WP-2016-08-Negative-emissions.pdf.

through the lens of IAM [integrated assessment modelling] appears easier and less expensive," a concern echoed in the recent literature (Anderson and Peters 2016; Williamson 2016).

In the real world, this "easier and less expensive" strategy poses fundamental risks to the realization of low emissions pathways, due to uncertainties about whether society will ultimately be able to realize the benefits of NETs when they are needed, as well as fundamental risks to development objectives, due to potentially unacceptable social and ecological impacts of negative emissions. We highlight three sequential risks, shown in Fig. 1.

First, the measures on which negative emissions strategies tend to rely most heavily are as yet unproven. What happens if the necessary negative emissions measures ultimately prove technologically infeasible, or cannot be deployed at the necessary scale because of fundamental biophysical constraints? (Type 1 risk in Fig. 1).

Second, even if the necessary negative emissions options are technically feasible, the ecological and social costs may be unacceptably high, preventing the realization of other development goals (Type 2 risk in Fig. 1). Land-based negative emissions options, insofar as they rely on the relatively inefficient processes of biological carbon fixation via photosynthesis, are inherently land intensive. There is 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 prove feasible if development and NET-reliant climate trajectories can be well aligned, but there is no assurance of this. It would require further research to understand whether and how synergies can be reaped and trade-offs avoided, and careful planning and governance to ensure effective implementation at large scales across diverse contexts.

Third, even if negative emissions options prove feasible and can be undertaken at large scale without adverse ecological and social consequences, the risk remains that they will prove less effective than expected at reducing climate impacts (Type 3 risk in Fig. 1). In the case of land-based NETs, the risk of reversal is a distinct possibility: carbon sequestered in land is vulnerable to release either through human action (e.g. land clearing) or natural forces (e.g. drought, fire and pests). Irreversible climatic changes could be locked in during the period of concentration overshoot before emissions are brought back down. Impacts that could be wholly or partially irreversible include species extinction, coral reef death, and loss of sea or land ice, some of which themselves lead to positive feedbacks or tipping points that current carbon cycle models do not currently take into account.

Considering these risks, it is critical to assess carefully any strategy that relies on negative emissions. 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 cannot be considered an equitable and effective approach to climate mitigation. 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. 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."

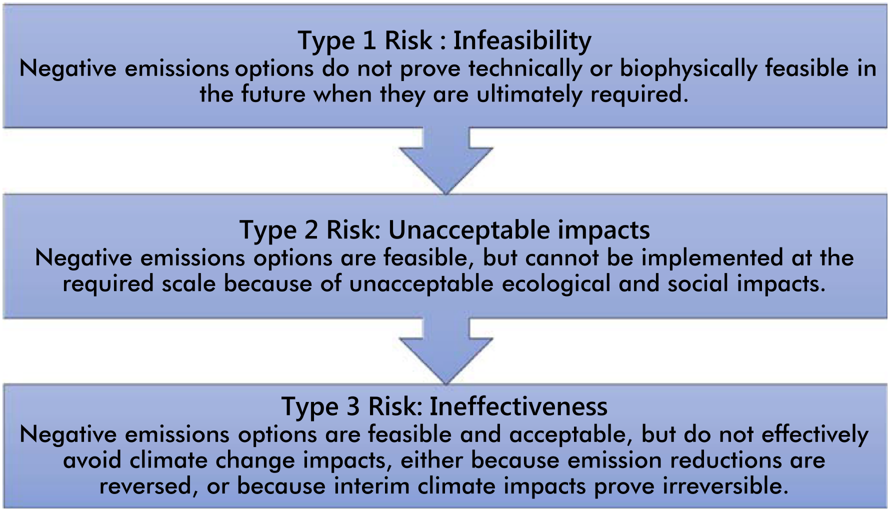

Fig. 1 Three types of risks posed by negative emissions measures

2.2 Applying risk evaluation framework to land-based negative emissions options

This section applies the risk evaluation framework outlined above to specific land-based options for NETs: forest ecosystem restoration; reforestation; and BECCs. We use this evaluation framework to organize a set of questions to comprehensively evaluate risks to successful deployment of land-based NETs (as summarised in Table 1).

Table 1 Risks to successful deployment of land-based NETs

Risks to deployment of land-based NETs		
Technical and biophysical infeasibility	Unacceptable social and ecological impacts	Ineffectiveness
Technological problems and constraints could prevent full-scale BECCS operation	Demand for land could compete with food production and security	Land-based carbon sinks may be prone to reversal, negating mitigation benefits
Sink saturation may limit sequestration potential of NETs NPP may limit expansion of crop production	Demand for land (exacerbated by lack of clear land rights) could cause dispossession of local communities and livelihoods	Temperature overshoot may lead to irreversible impacts, including on food production, and biodiversity, threatening adaptive capacity
Expected yield increases may not be achieved, particularly in the light of climate change	Demand for land could drive loss of natural ecosystems, weakening resilience and adaptive capacity, and result in conversion of forests, wilderness areas and biodiversity Replacing natural ecosystems with monocultures causes loss of biodiversity Increased inputs for energy crops and forests may cause land and water pollution	Temperature overshoot may cross tipping points preventing further temperature reduction

2.2.1 Risk type 1: Biophysical and technological feasibility

Land-based negative emissions options are limited by fundamental biophysical constraints. Sink saturation sets an upper limit on the total cumulative volume of carbon that can feasibly be removed from the atmosphere and stored in the biosphere,[4] and net primary production (NPP) from plant growth sets a limit on the feasible rate of removal of carbon from the atmosphere. The amount of carbon that can be sequestered in the terrestrial biosphere is finite—an assessment of past land-use change indicates an upper theoretical limit to cumulative terrestrial sequestration of approximately 187 GtC before ecosystem sinks would be saturated (equal to total terrestrial carbon loss though past land-use change) (Canadell and Schulze 2014; Mackey et al. 2013). The practical limit is lower, however, because current land uses, including settlements and agriculture, preclude restoring carbon stocks to their previous levels.

Uncertainties around technological feasibility apply mainly to BECCS, which is also most heavily relied on in mitigation scenarios for negative emissions,[5] even though BECCS plants have not been built and tested at scale, and deployment of CCS technology lags substantially behind targets consistent with typical 2 °C mitigation scenarios (Peters et al. 2017). Challenges are also posed by the logistics associated with the long-term reliable supply of biomass feedstock to large-scale industrial facilities, integration of disparate technological systems, the establishment of sufficient and spatially appropriate CCS capture, pipeline, storage infrastructure and reservoir capacity, and ensuring that full life-cycle emissions are indeed net negative (IPCC 2014).

2.2.2 Risk type 2: Unacceptable social and ecological impacts

Land-based negative emissions 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 3000 million hectares (Mha) (IPCC 2014). The upper end of this range is equal to twice the world's currently cultivated land—even though competition for productive land is already a global concern (Nilsson 2012; Searchinger and Heimlich 2015). Below, we consider risks related to social and ecological impacts in turn.

Social impacts generally relate to the expected scale of land use for NETs. Whether for bioenergy crops, reforestation, or other land-based sinks—large-scale land use can compromise food security by reducing the availability of land for food production (IPCC 2014). Food security has long been a global development priority. 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.

Dedicated use of land for negative emissions options could displace natural ecosystems and existing land uses that have an important role for subsistence production and sustainable livelihoods for local communities and smallholder food producers. Local communities and indigenous peoples already face increasing threats of dispossession, with

[4] Net carbon uptake in living biomass peaks at around 50–70 years in mature forests, although studies show mature forests continue to sequester carbon in soil and dead organic matter after living biomass saturates (IPCC 2014).

[5] Note that carbon capture and storage combined with fossil fuels cannot lead to negative emissions. Negative emissions are only possible with CCS combined with bioenergy, providing the carbon sequestered exceeds the net life-cycle carbon released from the land conversion, feedstock growth, harvest, transport, processing and usage of the bioenergy, including any ancillary fossil fuel use (See: Searchinger and Heimlich 2015).

around two-thirds of the world's land area under customary or traditional ownership but only a small fraction of that legally recognized (RRI 2015). The lack of clear legal rights to land is a major driver of illegal logging and forest loss, while also enabling large-scale land transfers and displacement that can exacerbate poverty, food insecurity and conflicts. Securing customary local land rights is recognized as an urgent global priority contributing to protecting livelihoods, food security and climate mitigation (RRI 2014).

Ecological impacts are seen primarily though land degradation and increased resource use from land-based mitigation activities such as extensive monoculture plantations for bioenergy crops. Industrial agriculture is already resulting in stress to land and water resources (Alexandratos and Bruinsma 2012). Large-scale deployment of land-based mitigation measures could add to this stress if energy crops lead to significant consumption of the world's fertilizer supply, impacting waterways and ecosystems, and resulting in significant GHG emissions (Smith and Torn 2013). Human perturbation of the nitrogen cycle already causes significant environmental pollution and would need to be reduced by 75% to keep within planetary boundaries (Rockström et al. 2009). Energy crop production may also lead to altering ecosystem function at scale, diminishing biodiversity and depleting scarce resources (Smith and Torn 2013). Biodiversity is now a critical global issue, with species extinction rates at 100–1000 times natural background rates (Rockström et al. 2009).

The scale of the land requirement for NETs suggests serious social and ecological risks, since land plays a crucial role in achieving multiple global sustainability objectives. Given that a large-scale reliance on land use for mitigation may conflict with these objectives (IPCC 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 (Fuss et al. 2014; Smith and Torn 2013).

2.2.3 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 carbon storage is thus inherently at risk of reversal. For an ecosystem to serve as a reservoir of carbon, it must remain undisturbed over timescales relevant to climate change (Mackey et al. 2013). Negative emissions options that rely on sequestering carbon into the terrestrial biosphere inherently entail a risk that those carbon stocks will be re-released to the atmosphere. 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, potentially undermining the effectiveness of NETs (IPCC 2014; Jones et al. 2016).

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 (IPCC 2014). Conversely, stocks of carbon in fossil deposits are stable on geological timescales and not vulnerable to unintended disturbance, therefore avoiding fossil fuel emissions does not present the same risk of unintentional reversal as is posed by sequestration of carbon into the terrestrial biosphere. While BECCS, which utilizes geological storage, is not subject to the same risk of reversal, very small leakage rates may imply the need for continued sequestration into the future, if BECCS is relied on at significant scale (Shaffer 2010).

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 removals), rather than total cumulative emissions (including removals) (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 (e.g. through albedo effects or methane emissions). The likelihood of irreversible impacts increases with the amount and duration of concentration overshoot (ICCI 2015).

3 Assessing land-based negative emissions options

There is a variety of options for land-based negative emissions, with differing potential impacts on development and climate goals. Ultimately, the extent to which society chooses to rely on these options involves fundamental value judgements. How much risk of overshooting its temperature goal—if the negative emissions options don't work out—is society willing to accept? What risks to other social and ecological objectives is society willing to accept on behalf of those who would suffer the consequences? These questions, clearly, go well beyond mere technical uncertainties. They should be decided within open, transparent, democratic processes, rather than embedded in technocratic modelling exercises.

Here, as an input to such deliberations, we offer an indicative evaluation of three types of land-based negative emissions—forest ecosystem restoration, reforestation, and BECCS, based on the risk evaluation framework. In assessing the potential social and ecological impacts of land-based NETs, we consider three SDGs and key associated targets (Table 2). The SDGs represent a consensus set of global objectives related to development, and it is inevitable that increased demands for land from climate mitigation will affect their

Table 2 Global objectives reliant on land, as defined by selected SDGs

SDG 2: zero hunger	SDG 13: climate action	SDG 15: life on land
End hunger and all forms of malnutrition by 2030	Strengthen resilience and adaptive capacity	Land degradation neutrality by 2020
Double agriculture production and incomes of small-scale food producers by 2030	Integrate climate change measures into national policies and planning	By 2020 halt deforestation, restore degraded forests and substantially increase afforestation and reforestation globally[a]
Ensure sustainable food production systems and resilient agriculture practices that maintain ecosystems	Raise capacity for effective climate change actions in LDCs and SIDs, focusing on marginalized communities	Halt the loss of biodiversity[b] Increase the capacity of local communities to pursue sustainable livelihood opportunities

[a]See also the Bonn Challenge, a global effort to restore 350 Mha of the world's forests by 2030. http://www.bonnchallenge.org

[b]Also the CBD Aichi targets to restore 15% of degraded ecosystems and halve the rate of natural habitat loss by 2020

attainment. We have selected the three SDGs that are most reliant on land (although there are clearly others, e.g.: SDG 6), as a starting point for our indicative assessment of the potential impacts that arise from land-based negative emissions. The potential impacts of climate actions on SDGs is a key area for further research, which could build on existing work to explore interactions between SDGs (Nilsson 2017).

We evaluate each NET option as follows: first, we report the proposed or assumed mitigation potential found in mitigation scenarios. We then discuss the potential impacts relative to the selected SDGs based on a review of the literature [SDG impacts (positive or negative) are noted in the text and summarized at the end of this section].

Based on this analysis, in Sect. 4 we provide an indicative estimate of what might be considered a "sustainable" mitigation potential for each NET, considering SDG constraints. Ultimately, as time passes, technologies develop, and socio-economic trends unfold, society will be able to make better-informed decisions about the risks involved and the plausible scale of sustainable negative emissions. In the meantime, presupposing the future availability of much greater quantities is extremely risky.

We begin by assessing the mitigation potential of avoiding emissions from deforestation and forest degradation. Although this does not constitute a form of negative emissions, we examine avoided emissions in the land sector first because these emissions are driven largely by demand for agricultural land (Lawson et al. 2014) and hence could be exacerbated by land-based NETs, and second, because enhancing land carbon stocks is dependent on society's success at reversing forest loss.

3.1 Avoided emissions in the land sector

Just under a quarter of global emissions are from the land sector, with around half of this (approximately 10% of global emissions) coming from land-use change, largely consisting of forest loss in the tropics (IPCC 2014). Reducing emissions from land-use change thus represents significant potential for permanent mitigation benefits. Net global emissions from forest loss (deforestation and degradation) currently average $\approx$ 1.1 GtC/year, although emissions from forest degradation are poorly quantified globally, with recent estimates putting this at almost 70% of overall carbon losses from tropical forests (Baccini et al. 2017). Drained peatlands (organic soils) also cause significant emissions, bringing the total net emissions from land-use change (excluding agricultural soils) to $\approx$ 1.4 GtC/year (Houghton 2013). This represents the maximum mitigation potential from avoiding emissions from land-use change.

Global efforts to reduce and halt forest loss have scaled up significantly in the past decade, largely due to the recognition of the significant climate mitigation potential. While progress has so far been slow, failure to achieve the variety of ambitious targets to halt and reverse forest loss would make the 1.5 °C target more challenging, if not impossible, to meet. Reducing forest loss brings significant benefits aside from carbon. Reducing forest degradation has disproportionately large benefits for biodiversity (Barlow et al. 2016) (SDG 15); intact forests increase resilience to climate change and in many cases increase adaptive and sustainable livelihood capacities for marginalized communities (SDG 13 and 15); and intact forests contribute to sustainable food production through resilient ecosystems (SDG 2). Reducing forest loss also contributes to improved livelihoods for forest communities: research shows that legally recognized tenure rights and local participation in decision-making lead to reduced deforestation and lower CO_2 emissions when compared with forest areas with unclear tenure rights (SDG 2, 13 and 15) (Nolte et al. 2013; Stevens et al. 2014).

3.2 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 (Baccini et al. 2017; Mackey 2008).

3.2.1 Unconstrained mitigation potential

Houghton (2013) suggests that forest ecosystem restoration, by protecting and enabling the regrowth of forests, could remove as much as 1–3 GtC/year from the atmosphere, if all harvest of secondary forests and swidden agriculture practices were ended and these lands permitted to regrow.[6] However, because degraded forests vary in the degree of fragmentation and the extent to which biodiversity has been lost, the potential for restoration will vary. Some areas can recover unaided if protected from further disturbance. This is likelier if forest loss is recent, residual trees and soil seed stores remain, and intact forests are still present in the 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 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 intact forests.

3.2.2 Impacts on SDGs

Restoration on the scale suggested by Houghton would increase competition over the remaining land, potentially undermining several development goals. Restricting swidden agriculture could have significant impacts on local and subsistence livelihoods, threatening customary access and ownership rights to land (SDG 2 and 15). Moreover, research suggests that shifting cultivation can often be climate neutral rather than emissive, suggesting that climate mitigation efforts targeting these practices might be misdirected (while undermining SDG 15) (Ziegler et al. 2012). Restoring and maintaining intact forest landscapes boost biodiversity, which in turn strengthen the resilience of forest ecosystems to external stressors, including climate change (Thompson et al. 2014), thereby decreasing the risk of reversal of forest carbon stocks (SDG 13 and 15). Yet, there are (limited) mitigation benefits to sustainable harvest of secondary forests—for example, substitution of timber for materials associated with high GHG emissions, such as steel and cement, and storage of carbon in (long-lived) harvested wood products (SDG 15) (Gustavsson and Sathre 2011; Pan et al. 2011). Hence, existing land uses compete with and constrain the potential of ecosystem restoration, while trade-offs exist between different mitigation options.

[6] This carbon sink potential is in addition to "other natural processes on land (that) remove approximately 25% of the carbon emitted each year" (Houghton et al. 2015, p. 1023).

3.2.3 Precautionary mitigation potential

Given these considerations, we argue that a precautionary assumption would be the lower end of Houghton's range, of 1.5 GtC/year in estimating the potential for future carbon sequestration from ecosystem restoration. Achieving this rate of carbon sequestration would still be extremely challenging, requiring a switch from a net carbon source of $\approx$ 1 GtC/year from forests to a net sink of at least the same magnitude. This would require both reversing forest loss and facilitating the effective long-term, stable regeneration of degraded forests.

3.3 Reforestation

Reforestation refers to the re-establishment through human intervention (planting, seeding, etc.) of forest on lands that were forests at some time in the past.[7] 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 and a greater elapsed time since forest clearance. 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 per hectare (Strassburg et al. 2010). As a result, the total carbon storage per hectare is lower in new forests than in restored degraded forests over timescales relevant to climate mitigation (Mackey 2008).

3.3.1 Unconstrained mitigation potential

Houghton (2013) suggests that reforesting an area of 500 Mha would provide a global sink of $\approx$ 1 GtC/year, which is towards the upper end of the range reported by the IPCC (2014). This land estimate is consistent with mapping of forest landscape restoration possibilities, which identifies 500 Mha of degraded forests and deforested lands that could in principle be restored to closed forests (Laestadius et al. 2011), although there is significant uncertainty around these estimates. In particular, the spatial extent of degraded forests is not well-captured by remote sensing techniques (Baccini et al. 2017), and thus, the degree to which estimates for reforestation potential overlap with estimates for restoring degraded forest ecosystems is difficult to ascertain.

A further 1500 Mha is estimated to be available for 'mosaic' restoration (Laestadius et al. 2011). Mosaic landscapes are defined as accommodating multiple land uses, such as agriculture, protected reserves, managed plantations and agroforestry systems. While the benefits across a range of SDGs from mosaic restoration are large, the climate mitigation benefits are uncertain and difficult to quantify (Lal 2004; Meadowcroft 2013); hence, we do not assume here the future availability of large amounts of atmospheric carbon removal from these activities.

[7] Reforestation here refers to reforesting historically deforested lands, while afforestation refers to establishing forests on landscapes that do not naturally support forests, likely requiring even greater nutrient input. It is worth noting that, while there are many different definitions of forests at international and national levels (i.e.: FAO, UNFCCC), "there is no internationally agreed definition of what a forest is, and the understanding of this term is highly context-specific" (CBD 2012, p. 5).

3.3.2 Impacts on SDGs

The ecological and social implications of closed canopy reforestation on such a large scale would depend on whether the potential impacts are proactively addressed as these 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. Biodiversity potential varies enormously depending on methods of reforestation, with faster growing species requiring significant nutrient and water inputs that can cause ecological damage and alter local hydrological patterns (undermining SDG 15) (Lamb et al. 2005; Smith and Torn 2013). Reforestation of mixed native species and in carefully chosen sites, on the other hand, could increase biodiversity and restore waterways, reducing run-off and erosion (SDG 2, 15) (Lamb et al. 2005). In addition, the climate effects of reforestation show significant geographical variation; at high latitudes, warming due to reduced albedo can potentially outweigh the benefits of carbon sequestration (SDG 13) (Arora and Montenegro 2011).

3.3.3 Precautionary mitigation potential

In the light of these considerations, it may be reasonable to assume that realistic reforestation extent may be well below the upper bound of the 500 Mha that Laestadius et al. (2011) estimated to be available for closed canopy reforestation through a global ecological mapping exercise that neglects these considerations. It is also important to note that reforestation efforts are driven solely not only by the desire to maximize carbon sequestration, but also by broader social and ecological benefits that can be generated. Localized decision-making can promote multiple objectives and reduce the risk of adverse impacts. The benefits of community-managed and -owned forests are 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 (contributing to SDG 2, 13, 15) (RRI 2014; Stevens et al. 2014; Persha et al. 2011). We take the “Bonn Challenge”, a high-level political goal of restoring 350 Mha of degraded and deforested lands by 2030 (consistent with SDG 15), as a more realistic multi-objective target reflecting the relevant ecological constraints.

3.4 Bioenergy with CCS (BECCS)

This section reviews the potential for negative emissions from bioenergy combined with carbon capture and storage (BECCS). As outlined in Sect. 2.2, one constraint on BECCS is the uncertainty of the application of CCS technologies to biomass. This section focuses on a second limiting factor—the availability of biomass supply.

3.4.1 Unconstrained mitigation potential

A key determinant of bioenergy potential is the maximum biospheric capacity of net primary production (NPP) of plant growth. Humans currently harvest just under a quarter of maximum NPP for food, feed, fibre and energy, with the remainder contributing to natural, protected, and cultivated areas (Haberl et al. 2013). NPP therefore limits the production of primary biomass feedstock supply. Based on the remaining NPP in land ecosystems, as well as bioenergy from residues and wastes, an upper biophysical limit in

primary bioenergy supply has been estimated at a similar amount as current human harvest: ≈ 250 EJ/year (Haberl et al. 2013; Kolby Smith et al. 2012). Note this is not an estimate of what could be considered sustainable primary bioenergy potential. Rather, it provides an upper biophysical limit on potential agricultural output (Haberl et al. 2013). In practice, reaching 250 EJ/year in bioenergy output would require more than a doubling of current human biomass harvest (all crops, feedstock and other materials) (Haberl et al. 2013).

Nevertheless, while some estimates of bioenergy potential in mitigation scenarios are well within this upper limit, many are close to or exceed it, with some prominent studies estimating as much as double this amount, and outliers in excess of 500 EJ/year (IPCC 2014). This sanguine outlook on future bioenergy availability has been adopted by many widely cited integrated assessments (as noted by Wiltshire and Davies-Barnard 2015). Creutzig et al. (2015) noted that beyond 100 EJ/year by 2050, there is decreasing agreement on the *technical* potential of bioenergy. The *sustainable* potential can of course be assumed to be much lower.

These estimates for bioenergy are typically based on two sources of biomass: energy crops (including woody biomass) requiring dedicated use of land, and bioenergy sourced from residues and wastes. Bioenergy from residues and wastes includes the utilization of forest and agricultural residues, and organic wastes. Primary bioenergy production is currently ≈ 55 EJ/year, mostly from residues and traditional biomass uses (Erb et al. 2012; Haberl et al. 2013).

3.4.2 Impacts on SDGs

Additional bioenergy production at or above current human harvest of biomass suggests the potential for serious social, economic and ecological constraints on bioenergy feedstock production at this scale (undermining SDG 2, 15) (Haberl et al. 2013; Searchinger and Heimlich 2015). Bioenergy production from forest harvest has been shown to lead to increased emissions (Holtsmark 2015), as could bioenergy crops that require high fertilizer input, or that lead to conversion of wilderness areas (directly or indirectly) (Kolby Smith et al. 2012). Bioenergy has been identified as an emergent global risk to food security and ecosystems due to indirect land-use change (undermining SDG 15). In worst cases, emissions from land-use change could exceed the potential climate mitigation value of BECCS on relevant timescales (undermining SDG 13) (Wiltshire and Davies-Barnard 2015).

Dedicated crops for bioenergy would be likely to increase demand for key resources such as fertilizer and freshwater irrigation, resulting in increased GHG emissions, nutrient loading, watershed stress and environmental degradation (Erb et al. 2012; Smith and Torn 2013). 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 (undermining SDG 2) (Hochman et al. 2014). Deriving bioenergy from wastes could limit land demand, but the availability of residues and wastes for bioenergy is limited by competing uses. 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, wastes and residues can be key to meeting other development goals, representing a trade-off with bioenergy feedstock potentials.

Land availability problems often do not arise in models because bioenergy crops are assumed to utilize degraded land, although there is large uncertainty around the scale, spatial location and existing uses of degraded land (Gibbs and Salmon 2015). Models also

circumvent land availability constraints through 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 future yield increases will be needed to help meet growing demand for food (SDG 2) (Alexandratos and Bruinsma 2012; Searchinger and Heimlich 2015).

However, potential demand-side measures exist for reducing the agricultural land requirements, such as diet change, by reducing demand for land-intensive commodities (SDG 15) (Nilsson et al. 2012). Although in recent decades, diets have shifted towards more land-intensive meat-rich diets as incomes have risen, diets could shift in the future in a manner that frees up agricultural land, with the potential to reduce net GHG emissions from agriculture and land use by about 45% due to decreased reliance on livestock (SDG 13) (Bajželj et al. 2014).

3.4.3 Precautionary mitigation potential

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. 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 to expect land to be available for future climate mitigation. Deploying bioenergy on any scale, even 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). Climate change itself also introduces further uncertainty into bioenergy potential (IPCC 2014).

A precautionary perspective in the face of land availability constraints and the possible negative impacts of large-scale expansion of bioenergy production on food security and ecosystems, would suggest that it is highly risky to rely on the future availability of significant amounts of land for producing biomass feedstock for BECCS. In a carbon-constrained world, the effective use of wastes and residues should be prioritized, which would enable bioenergy at fairly limited scales, and possibly 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 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. As noted by Haberl et al. (2013), “Identifying sustainable levels of bioenergy… remains a huge and pressing scientific challenge.” Until then, it is risky to base current mitigation strategies on the presumed future availability of large-scale bioenergy with CCS (Table 3).

Table 3 Synergies and trade-offs between land-based NETs and SDGs

NETs	SDGs		
	SDG 2: zero hunger	SDG 13: climate action	SDG 15: life on land
Avoided deforestation	+ Resilient ecosystems, sustainable food production for local communities	+ Avoided emissions + Increased resilience + Secure tenure, greater forest protection	+ Disproportionally large benefits to biodiversity + Sustainable livelihoods
Reforestation	+ Careful restoration can reduce environmental degradation, improve ecosystem resilience and food production − Quick-growing species can increase nutrient input	+ Significant mitigation potential from closed canopy reforestation − Reduced albedo effect at high latitudes	± Biodiversity impacts vary dependent on method of reforestation + Community-managed reforestation has greater livelihood, climate and biodiversity benefits
Forest ecosystem restoration	− Livelihoods threatened if subsistence ag. targeted + Resilient ecosystems, sustainable food production for local communities	+ Greater carbon density, increased mitigation potential + Increased resilience − Climate benefits reduced if (traditional) subsistence ag. targeted, or HWP[a] overly restricted	+ Correlation between carbon density and biodiversity − Local access threatened if subsistence ag. targeted − Constrained by existing land uses
BECCS	− Dedicated use of land for bioenergy competes with land for food production − Use of residues for bioenergy can reduce soil carbon, lowering productivity	± Carbon neutral bioenergy (hence negative emissions from BECCS), only if sequestered carbon exceeds net emissions (including initial and indirect land-use change emissions)	- HANPP[b] for bioenergy can compete with food, biodiversity and subsistence livelihoods − Large-scale bioenergy increases input demand, resulting in environmental degradation and water stress

[a]Harvested wood products

[b]Human appropriation of net primary production

4 Magnitude of "sustainable NETS"

Based on the analysis of various land-based options for NETs in Sect. 3, Table 4 presents a set of options for achieving 370–480 Gt CO_2 in carbon removal that may not exceed biophysical constraints, and could conceivably—though by no means guaranteed—be implemented in a manner that achieves the required amount of negative emissions without jeopardizing other critical land uses and sustainable development objectives. Achieving this level of NETs 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 if not implemented with strong governance, legal and human rights oversights.

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 emissions mitigation measures, we draw upon analysis by Rogelj et al. (2015), which shows that the range of expected negative

Table 4 Constrained negative emissions potential

Negative emissions category		Cumulative sequestration (21st c.)
Reforestation	This case assumes optimistic levels of reforestation consistent with meeting the Bonn Challenge to reforest 350 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. Over a period of 60 years until saturation, this would yield cumulative negative emissions of 40 Gt C	150 Gt CO_2
Forest 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 cumulative negative emissions of 60 to 90 Gt C	220–330 Gt CO_2
Bioenergy with CCS	Negative emissions from BECCS are deferred until uncertainties are resolved, especially regarding technological feasibility and land availability, and the need for effective institutions to protect socio-economic and ecological objectives such as food and water security. This is on the basis that the full technological system is not yet proven, and that BECCS would be able to contribute at significant scale only if undertaken in a way that does not undermine other social and ecological goals	Deferred
Total		370–480 Gt CO_2

Nb: Units in the middle column are given in GtC, as this unit (or the equivalent PgC) is most commonly used in literature related to terrestrial carbon fluxes. Units in the cumulative mitigation potential column are given in Gt CO_2, as this more readily relates to policy discussions. The conversion is given by 1 GtC = 3.67 Gt CO_2

emissions from published 1.5 °C scenarios is between 450 and 1000 Gt CO_2, and for the 2 °C scenarios, between 0 and 900 Gt CO_2, cumulative over the course of this century. In these scenarios, negative emissions measures are adopted widely in the second half of the century to reverse a large fraction of cumulative future fossil fuel emissions (up to 60% in the 2 °C scenarios, and as much as 100% in the 1.5 °C scenarios). 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.

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. In fact, a total of 480 Gt CO_2 would be sufficient to meet the negative emissions needs of more than one-third of the modelled 1.5 °C scenarios, an amount which could potentially be met with more sustainable options for negative emissions.

5 Conclusion

The Paris Agreement recognizes the urgency of responding to climate change and commits nations to doing what it takes to keep warming well below 2 °C and aiming for 1.5 °C. If the promise of future negative emissions leads policy makers to grossly underestimate the effort needed in the near term to meet these targets, 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 an unfounded assumption that BECCS or other measures can be used to "undo" emissions at a later date, would be woefully irresponsible and dangerous. Such a strategy could leave us—and future generations—stranded with an insufficiently transformed energy economy and a carbon debt that cannot be repaid. Ultimately, to ensure equitable climate mitigation pathways, policy choices must be governed by the objectives of sustainable development, which in the land sector provides the opportunity for important synergies between land, food and climate goals. These choices are fundamentally value-laden, relating as they do to our willingness to accept risks and how we choose to distribute the consequences among populations and generations. These profound choices fall in the domain of public discourse and political processes, rather than technocratic exercises.

As an input to such deliberations, we provide here a framework for understanding the risks and potential consequences, and an indicative assessment of the potential for negative emissions that may be more consistent with broader sustainability goals. This analysis suggests that measures such as ecosystem restoration and reforestation may possibly be able to achieve the carbon drawdown required for 1.5 °C, if the protection and restoration of carbon-dense and biologically rich natural forests are prioritized as a critical mitigation strategy. In addition to contributing to substantial climate change mitigation, such options contribute to a multitude of sustainability objectives, including preserving ecosystem services such as biodiversity and watershed protection, and development goals of food security, human rights and local livelihoods. Indeed, the second half of the Paris Agreement mitigation goal states that the "balance" must be achieved "in the context of sustainable development and efforts to eradicate poverty" (Article 4.2). Achieving these dual outcomes of climate and development goals will require political choices that maximize synergies between climate mitigation and broader development objectives.

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