Managing Land-based CDR: BECCS, Forests and Carbon Sequestration

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Abstract

Decisions about when, where and how to achieve widespread carbon dioxide removal (CDR) are urgently required. Delays in developing the requisite policy and regulatory frameworks increase the risks of overshooting climate goals and will necessitate much larger negative emissions initiatives in the future. Yet the deployment of bioenergy with carbon capture and storage (BECCS) at the scales assumed under most Paris-Agreement-compliant emission-reduction pathways is unlikely. More generally, the sustainability of large-scale BECCS is questionable given its extensive land, water, and energy requirements for feedstocks and the competing necessity of these resources for the provision of ecosystem services and attainment of multiple Sustainable Development Goals. BECCS on a more limited scale, however, could have more benign impacts if feedstocks were restricted to wastes and residues. There is also widespread recognition that extensive afforestation, reforestation and forest restoration have critical roles in reducing greenhouse gas emissions to net zero. To date there has been little focus on the optimum strategies for integrating land-based CDR approaches – under which circumstances forest areas are best left undisturbed, managed for conservation, and/or managed for harvested wood products, and how these options affect the availability of residual feedstocks for BECCS. This paper reviews this debate and suggests appropriate policy measures.

Policy Implications

- Abandon the assumption, common in integrated assessment models, that BECCS is the pre-eminent carbon removal solution, and analyse it alongside all other negative emissions technologies (NETs), on the basis of full lifecycle carbon balances (including dropping the assumption that biomass feedstock is inherently carbon-neutral), as well as other ecosystem and sustainability co-benefits and trade-offs.
- Take urgent action to scale up the development and deployment of sustainable NETs.
- Accelerate conventional abatement action as rapidly as possible, since there are too many drawbacks and uncertainties associated with BECCS and other NETs to place excessive reliance on them – though carbon removal solutions will undoubtedly be needed.

Carbon dioxide removal (CDR) requirements

Achieving the temperature targets of the UNFCCC Paris Agreement through emissions abatement alone is currently looking increasingly infeasible as global emissions continue to rise. Accordingly, this necessitates a step change in carbon dioxide removal (CDR) to sequester substantial volumes of existing atmospheric greenhouse gases and to compensate for future residual emissions from sectors where mitigation is more expensive, such as aviation and agriculture. CDR is also intrinsically required to meet the Paris Agreement target of balancing emissions sources and sinks (UNFCCC, 2015). This much is well established; virtually all integrated assessment models (IAMs) evaluated by the Intergovernmental Panel on Climate Change (IPCC) in its Fifth Assessment Report (AR5) (IPCC, 2014) and subsequent special reports on global warming of 1.5°C (SR1.5) (IPCC, 2018a) and climate change and land (SRCCL) (IPCC, 2019a) are reliant on CDR to achieve these targets. The AR5 synthesis report concluded that: ‘Many models could not limit *likely* warming to below 2°C if bioenergy, CCS, and their combination (BECCS) are limited (*high confidence*)’ (IPCC, 2014, p. 97). However, the volumes of carbon capture required under different scenarios vary widely and are dependent on two major related factors: the speed and successes, or sluggishness and failures, of economy-wide emissions abatement efforts; and how far greenhouse gases rise beyond target-level atmospheric concentrations before subsequently being brought back down through CDR.

Although ‘overshoot and retract’ approaches *may* ultimately achieve long-run temperature goals, they have significant consequences that render them highly undesirable (Obersteiner et al., 2018). Principal among these is the increased risk of exceeding climate tipping points, whereby abrupt changes to earth system processes are triggered, resulting in a cascade of positive feedbacks that lead to massive increases in emissions, changes in atmospheric circulation patterns and accelerated heating. Second, even without exceeding such tipping points, the volume of CDR ultimately required would be far greater compared to no-overshoot scenarios, to compensate for the greater volume of emissions generated in the intervening period. The land,

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water, and ecological consequences of deployment on this scale would have planetary-scale impacts, including for other sectors reliant on these resources. Third, deferring action is intergenerationally inequitable, burdening late-century generations with the huge costs of compensating for current generations' inert responses to the CDR and abatement challenges. Fourth, even if technically achievable, meeting the financial costs of massive late-century CDR may be implausible: the public costs of subsidising CDR alongside carbon taxes on emissions could conceivably exceed fiscal capacity, reaching up to a third of general government expenditure in advanced economies (Bednar et al., 2019). Consequently, although the majority of feasible 1.5 and 2°C emissions and removals pathways in IAMs are overshoot pathways with high discount rates, policy-makers need to prioritise pathways that avoid, or severely limit, overshooting the carbon budget even if 'overshoot and retract' is a scenario which can be modelled.

SR1.5 (IPCC, 2018a) sets out four illustrative model pathways to limit warming to 1.5°C, three of which involve no or limited overshooting of cumulative emissions targets (Figure 1). All four pathways include contributions from various CDR approaches, predominantly from bioenergy with carbon capture and storage (BECCS) but also from changes to agriculture, forestry and other land use patterns (mainly afforestation and reforestation):

- P1 focuses on reducing energy demand and has no contribution from BECCS.
- P2 has a broad focus on sustainability in which BECCS cumulatively captures 151 $GtCO_2$ by 2100.
- P3 is a middle-of-the-road scenario, largely following historical patterns, in which BECCS is required to cumulatively capture 414 $GtCO_2$ by 2100.
- P4 is an overshooting resource- and energy-intensive scenario in which emissions reductions are mainly achieved through BECCS, which is responsible for cumulatively capturing 1,191 $GtCO_2$ by 2100.

In all 1.5°C scenarios, negative emission generation must begin in the first half of this century with global CO_2 emissions reduced to net zero by around 2050–2060 (comparable 2°C pathways achieve net zero by around 2070) (IPCC, 2018b). The urgency and scale of the requirement under each pathway are dependent on the extent of emissions generated and abated elsewhere in the economy.

Assumed CDR modalities and consequences

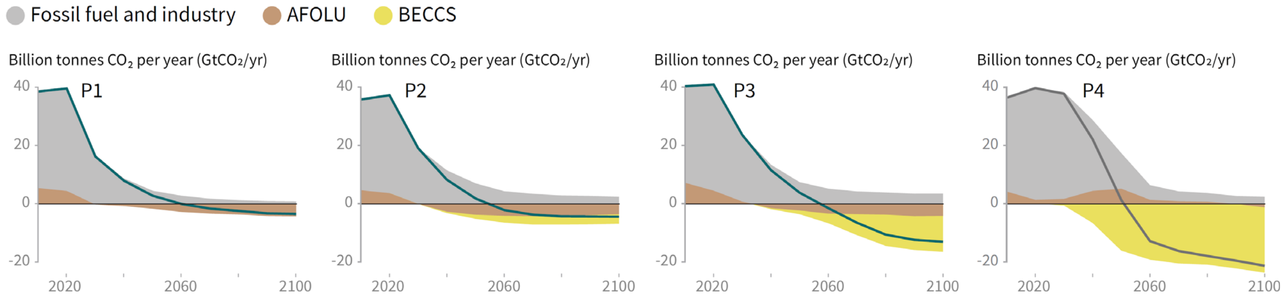
The prominence of BECCS in the IAMs and IPCC assessments is not, however, a prescriptive judgement about the merits of BECCS relative to other negative emissions options; rather, it simply reflects the need for CDR at these scales to meet the Paris Agreement temperature targets. Although other potential negative emissions technologies (NETs) – such as direct air carbon capture and storage (DACCS) and enhanced weathering – are increasingly reviewed in the literature and have been considered in SR1.5 and SRCCL, comprehensive quantitative assessments of their potentials in IAMs is far less common. The reality is that BECCS has assumed an almost default role in many of these models because it is relatively straightforward to quantify at various carbon prices compared with other (even) more nascent NETs (Smith and Porter, 2018). As a result of IAMs assuming perfect knowledge of future technologies and of their cost-optimising design (with carbon prices driven by either the temperature target or challenges hindering mitigation), and owing to the fact that the discount rates employed give less weight to future expenditure than present-day costs, the assumed costs of BECCS in later decades are lower than those of deep abatement actions today. The consequence is that delayed action appears favourable (Anderson and Peters, 2016; Bednar, Obersteiner and Wagner, 2019). This is at odds with the risk-minimising imperative of prioritising immediate action and the rising costs of responding to growing climatic hazards. It also fails to account for the increasing public costs of subsidising delayed carbon removal that, as economic growth is projected below the discount rate, are bound to increase as a share of expenditure, even under constant levels of negative emissions (Bednar et al., 2019). Thus, there is a dangerously unrealistic impression created that BECCS may be more suited to large-scale deployment than is borne out by closer scrutiny.

What, then, is BECCS; how mature is it; to what extent can it remove carbon from the atmosphere and satisfy energy demand; and what are the consequences of doing so at scale?

What is BECCS?

BECCS entails burning CO_2-absorbing biomass, capturing the emissions and storing them in long-term underground

Figure 1. Breakdown of contributions to global net CO_2 emissions in four illustrative model pathways (IPCC, 2018b).



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reservoirs. In principle, BECCS can utilise four main categories of bioenergy feedstock – wood, energy crops, agricultural residues, and organic wastes – and several different carbon capture technologies, most commonly capturing carbon dioxide emitted from the combustion of biomass for heat and power, which is then transported for long-term storage in geological sites such as saline aquifers or abandoned oil wells, just as with conventional carbon capture and storage (CCS) projects.

Wood feedstocks come either from whole trees harvested specifically for bioenergy, or from wastes and residues, such as small branches, bark and thinnings left over from forestry operations, and residues from wood processing industries such as sawmills and paper and pulp mills. Energy crops grown specifically for energy production include fast-growing trees (such as willow, poplar, and eucalyptus) and herbaceous crops such as miscanthus ('elephant grass'), switchgrass (*Panicum virgatum*) or energy cane (genetically modified sugarcane). Agricultural residues include materials left in the field after a crop has been harvested (field residues), such as stalks, stubble or leaves, and left-over materials from the processing of crops for food or other products (process residues), including husks, seeds, bagasse, molasses and roots. Organic wastes used as feedstocks include wood waste, the organic fraction of municipal solid waste, livestock manures, sewage sludge, tallow, and used cooking oil.

There is currently an extensive industry using modern technologies to generate energy (heat and power, and liquid fuels) from biomass without CCS. Both heat and power and liquid fuel production are amenable to the addition of CCS, though the capture potentials are generally higher for heat and power. Worldwide, the main biomass feedstock for heat and power is currently wood, though municipal wastes, agricultural residues and palm oil and other vegetable oils are also used in some locations. Wood is more energy-dense than most other feedstocks, and tends to be easier to collect, process, store and transport, often as wood chips or pellets. The main feedstocks for liquid biofuels – which are usually used for transport, though sometimes for heat and power – are oil crops such as oil palm, soybean, rapeseed and sunflower (for biodiesel) and starchy crops such as wheat, maize, sugarbeet and sugarcane (for bioethanol). A range of other biofuel feedstocks, including wastes, agricultural residues and algae (a high-energy-density feedstock with the potential to significantly reduce land and water constraints), are under development or beginning to emerge into commercial production; in principle, all could be deployed in BECCS systems. IAMs typically assume the widespread use of second-generation energy crops (i.e. non-food crops) to calculate sequestration and energy potentials.

CCS technologies amenable to pairing with bioenergy production are much the same as those beginning to be deployed and under development for conventional fossil fuel plants, and include post-combustion, oxy-combustion (combustion in pure oxygen rather than air), and pre-combustion, or gasification (high-temperature non-combustive reactions between biomass and oxygen and/or steam to produce synthesis gas ('syngas'), which is a combustible fuel). An alternative approach captures carbon dioxide from fermentation processes, such as those used to produce ethanol from crops such as maize, wheat or sugarcane. This has the advantage that it results in a purer stream of carbon dioxide that is then easier to process, though the ethanol produced is likely to be burnt as transport fuel, with those subsequent emissions reducing the overall emissions benefits from the carbon capture.

How mature is BECCS deployment?

Despite being more amenable to quantitative modelling than many other NETs, BECCS remains a fledgling technology, in spite of the fact that each part of the technology has been proven at demonstration and commercial scale. By 2019, only one BECCS project was operating at commercial scale worldwide: the Illinois Industrial CCS facility at Decatur in the US (Consoli, 2019). A few other ethanol plants have been established to capture carbon dioxide, but for use for enhanced oil recovery rather than storage.

This mirrors the lacklustre development of CCS technology deployment more broadly. In 2019, only 18 large-scale CCS facilities were in commercial operation globally (a further five were under construction), capturing 0.04Gt of carbon dioxide a year, with only around a tenth of this entering geological storage (Fajardy et al., 2019); this was an increase from 15 facilities and 0.028Gt of capture three years earlier (Global CCS Institute, n.d.). This falls significantly short of the Paris Agreement-compatible capture rates projected under the International Energy Agency's Energy Technology Perspectives (ETP) scenarios. Under the ETP Reference Technology Scenario, in which CCS expansion is consistent with 2017 growth rates, reflecting a continuing lack of investment incentives, deployment reaches only 1.3 $GtCO_2\ yr^{-1}$ by 2060; under the ETP 2°C scenario total CCS deployment reaches 6.8 $GtCO_2$ (of which 2.7 $GtCO_2$ is BECCS); and under the ETP beyond 2°C scenario, CCS deployment reaches 11.2 $GtCO_2$ by 2060 (of which 4.9 $GtCO_2$ is BECCS) (IEA, 2017). In general, the technology has proved more expensive and less effective than originally expected, and the falling prices of renewable energy technologies, particularly solar photovoltaics (PV) and wind, have undercut the appeal of CCS as a low-carbon option and accelerated the phasing out of coal, reducing demand for one of the sources of fossil fuels for which CCS installation was foreseen. As the IPCC observed in SR1.5, CCS is largely absent from countries' Nationally Determined Contributions under the Paris Agreement, and is generally ranked low in investment priorities (De Coninck et al., 2018). CCS was only identified as a priority in three of the Intended NDCs submitted in the run-up to the 2015 Paris conference, and BECCS was absent from all of them (Fuss et al., 2016).

How effective is BECCS at carbon dioxide removal and energy production?

It is commonly assumed that, in the absence of land-use change (such as converting forests to energy crops),

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biomass energy production is necessarily carbon-neutral, as combustion emissions are balanced by carbon sequestration during the lifetime of the feedstock. If so, it follows that if any proportion of the combustion emissions are captured, then BECCS must result in negative emissions.

But this assumption of default carbon-neutrality is wrong, as it ignores the counterfactual carbon sequestration potential of the vegetation and soil (soils store more than 40 per cent of forest carbon) in the absence of their utilisation for bioenergy supply, even if no land-use change occurs (Brack, 2017; Norton et al, 2019). If trees or crops are harvested specifically for energy, not only is the stored biomass converted into carbon dioxide (which may or may not be captured) but the carbon that would have been absorbed during the remainder of the tree or plant's lifetime is also foregone. If the tree or plant is replanted, only a fraction of the counterfactual sequestration can be realised as the initial rate of absorption is generally slower, particularly for trees: young trees grow faster than mature specimens, but they also absorb much less carbon as they have a smaller photosynthetic surface area (Center for the Study of Carbon Dioxide and Global Change, 2014; Norton et al, 2019; Stephenson, 2014). At the forest scale, however, the rate of carbon uptake does gradually slow as the forest ages and more trees die from disease or pests. It is also true that transferring carbon into geological repositories has the advantage that the storage is more or less permanent, whereas vegetative stores of carbon can rapidly be transformed from carbon sinks to sources if unsustainably felled or lost to wildfires.

Calculations of the impacts of BECCS must also take land-use changes into account, whether these are direct (e.g. conversion of grassland or forest to energy crops) or indirect (e.g. conversion of forest or grasslands to agriculture to compensate for the planting of energy crops on existing agricultural lands). As a result of all of these factors, the 'carbon payback period', that is, the duration of the carbon debt incurred as a result of harvesting (and land-use change if it occurs), may vary from decades to centuries for trees, depending on the species and conditions of regrowth. For fast-growing energy crops, and for forest or agricultural wastes and residues, particularly those that would otherwise be left to decay, the payback periods are much shorter, assuming carbon stores and sequestration potential have not been lost through land use conversions.

Where BECCS is reliant on a regular supply of forest feedstock, this necessitates the extensive planting of trees and regular harvesting and clearing of plantations, releasing stored carbon back into the atmosphere every 10–20 years during the harvesting process. In practice, 'plantations hold little more carbon, on average, than the land cleared to plant them' (Lewis et al., 2019, p. 26), in contrast to natural forests, which continue to sequester carbon for many decades. This implies that stopping deforestation and promoting natural forest restoration, where still possible, are likely to be better options for carbon removal.

For dedicated energy crops, where harvesting has a smaller impact on sequestration rates, the nature of land-use conversion to establish the crop has a much more significant impact on the carbon payback period. If energy crops are planted on lands with high carbon stock (such as converting established forests) then it can take decades to over a century to compensate for the carbon losses from the initial land-use change (Smith et al., 2019). Conversely, establishing energy crops on marginal lands can result in much faster carbon neutrality and much deeper CO_2 removals over time (Fajardy et al., 2019). The duration of the payback period is particularly important given the rapidity of the removals expected of BECCS in the IAMs and given that longer payback periods increase atmospheric forcing and therefore the risk of overshooting carbon budgets.

Beyond the immediate sequestration balances for feedstocks, there are also resource, energy, and emissions consequences of the BECCS supply chain including during harvesting, processing and transporting feedstocks. Forest and field residues are widely dispersed and can be expensive to collect, with resultant increases in energy consumption, soil carbon disturbances, and greenhouse gas emissions; mill and process residues are much easier to collect. Similarly, where the locations of feedstock production are remote from carbon dioxide storage facilities, this increases the requirement for transport either of the feedstock or of the captured carbon dioxide. It is estimated that the logistics of collating and transporting bioenergy on the scale envisioned could itself be up to half of total global primary energy consumption (Anderson and Peters, 2016), and may require a pipeline network similar in size to the current natural gas network (Fuss et al., 2016).

The concept of carbon neutrality on which current policy frameworks generally rest is therefore both uncertain and highly time and context-dependent; the net impact on the atmosphere is a combination of all these factors as well as the emission/capture volumes at the point of combustion.

The energy balance of BECCS is also uncertain. IAMs rely on the technology not only to remove carbon but to displace demand for fossil fuel energy; 14–20 per cent of global primary energy supply is frequently projected by 2100. Even in the absence of CCS, the quantity of bioenergy feedstocks used in these IAMs is generally unchanged, or even increases, due to this assumed fossil fuel-displacing energy production potential (Bauer et al., 2018; Smith et al., 2019). But calculations of the overall energy balance suggest that BECCS projects may in fact deliver relatively little net energy, far less than the models project. A 2018 study concluded that energy output was strongly case-specific, with the energy return on investment varying between 0.5 (i.e. more energy was consumed than produced) to 5.7 (roughly comparable to solar PV) (Fajardy and MacDowell, 2018). While improving power plant efficiency reduces energy losses, it also reduces the carbon sequestered, creating an effective trade-off between carbon capture and energy output. In general, biofuel fermentation processes capture less carbon but produce more energy.

Thus, to the extent that BECCS plays a role in future climate mitigation pathways, it might be better seen primarily as a means of capturing carbon rather than as producing

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energy, and should therefore be compared, in terms of cost and other impacts, with other carbon-capturing but not energy-producing approaches such as direct air capture, natural climate solutions (ecosystem restoration, reducing deforestation, etc.), and alternative uses for biomass that keep carbon out of the atmosphere, such as using wood for construction. Given ongoing power-sector transformations, exploring other ways of sequestering carbon from biomass that avoid the need to build potentially expensive or possibly unnecessary biomass plants should be worthwhile.

What are the consequences of BECCS at scale?

The scales of BECCS deployment assumed in Paris-Agreement-compatible IAM pathways are vast. Across the 116 scenarios reviewed in IPCC AR5 consistent with limiting global warming to 2°C, 101 involved some form of negative emissions – either through BECCS or afforestation and reforestation. The average annual level of BECCS deployment by 2100 in these scenarios was 12.1 $GtCO_2\ yr^{-1}$ (full range: 0–22 $GtCO_2\ yr^{-1}$) (Smith and Porter, 2018). Under the IPCC SR1.5 P4 overshoot scenario, the area of bioenergy crops required by BECCS, 7.2m km^2, is nearly two and a half times the size of India, for cumulative removals of 1,191 $GtCO_2$ to 2100. Even under the limited overshoot P3 scenario (414 $GtCO_2$ of removals to 2100) the area required for BECCS feedstocks, 2.8m km^2, is almost equivalent in size to India (IPCC, 2018b). Other assessments of IAM assumptions have put the land area plausibly required by BECCS feedstocks at anywhere between 3.8m and 7m km^2 (Smith et al., 2016).

Although there is low agreement on the overall availability of land (De Coninck et al., 2018), deployment on this scale, other than looking unlikely given the current development of BECCS, would 'have a far-reaching land and water footprint (*high confidence*)' (Hoegh-Guildberg et al., 2018, p. 180), with very substantial consequences for environmental and social objectives such as food production and the provision of ecosystem services and biodiversity. The exact impacts 'are context-specific and depend on the scale of deployment, initial land use, land type, bioenergy feedstock, initial carbon stocks, climatic region and management regime . . . (*high confidence*)' (IPCC, 2019b, p. 22).

Where could bioenergy or BECCS feedstock come from? One study (Beringer et al., 2011) considered the potential land availability for bioenergy plantations, both with and without CCS and excluding any consideration of CCS requirements such as geological storage sites, under four scenarios: with and without food cropland expansion and with higher and lower levels of nature conservation; it excluded land that is currently agricultural, severely degraded, in conservation areas, wetlands, or forested where carbon losses from land-use change would not be compensated for within 10 years. The study concluded that South America (26%), Sub-Saharan Africa (17%), Europe (14%), North America (11%), and China (7%) could collectively provide three-quarters of potential 2050 global biomass yields. Approximately a quarter of this came from woody plantations (coppiced every eight years), including temperate deciduous (e.g. poplars and willows) and tropical evergreens (e.g. eucalyptus), and the remainder from fast-growing grasses (e.g. miscanthus and switchgrass). These potentials imply 142–454 m ha of new biomass plantations replacing natural vegetation, 40% replacing natural grasslands and shrublands, 10% in place of semi-natural vegetation near existing agricultural areas, and 30% on currently forested areas. In aggregate this would expand the world's existing cropland area by 10–30%. Despite the sustainability constraints imposed, the ecological, economic and social consequences of converting much of this land to energy crops would still be significant. Also of significance is the quality of governance and enforcement of land-use planning in each potential feedstock location. Given that much of the potential lies in poorer countries with uneven track-records in these regards, it is questionable whether such constraints would actually be observed, jeopardising carbon and biodiversity-rich natural forests, especially in tropical regions.

The risks from widespread BECCS deployment are also closely linked to the overall sustainability of development trajectories. Considering the land-use risks from mitigation actions compatible with limiting warming to 1.5°C, the aggregate risks to food security, land degradation, and water scarcity in drylands only hit moderate levels when bioenergy or BECCS feedstocks occupy 1–4 m km^2 of land under more sustainable socioeconomic pathways (SSP1), with low populations, effective land-use regulation, low-GHG emission food systems and lower food losses and waste. At the other end of the spectrum, pathways with high populations, low income, and slow rates of technological change (SSP3), see moderate risks from bioenergy feedstocks emerge when they reach a more modest 0.1–1 m km^2 (IPCC, 2019b).

Land is not the only factor of production needed by BECCS deployment; cultivation of energy crops requires increased agricultural water and nitrogen fertiliser use. A study of the use of switchgrass for BECCS feedstock estimated that 200 million hectares (about half the total cropland of the US) would be needed to remove 3.7 $GtCO_2\ yr^{-1}$; the process would also consume 20 per cent of global fertiliser production (which is heavily fossil-fuel-dependent) and require 4,000 $km^3\ yr^{-1}$ of water, equal to current global water withdrawals for irrigation (National Research Council, 2015). Furthermore, the CCS process itself requires the use of water; one estimate suggested that the amount of water required to deliver 12 $GtCO_2\ yr^{-1}$ sequestration to be approximately 3 per cent of the total amount of water currently used by human activities – though some could be recycled from storage operations (Smith et al., 2016). Deployment of resources at this scale has planetary as well as localised effects; although BECCS is intended to reduce the pressures on the planetary climate boundary, large-scale deployment would likely increase the risk of earth systems transgressing the freshwater use boundary and further exceeding the land-system change, biosphere integrity and biogeochemical flows boundaries (Heck et al., 2018).

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Clearly, given the significant opportunity costs and trade-offs of deploying BECCS at the scale assumed by many Paris-Agreement-compliant IAM pathways, finding other means of achieving the same volumes of carbon dioxide removal is preferable. However, as SRCCL concluded, 'other land-demanding response options can have a similar range of consequences (*high confidence*)' (IPCC, 2019b, p. 22), and similarly land-sparing approaches present comparable resource-use challenges – for instance, requiring large amounts of energy and water. The sequestration and resource-use potential of other land-demanding CDR approaches is summarised in Table 1. The central CDR challenge to effective mitigation policy-making is not just to regulate and incentivise CDR approaches that minimise environmental and social externalities, but to do so in a manner that enhances the potential synergies between different approaches.

Complementary and synergistic sequestration solutions

Given that no approach to CDR is a panacea, it is likely that many forms of NETs, both technological and nature-based, will be (and will need to be) deployed, with varying degrees of success, over the coming decades. In this section we consider whether different terrestrial nature-based solutions (NBS) and BECCS can be complementary (other, non-land based, NETs are of course important, but are beyond the scope of our discussion). Prominent among nature-based solutions are afforestation and reforestation (AR), soil carbon sequestration (SCS) and biochar application (burying pyrolysed charcoal in soils to improve soil fertility and increase soil carbon saturation limits).

Afforestation and reforestation – permitting natural forest expansion, planting new trees and restoring felled or degraded forests – can increase carbon stocks either through rewilding or as part of sustainable forestry operations. In general, restoring landscapes to natural closed-canopy forests affords the possibility of realising greater biodiversity, ecological resilience and climate regulation benefits, in addition to long-term carbon sequestration and storage, particularly when compared to large-scale homogeneous plantations, which may have timber benefits but typically less ecological value and reduced carbon benefits. The sequestration potential (which comes not only from the trees themselves but also from improving soil quality) is greater under restoration to natural forest than to mixed uses such as agroforestry, plantations or rotational logging. Afforestation and reforestation offer relatively cheap means of providing negative emissions with negligible energy requirements, but, depending on how and where they occur, they can compete with food (or biofuel) production for land and water resources, and albedo effects limit the latitudes at which they are effective (Davin and De Noblet-Ducoudré, 2010).

Complementary improvements to soil quality can be made in non-forest environments through a variety of SCS approaches such as agroecology, agroforestry, conservation agriculture, and landscape management. These have co-benefits for agricultural resilience and productivity, food security, enhanced biodiversity, water cycling and climate change mitigation and adaptation (Vermeulen et al., 2019).

Both AR and SCS are constrained by their dependence on the widespread adoption of best-practice management and governance approaches. In many countries weaknesses in land-use governance mean that the permanence of re-established forest areas cannot be assumed. For SCS, bottom-up estimates of the maximum biophysical potential on cropping and grazing land suggest that only around 10 to 30 per cent (8 GtC to 28 GtC) of the remaining global theoretical soil organic carbon (SOC) sink potential – 88 GtC (323 GtCO_2), equating to recovering around two-thirds of total SOC losses – could be filled (Sanderman et al., 2017). Nonetheless, in particular locations, especially where existing soil carbon content is low, best management practices could achieve carbon sequestration rates of up to 1 per cent per year for 20 years, which compares well with the global aspiration of 0.4 per cent, under the '4 per 1000' initiative launched by France at UNFCCC COP 21 (EASAC, 2018).

The great advantage of many NBS, especially given the scale of additional carbon sequestration that needs to be developed in the next couple of decades, is that they can be deployed in the near term, at low cost, and are attainable from approaches that are already available, rather than being reliant on largely unproven technologies (EASAC, 2019). However, for many, especially AR-based approaches, immediate deployment does not equate to realising immediate CDR gains, given both the biological constraints on sequestration rates and the fact that for juvenile vegetation sequestration rates and total storage potentials are more limited than for mature vegetation. This points to the urgency of scaling up NBS, both to allow sufficient time to realise the CDR potentials from proactive restoration and land management activities, and to benefit from the immediate and substantial gains from avoiding further carbon losses from established vegetation as a result of land degradation and land-use changes.

Subject to appropriate, context-sensitive deployment and protection of existing resources, NBS have the potential to make significant contributions to CDR whilst maximising co-benefits that preserve the viability of other essential land-uses, ecosystem services, and biodiversity – especially for wetlands. Recent reviews suggest that, with food security, fibre security, and biodiversity conservation safeguards in place, NBS could potentially sequester up to 23.8 $\text{GtCO}_2\text{e yr}^{-1}$ by 2030. Approximately half of this (11.3 $\text{GtCO}_2\text{e yr}^{-1}$) is cost-effective at carbon prices at or below \$100 $\text{tCO}_2\text{e}^{-1}\ \text{yr}^{-1}$ in 2030, with forest-based NBS (notably including reforestation and avoided forest conversion) offering over two-thirds of these cost-effective options (Figure 2; Griscom et al., 2017).

A similar, safeguard-constrained, assessment of potential land sector contributions to keeping temperature increases to 1.5°C concluded that avoided emissions from halting deforestation and degradation, restoring peatlands, and preventing grassland conversion to croplands could account for

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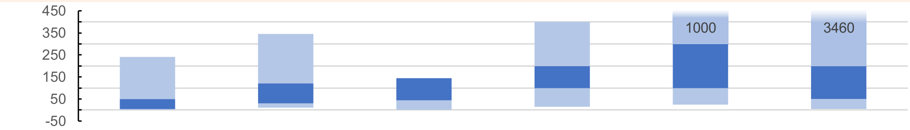
Table 1. Carbon dioxide removal abatement costs, deployment potentials, and key side effects (compiled from De Coninck et al., 20182018; Morrow et al., 20182018; Smith et al., 20162016).

	Land-based					
	Saturable					
	Afforestation/ Reforestation	**Biochar**	**Soil Carbon Sequestration**	**BECCS**	**DACCS**	**Enhanced Weathering**
Sequestration potential						
Potential sequestration rate by 2050 ($GtCO_2\ y^{-1}$) [a]	0.5 - 3.6	0.5 - 2	2 - 5	0.5 - 5	0.5 - 5	2 - 4
Potential rate by 2100 ($GtCO_2\ y^{-1}$)	0.5 - 7	1 - 35	0.5 - 11	1 - 20+	1 - 20+	1 - 27
Cumulative potential by 2100 ($GtCO_2$)	80 - 260	78 - 477	104 - 130	100 - 1170	100 - 1000+	100 - 367
Required 2100 annual removals in 2°C scenarios ($GtCO_2\ y^{-1}$) [b]	4 [12]	-	-	12	12	1 [4]
Saturation & permanence [a]	Saturation of forests; Vulnerable to disturbance; Post-AR forest management essential	Mean residence times: decades to centuries depending on soil type, management, and environmental conditions	Soil sinks saturate and can reverse if poor management practices were to resume	Long-term governance of storage; Limits on rates of bioenergy production and carbon sequestration	Long-term governance of storage	Saturation of soil; Residence time from months to geological time scales
Costs						
2050 cost (2011$ per tCO_2) [a] Author judgements (central band) & full range						
Resource requirements & impacts (2100) [b]						
Total land required (Mha)	*320 [970]*	-	-	*380 - 700*	*Very low (unless solar PV used for energy)*	*2 [10]*
Land required ($Mha\ GtCO_2^{-1}$)	80	16 - 100	0	31 - 58	0	3
Total water required ($km^3\ y^{-1}$)	*370 [1040]*	-	-	*720*	*10 - 300*	*0.3 [1.5]*
Water required ($km^3\ GtCO_2^{-1}$)	92	0	0	60	0.8 – 24.8	0.4
Impact on nutrients ($Mt\ N,P,K\ y^{-1}$)	0.5	N: 8.2 P: 2.7 K: 19.1	N: 21.8 P: 5.5 K: 4.1	Variable	0	0
Side effects (scale-dependent)						
Air pollution	—	—	—	✗	?	✗
Albedo [b]	✗ (or reduced GHG benefit where not negative)	—	—	Variable, depends on source of biofuel (higher albedo for crops than for forests) and on land management (e.g. no-till farming for crops)	?	—
Biodiversity	✗	—	—	✗	?	—
Ecosystem changes	—	—	—	—	?	—
Food security	✗	✗	✓	✗	?	—
Ground/water pollution	—	—	—	—	?	✗
Soil quality	✓	✓	✓	—	?	✓
Mining and extraction	—	—	—	—	?	✗
Trace GHGs	—	✓	✗	✗	?	—

Legend:

✓	Desirable change	—	No significant change
✗	Undesirable change	?	No estimate available

DACCS is theoretically only constrained by geological storage capacity, estimates presented consider upscaling and cost challenges

BECCS potential estimates are based on bioenergy estimates in the literature ($EJ\ yr^{-1}$), converted to $GtCO_2$

Potentials cannot be added up, as CDR options would compete for resources (e.g. land)

[a] assessed ranges by Fuss et al. (2018)

[b] based on 2100 estimate for mean [max] potentials by Smith et al. (2015)

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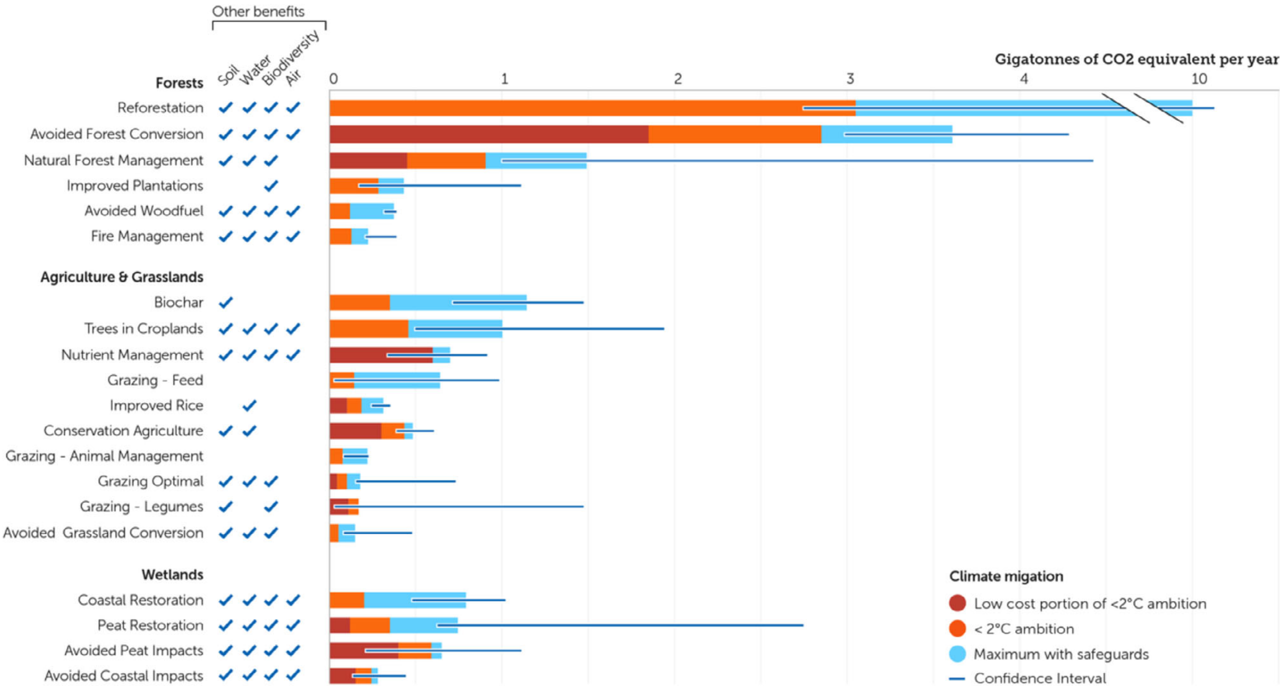
Figure 2. Maximum climate mitigation potential with safeguards for reference year 2030 (Redrawn from Griscom et al., 2017).



41 per cent (6.1 $GtCO_2e\ yr^{-1}$) of land-use mitigation potential by 2050 (14.4 $GtCO_2e\ yr^{-1}$ in total, with a further 8.5 $GtCO_2e\ yr^{-1}$ possible in agriculture). The additional sequestration (and biodiversity-enhancing) potentials come from restoring a quarter of degraded forest ecosystems globally, promoting the expansion and regeneration of natural forests (as opposed to monoculture tree plantations), and more efficient and responsible use of forests and forest products, including lengthening rotation times and reducing harvest rates. In tropical forests, responsible use was assumed to mean no commercial extraction of timber, given that over 50 per cent of biomass in those forests resides in valuable hardwood trees that take centuries to regrow (Dooley et al., 2018).

Realising these positive impacts is far from a given however, so appropriate safeguards and governance arrangements will need to be developed, verified, and enforced (just as for BECCS deployment). For example, monoculture-based reforestation can have negative consequences for biodiversity, carbon storage, and water supplies; inappropriate afforestation can increase fire risks and result in damage to proximal crops from wildlife or water abstraction; poor governance of restored lands can result in inequitable distributions of costs and benefits and exacerbate existing inequalities (Chazdon and Brancalion, 2019). This is especially the case given the significant role of ecosystems in tropical latitudes, where forest governance has historically been poor and law enforcement weak.

Orange-coloured portions of bars represent cost-effective mitigation levels assuming a global ambition to hold warming to <2°C (assuming an annual carbon price at or below US$100 per tonne of CO_2e – the maximum cost of emissions reductions to limit warming to below 2°C). Rust-coloured portions of bars indicate low cost (<US$10 per tonne of CO_2e per year –approximating existing carbon prices) portions of <2°C levels. Ecosystem service benefits linked with each pathway are indicated by tick marks for biodiversity, water (filtration and flood control), soil (enrichment), and air (filtration).

However, NBS may face diminishing marginal increases in sequestration: 'these methods cannot provide a complete long-term sustainable solution, because the capacity of the biological reservoirs will be saturated within a few decades, and because they are not secure as they could revert to carbon sources unless appropriate management is maintained indefinitely' (EASAC, 2019, p. 5). This contrasts with the relatively secure and permanent geological storage possibilities of utilising BECCS and other CCS-based approaches. Griscom et al. (2017) similarly caution that climatic impacts on terrestrial carbon stocks are uncertain and that unchecked climate change could reverse terrestrial carbon sinks by mid-century. Principal risk factors include temperature increases, drought, fire, pest and disease outbreaks, and social, political and economic anthropogenic exploitation.

The saturation limits on soils as carbon sinks, even with biochar application, are well recognised (EASAC, 2018); the saturation and sequestration dynamics of trees and forests are more complex, however, and there is little consensus in the literature on the most appropriate forest management regime for maximising carbon uptake. Probably the most commonly accepted view is that active forest management enhances carbon uptake, both because the rate of carbon uptake slows as forests mature, net primary productivity declines and natural mortality increases, and also because

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unmanaged forests increase the chance of massive carbon losses from disturbances (Hektor et al., 2016). Harvesting mature trees and replanting could therefore increase the rate of carbon uptake, as well as generating timber for wood products. Other studies suggest, however, that while this may be true in some plantations (possibly because of relatively low soil nutrient contents), it is not necessarily the case for natural forest, particularly in old-growth carbon-dense temperate forests with lower vulnerabilities to risk factors. In one such example in Oregon, carbon residence times in timber harvested for construction were lower than if the trees remained unharvested, and utilising harvest residues for bioenergy production instead of leaving them in the forest to decompose increased short-term emissions; lengthening and restricting harvest cycles had the most significant positive impact on reducing ecosystem carbon emissions (Law et al., 2018). In practice the appropriate form of forest management to maximise carbon uptake and storage will vary with the type of forest, ecosystem and local climate.

The implications for utilising biogenic resources as BECCS feedstocks, therefore, are not clear-cut and are dependent, among other factors, on geography, ecology, and counterfactual uses. Compared with other BECCS feedstocks, agricultural and forestry residues generally have the lowest impact on land use change and, depending on the residue type and collection method, soil and forest carbon stocks. But residues are also limited in availability, harder to collect, and can have other uses such as for engineered wood products or to maintain soil carbon and nutrient levels; if forest and agricultural residues that would otherwise have been left to rot and fertilise soils are removed this may cause significant negative impacts on soil degradation, with associated declines in levels of soil carbon and rates of tree growth (IPCC, 2019b). Afforestation and reforestation could increase the volume of residues, but this depends partly on whether wood-based industries expand correspondingly; the proximity of forests to CCS and storage facilities will also affect their economic and carbon-balance viability. In many countries there is potential for more extensive use of harvested wood products in climate-mitigating roles, for example in construction; in other contexts, forests may generate greater sequestration and ecological benefits if left unmanaged or only lightly harvested. Yet, in other instances where biogenic carbon storage is at risk of reversibility, utilising BECCS to access permanent geological storage could be advantageous.

As discussed above, the use of additional feedstock from forests or dedicated energy crop plantations – if not sustainably integrated with the existing ecology – carries the largest risks to the overall carbon balance and to sustainable land use. The most negative impacts involve land-use change such as converting natural forests to plantations, displacing other uses which already realise CDR and social and/or environmental co-benefits, or increasing harvest volumes or frequencies in already managed forests. Yet, in some ecosystems positive, synergistic, outcomes – such as managing dryland salinity, enhancing biodiversity and reducing eutrophication – are possible if perennial bioenergy crops are appropriately integrated with conventional crops; if they are planted in poor, carbon-depleted, soils, for example, perennial bioenergy crops can enhance SCS (Anderson-Teixeira et al, 2009; Smith et al., 2019).

Policy discussion

Emerging from all this complexity are several challenges that are simple to describe but difficult to solve. First, common to all CDR approaches is the necessity of achieving meaningful volumes of carbon sequestration and storage, in a sufficiently short period of time to contribute to emissions reductions and avoidance of overshoot, once full lifecycle emissions balances have been accounted for. These balances will vary considerably not just across approaches, but on a case-by-case basis, depending on the specific details of implementation. This requires robust lifecycle accounting measures to be developed, verified, and enforced for each sequestration supply chain.

Second, while the carbon balance is paramount to success, design and evaluation of CDR approaches cannot afford to be parochial if social, environmental, and political risks are to be avoided, co-benefits are to be realised, and public acceptance is to be achieved. Given the breadth of the considerable trade-offs resulting from all land-based carbon dioxide removal solutions and the specificity of the removal, energy, environmental, economic, social, and political benefits and costs to each deployment ecosystem, proactive policy engagement is required to cap the downside risks and unintended consequences of each potential deployment.

Third, carbon dioxide removal is a system, more so than conventional abatement approaches, requiring expansive and uncommon engineering, scientific, and geographic integrations and alignment, which must be mediated and governed by policy and political approaches that are equally holistic in scope. Such policy arrangements will need to be designed synergistically, to ensure that safeguards, legislation, enforcement mechanisms, and other governance modalities are mutually reinforcing and comprehensive in their treatment of CDR consequences. There is a significant challenge ahead in achieving the co-ordination and alignment required between multiple policy domains (and at different scales) to successfully implement a portfolio of CDR approaches, as they cut across agricultural, forestry, environmental, water, energy, and climate policy jurisdictions.

At a fundamental level, greater understanding is still required about the availabilities, costs, and performances, of different CDR systems and technologies (and how these will evolve as systems mature); their aggregate potentials compared with the aggregate removal requirements; and where the burdens and benefits will fall. Consequently, there are still large uncertainties over what an appropriate policy roadmap looks like and over which existing policy frameworks can be adapted and harmonised to foster progressive and risk-mitigated CDR implementations. Nonetheless, irrespective of the particular machinations of policy design,

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there are several priority factors that will need to be universally considered, supported by a political economy analysis of the enablers and barriers to progress.

Principal among these is furthering appropriate risk-calibrated investment and financing options for advancing the most appropriate forms of CDR. These will need to include support for nature-based solutions that struggle to attract capital investment. At a minimum, financial incentives will require economy-wide carbon pricing – for carbon both emitted and sequestered – but this alone will be insufficient. Additional measures might include requiring emissive entities that wish to avoid further emissions taxes to hold verifiable certificates of sequestration commensurate with the volume of their emissions. And there will need to be appropriate additional incentives to sequester carbon on land, such as through reorienting agricultural subsidies towards 'payment for ecosystem services'-based approaches. Given the currently limited public investment in CDR research and development, some early-stage prioritisation of investments may also be required to ensure optimal outcomes and to accelerate progress towards the more promising approaches. Historical precedent from the declining costs of solar photovoltaic panels suggests the price trajectory between first commercial deployment of a climate technology and reaching unsupported marketable prices is too shallow for CDR to make a meaningful contribution to emissions reductions on the required timescales. Some backing of perceived winners and risk of lock-in therefore may need to be accepted to accelerate cost reductions.

Financial mechanisms will need to be bolstered by robust land rights legislation to protect existing land-owners, land-users, and land with high ecological value. This is especially urgent in jurisdictions where land governance is currently weak, weakly enforced, or contested, including where customary tenure arrangements may be vulnerable to being overturned.

Decision-making also needs to be supported by improved modelling approaches. IAMs are blunt decision-support tools; this is not their primary purpose, yet they remain influential in setting the level of, and approaches to realising, mitigation ambition. Thus, it would be worthwhile to systematically evaluate the roles played by different factors that drive large-scale BECCS as an optimal solution to meeting Paris Agreement carbon budgets, including through sensitivity analyses of the underlying assumptions. Also of value would be developing a suite of models that variously incorporate a broader range of CDR approaches, impose geographic and volumetric constraints on land utilised for different approaches, informed by internalising social and ecological costs that are currently out of scope, and which give more attention to non-linear earth-system feedbacks.

Policy conclusions for risk-calibrated policy making

No single NET, whether BECCS, nature-based, or otherwise, will achieve the scale of CDR required in the vast majority of 1.5°C and 2°C mitigation scenarios, let alone do so sustainably. But portfolios of multiple NETs, deployed sensitively at modest scales, will be invaluable for achieving climate security (Minx et al., 2018). Provided that each potential deployment is holistically evaluated against a broad and consistent risk-adjusted framework, including place-based social and environmental criteria, in addition to the attainable carbon balances, this could foster healthy competition among implementation approaches. The policy challenges, therefore, are as follows:

First, to determine the suitability of different NETs on a case-by-case basis, including full assessments of life-cycle CDR potentials (including abandoning the assumption that biomass feedstock is inherently carbon-neutral), socio-environmental impacts, and the adequacy, or otherwise, of the existing regulatory, economic, and political environment (cf. NAS, 2018).

Second, to design policy and financial mechanisms that are sufficiently attuned to these contextual specificities, but which are sufficiently catalytic to galvanise appropriate and complementary actions at adequate scale and with enough urgency. For land and forest-based solutions, this requires almost immediate implementation due to the time taken for these natural solutions to realise their full sequestration potential. For technological solutions, this requires a step-change in research, development, iteration, and deployment of promising options. Both approaches require significant investment, financial mechanisms, and the development of supportive governance arrangements and safeguards.

And third, to accelerate conventional abatement action as rapidly as possible; there are too many drawbacks and uncertainties associated with BECCS and other NETs to place excessive reliance on them – though they will undoubtedly be needed if Paris Agreement temperature targets are to be met.

Delaying these decisions increases the risk of missing climate goals and increases the scale of negative emissions needed in the future. The danger at the moment is that policy-makers are 'sleepwalking towards BECCS' simply because most models incorporate it – or, almost as bad, that they are simply ignoring the need for any meaningful action on CDR as a whole.

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