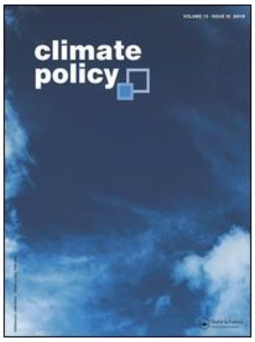

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SYNTHESIS ARTICLE

Potential implications of carbon dioxide removal for the sustainable development goals

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ABSTRACT

As the international community's best expression of a collective vision of a desirable future, the 2015 UN Sustainable Development Goals (SDGs) present a framework against which to assess the broader impact of emerging technologies. Implications of technologies and practices for removing CO_2 from the atmosphere (CDR) are not fully understood and have not yet been mapped against the full range of SDGs. CDR is widely seen as necessary to achieve the Paris Agreement's global goal of limiting warming to 1.5-2°C, yet local geographical, socio-economic, and political interdependencies are often overlooked. This review synthesizes the best available understandings of potential implications of CDR options aiming to complement emissions reductions. It seeks to identify effects on and interactions between specific social, environmental, and policy environments, in which various CDR options could be pursued. Climate change mitigation and co-benefits from CDR could significantly benefit SDGs, yet poorly designed CDR policies could also challenge SDGs. Specific CDR options could generate conflicts over land, water, biomass, or electric power resources, and exclude communities from policy benefits with negative cascading effects for a range of SDGs. In the literature, implications of CDR activities on sustainable development are derived from current pilot activities, inferred from similar practices already operational or model outputs regarding land, energy, or material requirements. Important gaps remain. We identify questions for further disciplinary and inter- or transdisciplinary work strengthening understanding of how CDR could either support or threaten the achievement of the SDGs.

Key policy insights

- CO_2 removal (CDR) appears essential for limiting warming to well below 2°C; such stabilization of global climate is a precondition for at least partially achieving the SDGs.
- CDR options can generate positive and negative local/regional impacts on various SDGs via physical, social, economic, and political channels. None of these options are universally 'good' or 'bad'.
- The scale of implementation of CDR and related impacts are highly dependent on policy design and national planning processes.
- More research is needed to clarify how policy design can allow CDR options to generate synergies between, and prevent harm across, multiple SDGs.

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Carbon dioxide removal; negative emissions; co-benefits; sustainable development goals; mitigation; technology assessment

1. Introduction

Already at the current warming level of ~1°C, climate change is having detrimental effects on the pursuit of the 2015 UN Sustainable Development Goals (SDGs) and any further warming renders their achievement more

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difficult (IPCC, 2018). Current mitigation pledges (the nationally determined contributions (NDCs) under the Paris Agreement) fall short of the Agreement's temperature goals of limiting warming to 'well below' 2°C and 'pursuing efforts' towards 1.5°C, leading instead toward at least 3°C of warming by 2100 (UN Environment, 2019), which would jeopardize achievement of the SDGs (Nerini et al., 2018). Limiting warming to any temperature level requires stabilization of atmospheric greenhouse gas (GHG) concentrations by achieving net-zero global GHG emissions. This means that all remaining emissions are counterbalanced by natural or technical sinks or removals into long-term storage. Such Carbon Dioxide Removal (CDR)[1] technologies or practices are already built into the vast majority of Integrated Assessment Model (IAM) scenarios that allow limiting warming to below 2°C, in some cases starting as early as the 2020s (Rogelj et al., 2015) and increasing in scale over the remainder of the twenty-first century (IPCC, 2018). Most scenarios envisage annual removal rates of around 10 billion tCO_2 in the second half of the century – around one-third of current global CO_2 emissions (UN Environment, 2019). Some scenarios have attempted to limit the amount of CDR by modelling even more rapid emissions reductions (van Vuuren et al., 2018), but no scenarios consistent with 1.5°C pathways completely exclude CDR (IPCC, 2018) and reaching any such scenario will pose an unprecedented policy challenge (Michaelowa et al., 2018). While all mitigation options have to be considered to keep ambitious temperature targets within reach (Waisman et al., 2019), many governments are yet to start considering CDR within their mitigation policy portfolios (Torvanger, 2019). This reluctance may in part be due to uncertainties regarding broader implications of CDR applications.

The SDGs represent the best available global vision of a desirable future and aim at aligning global efforts to this end (Biermann et al., 2017). They thus allow to map out broader potential implications that the pursuit of various CDR activities could entail. Specific mapping exercises have addressed relationships such as between the SDGs and particular issues such as energy (Nerini et al., 2018), urban ecosystems (Maes et al., 2019), ecosystem services (Wood et al., 2018), or soils (Keesstra et al., 2016). The limited degree of SDG operationalization through appropriate indicators (Hák et al., 2016), and the importance of geographical context, resource endowments, time horizon and governance for actual SDG attainment (Nilsson et al., 2018) are factors that limit the relevance of the outcomes of these global studies.

Others have studied various synergies and trade-offs between SDGs (Liu et al., 2018), identified opportunities for reaching several targets by an integrated approach (Stafford-Smith et al., 2017), and explored the potential role of particular technologies such as vaccines (Possas et al., 2020) or artificial intelligence (Vinuesa et al., 2020) in reaching the SDGs. Our study traces the footsteps of the technology-related studies by exploring consequences of technology interventions for the SDGs. It structures known and expected effects that specific CDR activities could have on efforts to achieve the range of objectives addressed by the SDGs, while mindful of the specificities raised by Nilsson et al. (2018).

While there are increasing efforts to systematize understanding of potential consequences of specific, upscaled CDR applications (Fuss et al., 2016; Nemet et al., 2018; Smith, Adams, et al., 2019), such studies have not yet sought to identify potential effects for all relevant land- and ocean-based approaches and across all 17 SDGs, notably regarding social, institutional or policy dimensions. Consideration of the role of governance and institutions, including at the local level, remains thin despite indications that regional, cultural, socio-economic and political differences and their influence on policy design could strongly affect outcomes of CDR applications. This is why the present review – building on expert elicitation – goes beyond the existing CDR literature in identifying gaps in our understanding of potential co-benefits and risks of CDR. Our contribution builds on previous work toward transdisciplinary integration of knowledge on 'climate engineering' (Honegger et al., 2018) and draws on broader insights from GHG mitigation policy and sustainability governance regarding processes mediating the potential outcomes of various CDR approaches for pursuit of sustainable development. Our paper first introduces our methodological approach (section 2), outlining six categories of CDR and two types of implications for the SDGs (section 3), before presenting the case-by-case range of possible implications across the 17 SDGs (section 4) and concluding by identifying further research needs (section 5).

2. Methodology

As a starting point, we first compiled potential consequences of CDR deployment identified in seminal interdisciplinary assessments of CDR or 'climate engineering' technologies (National Academies of Science, 2015;

Royal Society, 2009; Schäfer et al., 2015), reports of the Intergovernmental Panel on Climate Change (IPCC) (2014, 2018, 2019) as well as systematic reviews of the academic literature (Fuss et al., 2016; Nemet et al., 2018). Consequences identified in the Global Assessment Report on Biodiversity and Ecosystem Services (IPBES, 2019) and a recent review of land-based CDR (Smith, Adams, et al., 2019) have also been included.

Second, an expert elicitation served to validate the range of identified consequences and to identify further gaps and open questions. The 31 contributing individuals were selected for their complementary expertise to collectively span the 17 SDGs, the relevant policy sectors, and mitigation policy instruments. Academic fields included biology, earth systems modelling, economics, engineering, (environmental/humanitarian) law, environmental studies, innovation studies, geophysics, international politics, international relations, philosophy, physics, sociology, science and technology studies, sustainable development, and policy analysis. Individuals contributed policy experience in multilateral, international, and domestic governance of the environment, climate, food and agriculture, energy, water, and in the design of mitigation policy instruments (including regarding forestry, land-use change, industries, carbon pricing, and carbon markets). The group spanned western and eastern Europe, central and southeast Asia, western Africa, as well as North and South America.

Third, a keyword search tailored to the identified gaps revealed additional publications including literature on similar policy challenges in various mitigation domains, particularly relating to land-use change. Criteria for inclusion were: publication date 2018-2020, in order to cover literature not taken into account in the most recent relevant IPCC reports, namely, the 2018 Special Report on Global Warming of 1.5°C, and the 2019 report on Climate Change and Land; complementary perspective (particularly a focus on social and political aspects); and an analytical approach allowing consideration of potential local specificities.

Ten reports and reviews were included under step 1. A total of 123 papers were covered, 94 in the first round and 29 added due to the expert input in step 3. Some of them are not covered in the reference list of this article as they generated similar findings to other papers.

Research into the effectiveness and possible side-effects of many CDR approaches is still a relatively new and evolving field of enquiry. Some consequences (notably the effect of overall climate mitigation pathways on some SDGs) have been assessed and allocated confidence levels (IPCC, 2018). IPCC (2019) does not provide a focused mapping of these consequences across all land-related CDR categories with consideration of socio-economic conditions and policy design. Other consequences lack such assessment to date, but might nonetheless turn out to be important. Furthermore, the effects of specific CDR categories on SDGs may be assessed in an inconclusive manner because they are highly region-, scale, and policy design dependent. Scoring the consequences through a general scale such as the one proposed by Nilsson et al. (2018) for interactions between SDG-targets ignores these dependencies. Here, we thus specify causal relations and whether they appear in the literature as predominantly positive (+), negative (-) or particularly dependent on specific conditions (+/−), indicating how various local conditions and policy designs might shape outcomes (Tables 2–7). We also define questions for further research for particularly ambiguous consequences.

3. Categories of CDR approaches and SDG implications

In the following, we outline six categories of CDR (3.1) and two different types of implications for the SDGs: general consequences of CDR for SDG-13 (climate action; in 3.2) and co-benefits and trade-offs of the CDR action on other SDGs (3.3).

3.1 CDR categories

We address the five categories of CDR covered by the IPCC (2018), and additionally, consider ocean fertilization given a continuous interest in such approaches (see Table 1).

3.2 CDR and climate action

CDR is overall expected to contribute substantially to SDG-13 by complementing deep and fast reductions in GHG emissions. Any contribution to achieving SDG-13 would have significant knock-on effects for the pursuit

Table 1. Six categories of CDR (land-based CDR approaches as defined by IPCC, 2018).

CDR category	Definition
Bioenergy and carbon dioxide capture and storage	Carbon dioxide capture and storage (CCS) technology applied to a bioenergy facility.
Direct air carbon dioxide capture and storage	Chemical process by which CO_2 is captured directly from the ambient air, with subsequent storage.
Afforestation and reforestation	Planting of new forests on lands that historically have not contained forests. Planting of forests on lands that have previously contained forests but that have been converted to some other use.
Soil carbon sequestration and biochar	Land management changes which increase the soil organic carbon content, resulting in a net removal of CO_2 from the atmosphere. Stable, carbon-rich material produced by heating biomass in an oxygen-limited environment, which may be added to soils to improve soil functions, reduce greenhouse gas emissions, and for carbon sequestration.
Enhanced weathering	Enhancing the removal of carbon dioxide (CO_2) from the atmosphere through dissolution of silicate and carbonate rocks by grinding these minerals to small particles and actively applying them to soils, coasts or oceans.
Ocean fertilization	Deliberate increase of nutrient supply to the near-surface ocean in order to enhance biological production through which additional carbon dioxide (CO_2) from the atmosphere is sequestered.

of all the SDGs: Fuso Nerini et al. (2019) have found published evidence for climate change endangering progress on SDGs 1 through 16. Specifically, their findings suggest that climate change mitigation directly benefits goals relating to material and physical well-being such as prosperity and welfare, poverty eradication and employment, food, energy, and water availability, health, and the quality and strength of ecosystems. Their findings also suggest mitigation can improve humanity's potential for attaining justice and equality across the world.

CDR is, however, also associated with risks pertaining to SDG-13: CDR might underperform compared to expectations due to uncertainties in projections, inacceptable impacts, or unexpected reversals (Dooley & Kartha, 2018; Smith, Haberl, et al., 2013). Inadequate regulation or neglect of rules for carbon accounting or measuring, reporting and verification systems could undermine environmental integrity (Gough & Mander, 2019), and land-use change could unexpectedly result in increased GHG emissions (Harper et al., 2018).

3.3 CDR and other SDGs

Concerns over potential harmful trade-offs often dominate discussions of CDR, driven by a concern over the very large scales of application inferred from IAMs. Activity-level assessments of region-specific adverse side-effects or positive co-benefits of particular categories of CDR are, however, not readily available. Instead, negative impacts are often inferred from globally modelled land-use, energy or material requirements. This is particularly true for bioenergy with carbon capture and storage (BECCS) given its billion-ton scale in many model scenarios.

Early indications for possible interaction between policy design, geography and local or regional socio-political structures can, however, be inferred from past experience in broader mitigation policy. The specifics of mitigation policy designs are known to determine the occurrence of co-benefits or trade-offs (IPCC, 2014). Policies often have distributive effects (IPCC, 2018, pp. 447–449) that can be regressive. They can increase prices of basic commodities (Kline et al., 2017) or infringe on rights of indigenous communities (Ding et al., 2016a).

The importance of policy design is perhaps best illustrated in the context of biomass-reliant CDR approaches, where incentives determine which type of biomass and how much of it is selected, sourced and renewed and in what location, which in turn likely affects the policies' sustainability (Humpenöder et al., 2018). Governance and policy instrument design crucially shape both the form and scales of regional application. Policies targeting deployment at a limited scale through retrofitting CCS to existing biomass-energy or waste-treatment plants would, for example, avoid some potential negative effects linked to the upscaling of biomass production (Zhang et al., 2020).

4. Consequences of specific CDR applications for SDGs

In the following we describe and list the identified consequences on the SDGs from each of the six CDR categories identified above.

4.1 Bioenergy with carbon capture and storage (BECCS)

BECCS comprises two well-known technology components: (i) production of electricity or heat based on (near) carbon-neutral biomass; and (ii) carbon capture and storage (CCS). While bioenergy use is growing globally, CDR rates of 10 billion tCO_2 through BECCS would imply a tenfold increase (Honegger & Reiner, 2018). There are large uncertainties regarding the technical, economic, and political feasibility of BECCS at such scales (Forster et al., 2020; Nemet et al., 2018). Disease, pests, fire, and climate impacts could also limit potentials (Vaughan & Lenton, 2011). It is unclear what amounts of bioenergy could be sourced sustainably, given that unsustainably harvested biomass could result in additional emissions instead of removals (Harper et al., 2018). Most studies see two potential negative consequences of BECCS – destruction of forests and reduction of food supply (Humpenöder et al., 2018; Kline et al., 2017 Yamagata et al., 2018). The SDG implications are more complex; BECCS based on secondary (waste) biomass (timber industry and agriculture residues) and BECCS that draws upon dedicated biomass plantations have different consequences. The former would contribute less to mitigation as secondary biomass supply is limited and there are risks of disrupting nutrient cycles and soil degradation, which can cause carbon emissions. The latter could ramp up mitigation, but would entail land-use change (Zhang et al., 2020). The level of participation in policy implementation could determine the social impact of such land-use change (Dooley & Kartha, 2018). Specificities of incentives are likely to affect the biomass sourcing behaviour (Rouleau & Zupko, 2019). Changes in local water consumption (Yamagata et al., 2018) and retention due to a change of land cover (Smith & Torn, 2013), and nutrient cycle effects are intertwined (Smith, Adams, et al., 2019). Changes in land vegetation can induce changes in local precipitation and temperature that go in different directions (IPCC, 2019). An increase of precipitation and reduction of temperature may be desirable where it counters desertification, a trend in the other direction would exacerbate it. An unequivocally negative effect on all scales occurs where plantations replace primary forests, thereby almost inevitably reducing biodiversity (Smith, Davis, et al., 2016) and increasing emissions (Harper et al., 2018); here policy needs to anticipate and prevent perverse incentives. Biomass plantations could offer income sources (Wang et al., 2020), but large-scale top-down implementation with weak governance can also lead to the marginalization of local populations (Gutiérrez Rodríguez et al., 2016).

Geological storage of CO_2 places a significant energy penalty of about 30% on electricity production and requires water (Bui & Mac Dowell, 2019). Further challenges are associated with concerns over the potential toxicity of CO_2 leaking into underground water resources, although these have proven manageable in CCS undertaken to date (Celia, 2017; Lawter et al., 2017). Table 2 offers a summary of potential consequences of BECCS for the SDGs, while identifying open questions.

4.2 Afforestation, reforestation, and ecosystem restoration

CDR can be achieved by either expanding forest area, enhancing forest density, or increasing the carbon content of forest soils. This can be done through reforestation (planting trees in deforested areas), afforestation (planting trees in historically treeless areas), and altered forest management.

Afforestation/reforestation can cause displacement of land-use (e.g. agricultural land) or indirectly trigger deforestation elsewhere (Gutiérrez Rodríguez et al., 2016;; Kreidenweis et al., 2016 Veldman et al., 2015). Moreover, afforestation/reforestation needs to be implemented in a locally adapted manner to provide benefits for local communities and ecosystems; poorly designed interventions can cause displacement of indigenous communities, isolate people from ecosystem services or cause biodiversity loss (Smith & Torn, 2013; Smith, Adams, et al., 2019). If afforestation is conducted exclusively to maximize short-term CO_2-uptake, e.g. via monocultures of fast-growing species such as pine and eucalyptus, these risks may be particularly high (Wright et al., 2000). Effects depend on prior vegetation cover and state of degradation (IPBES, 2019), which suggests policy should

Table 2. Summary of potential consequences of BECCS for the SDGs.

SDG	Potential impact	Type
1	• Potential displacement of poor populations (Dooley & Kartha, 2018)	–
	• Distributional effects depend on policy design (Fuss et al., 2018)	+/–
2	• Additional biomass production could displace food production, especially in the case of subsistence farming (Dooley et al., 2018; Humpenöder et al., 2018), and lead to rising food prices (Hochman et al., 2014)	–
	• Land- use conflict regarding food production may be attenuated - through alternative biomass and food production systems (Beal et al., 2018) - if global or regional meat consumption is reduced (Dooley & Kartha, 2018)	+ +
3	• Climate change health impact attenuation could be substantial (e.g. avoided deaths from malnutrition, avoided forced migration and associated health risks, reduced pervasiveness of malaria, diarrhoea and heat stress) (WHO and WMO, 2012)	+
	• Groundwater chemistry and drinking water quality could be adversely affected (Wilkin & DiGiulio, 2010); seismic activities might be triggered by geological sequestration (Fuss et al., 2018)	–
4	• Climate change mitigation could help maintain opportunities for education (via poverty alleviation, nutrition, health, prosperity, infrastructure), (Glewwe, 2005)	+
5	• Effects pertaining to land-use conflict, and limited access to funding instruments could particularly affect women who often lack adaptive capacities or mobility (Buck et al., 2014)	–
	• Women may lack access to capital or educational opportunities to participate in BECCS and benefit from it (Buck et al., 2014)	–
6	• CCS requires water (Fajardy & Mac Dowell, 2017) and could contaminate groundwater it (Lawter et al., 2017)	–
	• Biomass production alters water runoff (upstream storage, downstream reduction; Farley et al., 2005; Smith, Davis, et al., 2016)	+/–
	• Land coverage can enhance local precipitation but also affect other regional precipitation patterns (Smith, Adams, et al., 2019)	+/–
7	• Energy penalty associated with CCS energy requirements (Fajardy & Mac Dowell, 2017)	–
	• Improved access to power if BECCS policies support new infrastructure in energy-poor regions (Urban et al., 2007).	+
	• Energy demand for fertilizer production (Smith & Torn, 2013)	–
8	• Biomass production and harvesting could offer an additional income to smallholder farmers or put them in unfair competition with large enterprises depending on policy design (Wang et al., 2020)	+/–
9	• Investment in CCS could stimulate technological innovation (Liu & Liang, 2011)	+
	• Impact on transport infrastructure between biomass sources, storage sites and CCS facilities (IPCC, 2005)	–
10	• New job opportunities in biomass production and harvesting could lead to an income growth of smallholder farmers or further disadvantage them depending on policy design (Wang et al., 2020)	+/–
12	• Large-scale BECCS deployment could limit the potential for sustainable production practices in agriculture and industrial production (EASAC, 2018; EASAC, 2019)	–
13	• Potential for mitigation via BECCS currently judged highest among all CDR approaches, but significant uncertainty regarding feasibility and desirability at large scales (IPCC, 2018)	+ –
	• Land-use change related emissions and potential forest displacement could increase emissions (Harper et al., 2018; Vaughan & Lenton, 2011)	+
	• Low risk of sink reversal (compared to biological sinks) (Fuss et al., 2018)	–
	• Risk of increased emissions due to high fertilizer input depending on the intervention's design (e.g. requirements of cultivated bioenergy crops) (Smith & Torn, 2013)	–
	• Carbon losses due to land-use change could undo sequestration results (EASAC, 2019)	

14	• Fertilizer runoff to oceans, rivers and lakes can result in toxin formation, species composition and food web shifts (Smith & Torn, 2013)	–
15	• Land requirement for additional biomass production causing pressure on biodiverse lands (Dooley & Kartha, 2018; EASAC, 2019; Smith, Davis, et al., 2016)	–
	• Increased mitigation efficiency per unit of biomass reducing overall land requirement (Smith, Adams, et al., 2019)	+
	• Fertilization can be problematic for biodiversity (Smith & Torn, 2013)	–
	• Plantations on degraded lands can help restore soils (Fuss et al., 2018)	+
Questions	• What are options to adapt BECCS to local circumstances (choice of various types of biomass (incl. waste-products), small-scale plants, avoidance of carbon-intensive land-use changes?	
	• How can policy instruments be based on understanding of local circumstances?	
	• How to identify regional potentials for geological storage?	
	• How to improve judgments of scale and feasibility in global mitigation pathways?	

Note: + positive consequence, - negative consequence, +/–: consequence depending on specific circumstances.

ensure any incentives are dependent on demonstrating improvements. Afforestation/reforestation can cause changes in albedo and evapotranspiration, which can result in additional local warming in Northern latitudes (Alkama & Cescatti, 2016), or cooling in the tropics where new clouds form due to new forest cover (Smith, Adams, et al., 2019). Targeted afforestation/reforestation can help to slow or halt desertification, but in unsuitable areas such afforestation can also lead to nutrient and water scarcity as well as fertilizer runoff with implications for local ecosystems and communities (Nosetto et al., 2012). The filtering capacity of forests can enhance air quality, but large-scale forest fires can also cause haze problems (Smith, Adams, et al., 2019). Freshwater quality and quantity can be enhanced due to the capacity of forest soils for water retention and filtering; yet the added water consumption of forests can also limit availability depending on local precipitation patterns (Jackson et al., 2005; Veldman et al., 2015). Formation of soils, soil quality, nutrients, and soil organic carbon can be altered by afforestation/reforestation in positive and negative ways, depending on local conditions. Afforestation/reforestation can reduce impacts from extreme weather events by slowing winds and providing flood- and erosion control (Smith, Adams, et al., 2019).

The restoration of wetlands by re-establishing wetland hydrology and reintroducing native vegetation in freshwater and coastal wetlands offers significant benefits for clean water, fisheries productivity, flood-protection for urban and rural communities, aquatic and land ecosystem protection, improving air quality, and CO_2-removal (Kadlec et al., 2000; Kroeger et al., 2014; Nagelkerken et al., 2008; Robertson A & Phillips M, 1995; Ronnback, 1999). However, wetland restoration can also conflict with agriculture and aquaculture food production, and local livelihoods (Kreidenweis et al., 2016).

Climate policy around forestry and land-use change has seen mixed success to date (IPCC, 2019), as land-use pressures rise in many countries and international support has been inconsistent (Pasgaard et al., 2016). Risks of reversals from future land-use changes (and thus depending on policy consistency) or forest fires are significant (Henders & Otswald, 2012).

Scale and policy design determine afforestation and ecosystem restoration implications for SDG delivery. Large-scale monoculture plantations executed in a top-down, non-participatory manner are likely to result in negative implications for delivering many of the SDGs (Bonsch et al., 2016; Heck et al., 2016). On the other hand, community-driven and locally appropriate approaches to forest ecosystem restoration might consistently achieve CDR in ways that ensure substantial, net positive implications for SDG delivery (IPCC, 2018, pp. 462–463). Policy design at national levels may be challenging as key drivers of success are based on local conditions (Le et al., 2012). Table 3 offers an overview of potential consequences, along with open questions.

4.3 Enhancing agricultural soil carbon

Soil carbon sequestration aims to increase soil carbon stocks through land management practices such as reducing tillage (Chabbi et al., 2017; Powlson et al., 2014), agro-forestry (production of crop, livestock, and tree biomass on the same land; Lorenz & Lal, 2014), or by introducing biochar (Lehmann et al., 2015). Biochar production can lead to land-use conflicts comparable to those of BECCS (IPCC, 2019). Soil carbon sequestration potentials vary regionally and are limited once soil carbon reaches an equilibrium (Smith, Davis, et al., 2016). Although restoring levels of carbon lost from historic land-use change would correspond to 840 Gt CO_2 removed (Lal, 2001), maximum global removal rates are estimated at only 1 Gt CO_2 per year (Chabbi et al., 2017) due to challenges in altering production practices and trade-offs with productivity (Pittelkow et al., 2015).

Practices adapted to local soil compositions can enhance water retention capacities (Bamminger et al., 2016), reduce soil erosion, enhance crop production (by approximately 10%; Jeffery et al., 2011), counteract acidification (Dai et al., 2017), and sustain soil fertility, but trade-offs among these effects can also exist, particularly if measures are not adapted to specific soil compositions (Ding et al., 2016b; Smith, Haberl, et al., 2013). Biochar soil amendments can also lower nitrous oxide and methane emissions (Kammann et al., 2017).

Policy designs that prioritize carbon sequestration above other objectives could negatively affect biodiversity (Morán-Ordóñez et al., 2017) as excessive biochar application could alter microbial soil composition (Jiang et al., 2016). Soil carbon increases can also darken the soil thus causing local warming if soil is exposed (Bozzi et al., 2015). Biochar particles released during production, transportation and distribution can affect air quality and health (Yargicoglu et al., 2015), and cause further warming (Genesio et al., 2016; Ravi et al., 2016). Rapid

Table 3. Summary of potential consequences of afforestation, reforestation, and ecosystem preservation or restoration for SDGs.

SDG	Potential implication	Type
1	• Risk of displacement of indigenous communities or isolation of people from ecosystem services (Smith & Torn, 2013; Smith, Adams, et al., 2019)	–
	• Forestry and land use responses can contribute to the eradication of poverty if they do not increase competition for land (IPCC, 2019, *p.* 20)	+/–
	• Wetland restoration can impact local livelihoods (Kreidenweis et al., 2016)	–
2	• Potential displacement of existing land uses for subsistence production (Dooley & Kartha, 2018)	–
	• Re-/afforestation of fast-growing species can lead to nutrient and water scarcity (Nosetto et al., 2012)	–
	• Re-/afforestation of mixed native species and ecosystem restoration reduces run-off and erosion (Dooley & Kartha, 2018)	+
3	• Climate change-related health impact attenuation due to successful forestry and land use policies could potentially surpass potential health hazards (e.g. avoided deaths from malnutrition, avoided forced migration and associated health risks, reduced pervasiveness of malaria, diarrhoea and heat stress) (WHO and WMO, 2012)	+
	• Attenuation of landslide and storm hazards for health (Smith, Adams, et al., 2019)	+
4	• Climate change mitigation by forestry and land use policies could help maintain opportunities for education (via poverty alleviation, nutrition, health, prosperity, infrastructure; Glewwe, 2005)	+
5	• Women could potentially be disadvantaged regarding their participation in decision-making processes on community-managed re-/afforestation efforts (Ahimbisibwe et al., 2019)	–
6	• Biomass production altering water runoff (enhanced retention can be positive or negative) (Smith, Adams, et al., 2019; Veldman et al., 2015)	+/–
	• Tree coverage can enhance local precipitation, but also weaken precipitation elsewhere (Smith, Adams, et al., 2019)	+/–
	• Restoration of wetlands can improve water quality and availability (Nagelkerken et al., 2008)	+
7	• High energy demand for conventional fertilizer production (Smith & Torn, 2013)	–
	• Ecosystem restoration has negligible energy requirements (Royal Society, 2018)	+
8	• Re-/afforestation projects could offer an additional income to smallholder farmers or disadvantage them depending on accessibility to incentives.	+/–
10	• Risk of displacement of vulnerable populations, thus further increasing inequality (Dooley & Kartha, 2018)	–
13	• Climate policy around forestry and land use has revealed mixed success to date (IPCC, 2014)	+/–
	• Local warming in mid- and high-latitudes due to reduced albedo through re-/afforestation with certain species (Smith, Adams, et al., 2019)	–
	• High risk of carbon leakage due to forest fires, pests and future land-use changes (Henders & Otswald, 2012; Streck & Scholz, 2006)	–
	• Climate change itself contributes to a higher risk of sink reversals (IPCC, 2014)	–
	• Risk of increased emissions due to high fertilizer input depending on the intervention's design (Smith & Torn, 2013)	–
14	• Fertilizer runoff to oceans, rivers and lakes can result in toxin formation, species composition and food web shifts (Smith & Torn, 2013)	–
15	• Re-/afforestation projects can improve soil quality, and counteract desertification and erosion (Nosetto et al., 2012)	+
	• Ecosystem restoration can increase ecosystem resilience (and reduce the risk of carbon reversals; Dooley & Kartha, 2018)	+
	• Land degradation and biodiversity loss can be reversed or aggravated if interventions are (not) suitable to local conditions (Dooley & Kartha, 2018; Smith & Torn, 2013)	+/–
17	• International transfers around re-/afforestation or ecosystem preservation/restoration can strengthen or erode international institutions depending on the quality of the policy design	+/–
Questions	• How do social, economic and legal structures intersect with reforestation and ecosystem preservation potentials?	
	• How can locally appropriate participatory policies be designed; informed by robust understanding of local cultural and socio-economic conditions?	
	• What policy instruments, institutional structures and accounting rules can hedge biosphere carbon storage from reversal risks?	

introduction of policies regarding agricultural practices could cause short-term fluctuations in local food prices; a phased and gradual introduction with close monitoring of effects on food prices might reduce or avoid such problems (Humpenöder et al., 2018). Soil carbon enhancements could potentially be implemented via participatory, community driven approaches, with benefits for a range of SDGs; the opposite could also be true if, instead, policies cater to large-scale and non-participatory agricultural practices. Table 4 offers a summary of the potential consequences, along with open questions.

4.4 Enhanced weathering or ocean alkalization

As part of the inorganic carbon cycle, silicate rock weathers, reacts with dissolved atmospheric CO_2, and forms limestone on land or in the ocean. Spreading powdered silicates onto the land surface would accelerate the uptake of CO_2. Effective rates of reaction under real-world conditions are not fully understood (Hartmann et al., 2013; Strefler et al., 2018). Limestone reaching the oceans would counteract ocean acidification, thereby enhancing CO_2-uptake at the water–air surface. Ocean alkalization would achieve the same by dispersal of alkaline minerals directly in the ocean. The physical removal potential is very large (up to 940 Gt according to González and Ilyina (2016)), yet limitations might arise from the logistical implications of producing vast quantities of powdered minerals. Large-scale mining and grinding operations and physical distribution could have implications across a range of sustainability dimensions. Airborne powder could have health implications. Mining, transport and distribution could come with substantial public expenditure with limited local benefits (cost estimated at US$60-200/t$CO_2$; Strefler et al., 2018). Ecosystems and food production on land and under water could benefit from counteracting acidification (Feng et al., 2016; Raupach et al., 2014). Enhanced weathering can also increase agricultural productivity as some rocks also contain elevated concentrations of potassium, phosphorus, and silicon (Beerling et al., 2018; Kantola et al., 2017).

Policies and practices would, however, need to ensure farmers are incentivized to evenly apply minerals and monitor effects on soil chemistry. Large uncertainties are associated with ocean dispersal methods including on how to achieve even distribution to avoid excessive changes in ocean water chemistry and what monitoring would be required to adapt applications to new insights. Potential effects of enhanced weathering and ocean alkalization and open questions are summarized in Table 5.

4.5 Direct air carbon capture and storage

Direct Air Carbon Capture and Storage (DACCS) describes the combination of direct capture of CO_2 from ambient air via a chemical process with subsequent geological storage. The most important resource requirement is the heat and power needed for the capture and storage processes (Gambhir & Tavoni, 2019). Some DACC approaches rely for the most part on low-temperature heat (80-120°C; Beuttler et al., 2019), which can to a limited degree be sourced as waste-heat from industrial facilities (Ammar et al., 2012). Costs for the capture process are presently high (several hundred US$ per tCO_2), but they could come down significantly (Sinha et al., 2017), by some estimates to US$100 by 2030 (Beuttler et al., 2019) in addition to the costs of geological storage (estimated at US$8-20 per tCO2; Skagestad et al., 2015). Costs and energy requirements likely dominate possible implications for the SDGs and could severely limit CDR potential of DACCS. If deployed where there is excess low-carbon heat and power, there are no foreseen implications for ecosystems or land-use conflicts, and no foreseeable health or ecosystem implications other than those associated with CCS (as described in section 4.1). Table 6 summarizes the identified potential impacts of DACCS and open questions.

4.6 Ocean fertilization

Phytoplankton living on or near the ocean surface contribute substantially to the ocean's large CDR capacity. A small fraction of plankton biomass continuously sinks to great depths before decomposing – a process known as the 'biological carbon pump' (Volk & Hoffert, 1985). Phytoplankton growth is often limited by nutrients such as nitrate, phosphate, or iron. Fertilizing surface waters with growth-limiting micro or macronutrients can

Table 4. Summary of potential consequences of enhancing agricultural soil carbon for SDGs.

SDG	Description of potential impact	Type
1	• Biochar requires biomass feedstock production and can either in- or exclude the local population depending on the intervention's design (Royal Society, 2018) • Soil carbon sequestration can result in short-term productivity reductions yet long term yield stability improvements (Pittelkow et al., 2015)	+/– +/–
2	• Biochar additions can counteract soil acidification (Lal, 2008) • Enhanced soil carbon can have negative or positive effects on yield depending on soil types, environmental conditions (Fuss et al., 2018) • Biochar use in agricultural practices can enhance agricultural resilience (Humpenöder et al., 2018) • Biochar can lead to a lower defence effectiveness of plants (Fuss et al., 2018)	+ +/– – + –
3	• Biochar production and transportation may cause respiratory health issues (Yargicoglu et al., 2015) • Biochar can stabilize heavy metals, prevent them from entering food chains (Royal Society, 2018)	– +
5	• Without dedicated support measures, women may be disadvantaged due to limited access to enabling infrastructures for implementing soil carbon enrichment efforts (Tsige et al., 2020)	–
6	• Altered soil composition can enhance water retention, which can be positive or negative depending on up- and downstream water requirements (EASAC, 2018) • Recommended land management practices have a positive impact on water quality (Lal, 2008)	+/– +
7	• Production, wastewater treatment (after pyrolysis process), transportation and handling of biochar is energy-intensive (Royal Society, 2018; Yargicoglu et al., 2015)	–
8	• Yields can increase due to soil carbon enrichment thus improving living conditions of farmers will improve (Smith, Adams, et al., 2019)	+
9	• Investments in biochar production technologies and application strategies could stimulate innovation (Pourhashem et al., 2019)	+
10	• Inequalities between rural and urban areas could be improved or worsened depending on whether interventions are designed such that smallholder farmers can access them with limited transaction costs • Increased self-sufficiency due to higher yields contributes to the reduction of inequality	+ +
12	• Enhanced soil carbon can improve soil productivity (Fuss et al., 2018)	+
13	• Capacity of soil carbon sequestration varies regionally (Chabbi et al., 2017), greatest potential for biochar in warm and moist climates (EASAC, 2018) • Accumulation of soil carbon content previously lost due to land-use change takes decades (Chabbi et al., 2017) • Soil carbon accumulation potentials are limited and prone to reversals if not continuously applied (Fuss et al., 2018) • Biochar may be less prone to reversals (Fuss et al., 2018) • Potential local warming due to darker soil and airborne biochar dust (EASAC, 2018) • Biochar can prevent N_2O or CH_4 emissions (Fuss et al., 2018) • Biomass use for biochar production and for BECCS are in competition with each other (EASAC, 2018)	+/– – + – + –
15	• Biochar additions can counteract soil acidification (Lal, 2008) • Soil carbon sequestration can lead to improved soil quality (Lal, 2008)	+ +
Questions	• What policies could induce locally adapted changes in farming practices that benefit smallholder farmers, and strengthen food security and soil quality? • What instruments, structures and accounting rules can hedge from reversal risks? • How can soil carbon sequestration be integrated in regional and national planning? • How can soil carbon saturation be considered in policy instruments?	

Table 5. Summary of potential consequences of enhanced weathering or ocean alkalization for SDGs

SDG	Potential implication	Type
1	• Increased food production due to fertilization and alkalinisation; nutrients released could help counteract rising fertilizer prices (Fuss et al., 2018)	+
2	• Enhanced weathering can have a fertilizing effect on agriculture and fisheries (Royal Society, 2018) • Application to soils would likely benefit food production unless applied excessively (Royal Society, 2018)	+ +/–
3	• Mining and distribution of powdered minerals worsens respiratory health (EASAC, 2018; Patra et al., 2016)	– –
6	• Land application increasing alkalinity could cause release of heavy metals into groundwater, river water and coastal zone water (Fuss et al., 2018)	–
7	• Large energy requirements of rock grinding and transportation (EASAC, 2018), conventional calcination (GESAMP, 2019) and distribution operations	–
8	• Enhanced weathering could enhance agricultural productivity (Royal Society, 2018)	+
9	• Pressure on transport infrastructure between rock sources, rock grinding facilities and deployment sites (Fuss et al., 2018) • Investments in enhanced weathering/ ocean alkalinisation could stimulate the development of unconventional technologies (Fuss et al., 2018)	– +
10	• Locally appropriate distribution benefiting soil productivity particularly in poor populations could help reduce inequality by fostering productivity (Smith, Adams, et al., 2019)	+
12	• Effects on soil chemistry with (un)favourable impacts on sustainable food production depending on the ecosystem (Fuss et al., 2018)	+/–
13	• Uncertainties remain regarding the effective rate of weathering under varying conditions (EASAC, 2018; Hartmann et al., 2013; Strefler et al., 2018) • High permanence: Mean residence time of carbonate minerals or ocean alkalinity is long (Gattuso et al., 2018; GESAMP, 2019) • Large mitigation potential due to an abundance of raw material, yet unknown logistical constraints (EASAC, 2018).	+/– + +
14	• Enhanced weathering leading to ocean alkalinisation that counteracts CO_2-induced ocean acidification (Feng et al., 2016; Gore et al., 2019) • High uncertainties regarding biochemical effects on biodiversity; distributed dispersal important due to otherwise very large local ecosystem changes (Gore et al., 2019) • Application in the open water could potentially release heavy metals and impact marine ecosystems (Fuss et al., 2018)	+ – –
15	• Enhanced weathering can counteract soil acidification (Fuss et al., 2018) • Mining and distribution of powdered minerals can harm land ecosystems • Land-use requirements for low-carbon energy production needed for grinding minerals could pose problems (EASAC, 2018)	+ – –
17	• Interventions in international waters require further international cooperation and clarification of legal status (GESAMP, 2019)	+/–
Questions	• Can adverse health, and ecological effects from mineral powder dispersal be reduced/avoided? • What actors and stakeholders could be involved in-, benefit from, or be harmed by applications? • How might various forms of application (technologies, intensities and distribution) intersect with different land and water ecosystems? • What regulatory and institutional measures would be needed to prevent harm?	

Table 6. Summary of potential consequences of direct air carbon capture and storage for SDGs.

SDG	Description of potential impact	Type
1	• DACCS energy demands could conflict with energy access for the poorest (Jones & Warner, 2016). • The significant public spending required to operate large-scale DACS (and lack of co-benefits) could disadvantage poverty-alleviation efforts (Campagnolo & Davide, 2019).	– –
3	• Inappropriate storage site selection could affect groundwater drinking water in cases of (Wilkin & DiGiulio, 2010) and cause seismic activities (Fuss et al., 2018)	–
6	• Water requirements of CCS could be problematic, yet some DAC pathways capture water from air, offering it as co-product. (Beuttler et al., 2019; ICEF, 2018; IPCC, 2005). • CCS could affect groundwater chemistry and drinking water sourced from local groundwater wells (Lawter et al., 2017 Wilkin & DiGiulio, 2010;)	+/– –
7	• Low-carbon power requirements for direct air capture and for storage can conflict with local power needs (EASAC, 2018, 2019), yet balancing the grid by using off-peak power could help achieving a high-percentage renewable power mix (Beuttler et al., 2019).	+/–
8	• DACCS would likely require much higher public expenditure than current mitigation policies provide, by one or two orders of magnitude but could become more competitive over time and lower overall mitigation costs (Realmonte et al., 2019)	–
9	• DACCS requires big infrastructure investments competing for resources, but potentially sparking innovation (EASAC, 2018) • CO_2 transportation to storage sites could adversely affect transport systems (but less than transportation requirements of enhanced weathering) (IPCC, 2005).	+/– –
12	• Energy requirements could limit the low-carbon power availability for sustainable industrial production practices and for transportation (Palmer-Wilson et al., 2019).	–
13	• Low risk of sink reversal (compared to biological sinks) (Fuss et al., 2018)	+
14	• Some risk of local changes to water chemistry in case of leaking from sub-seabed CO_2 storage (GESAMP, 2019).	–
15	• Land requirements for production of necessary zero-carbon power (e.g. via wind or solar) could cause local land-use conflicts (Palmer-Wilson et al., 2019)	–
Questions	• What research and policy planning processes could allow reliably identifying regional and global potentials in light of resource demands for low-carbon power, waste heat and geological storage? • What are likely cost-reduction trajectories and what policies could accelerate cost-reductions? • What institutional and regulatory requirements could ensure storage site-identification processes are reliably conducted across the world in a way that ensures no future leakage? • What policy instruments could reliably incentivize the operation of CO_2 storage sites? • What regional implications of energy requirements of DACCS would have to be expected in different parts of the world and could DACS complement power fluctuations and run solely on peak power? • What role might cities and private actors play in implementing DACCS?	

accelerate growth, as demonstrated by natural dispersal of iron-rich desert dust or volcanic ash in oceans (Blain et al., 2007; Olgun et al., 2013; Pollard et al., 2009).

The effectiveness of ocean fertilization for CDR is not yet fully determined, with research in the open ocean yielding varying results. Evidence suggests that it is possible to enhance algal and plankton growth, but there remain serious uncertainties regarding the actual volume of CO_2 removed; in some cases second-order alterations in the oceanic food-chain have prevented the additional biomass from sinking to sufficient depths (Martin et al., 2013).

Deploying ocean fertilization using macronutrients (such as nitrate or phosphate) would require very large amounts of material. The corresponding mining and transportation operations could pose problems due to the associated energy demand and environmental pollution. With the same nutrients required in agriculture, such applications would also potentially compete with agricultural fertilization (Schäfer et al., 2015). Fertilizing with micronutrients (such as iron), would however require considerably less material for comparable results (2600-26,600 tCO_2 could potentially be removed for each tonne of iron added according to de Baar et al. (2008)) and thus drastically reduce further consequences along the supply-chain. Effects on life under water are complex: accelerated short-term productivity could have implications on long-term biological productivity (Denman,

Table 7. Summary of potential consequences of ocean fertilization for the SDGs.

SDG	Potential implication	Type
1	• Positive or negative effects on fisheries could variously affect poor populations who are depending on them (Gattuso et al., 2018; GESAMP, 2019)	+/−
2	• Both increase (GESAMP, 2019) and decrease (Gattuso et al., 2018) of fisheries are possible.	+/−
	• Algal productivity can be enhanced, yet unwanted second-order effects in ocean food-webs are also possible (Güssow et al., 2010)	+/−
3	• Dust particles could induce respiratory problems if they become airborne along the production process of ocean fertilization (Patra et al., 2016)	−
6	• Mining, grinding and transportation of large quantities of minerals could result in additional and unwanted pollution of water sources	+/−
7	• Substantial energy requirements for iron sulphate production, transport and distribution could be problematic (Royal Society, 2018)	−
9	• Ocean fertilization would require substantial transport and distribution infrastructure (Royal Society, 2018)	+/−
13	• Significant uncertainties regarding the actual volume of CO_2 removed at current scientific understanding preclude imminent applications for climate action (Royal Society, 2018)	−
	• Unintended effects on ocean biogeochemistry may also influence the production and fluxes of trace greenhouse gases, such as methane and N_2O that could reduce or undo the benefits derived from increased uptake of CO_2 (Royal Society, 2018)	−
14	• Algal productivity can be enhanced, revitalize oceanic ecosystems; yet unwanted second-order effects on ecosystems are also possible (GESAMP, 2019).	+/−
	• Potential subsurface ocean acidification, deoxygenation; altered regional meridional nutrient supply, fundamental changes to food webs (EASAC, 2018; GESAMP, 2019)	−
16	• Need to address challenging jurisdiction of the high seas, and transboundary issues for coastal waters (GESAMP, 2019)	−
	• Lacking clarity regarding applicability of national marine protection laws, CBD decisions, and LC/LP depending on scale and type of intervention (GESAMP, 2019)	−
	• The applicable London Protocol amendment is not yet in force, but could provide some regulation. (GESAMP, 2019)	+/−
17	• Risk of conflict if marine resources are significantly affected or changes are misattributed to an intervention (GESAMP, 2019)	−
Questions	• How could ocean fertilization be robustly governed by international law and institutions pertaining to the high seas or coastal waters?[a]	
	• How might ocean fertilization affect complex interactions within ocean food-chains and oceanic chemistry, as well as the associated impacts on fisheries?	
	• How could governance of the high seas be strengthened including to address issues related to ocean-based CDR?	

[a]GESAMP (2019) identify starting points for governance.

2008; Matear & Elliott, 2004) and ocean acidity (Cao & Caldeira, 2010). Impacts on the food web are hard to predict (Strong et al., 2009) and in case of overfertilization, excessive blooms could cause patches of oxygen depletion (anoxia) (Russell et al., 2012) or toxicity (Denman, 2008). Deep waters could potentially also be affected by a decline in oxygen content (Matear & Elliott, 2004). As a consequence of second-order changes in the food-web and associated water chemistry, production of nitrous oxide and methane can occur; such effects are scale- and concentration dependent (Denman, 2008).

Should further research consistently find ocean fertilization to work as intended, it could potentially be executed in such a way as to cause beneficial outcomes on fishery productivity. However, given significant uncertainties (Aumont & Bopp, 2006) and likely regional differences, negative outcomes for food production and life under water are also a possibility. Table 7 summarizes potential impacts of ocean fertilization on the SDGs, along with open questions.

5. Conclusions

Exploring potential impacts of various CDR technologies and practices driven by dedicated policies on the pursuit of SDGs reveals that CDR of the same type may have different impacts depending on the situation in which it is implemented. Thus, specific impacts can only be judged in the context of specific local circumstances, considering economic and social structures, rule of law and quality of institutions, local or regional governance, and environmental conditions.

We can make some observations applicable to CDR policy planning overall: policies designed to firmly prioritize one goal over all others can trigger serious and arguably avoidable trade-offs between SDGs (Smith, Adams, et al., 2019). Experience with policy design and implementation in the areas of land-use and land-use change (Dang et al., 2019), CCS in industry (Lipponen et al., 2017), roll-out of alternative energy technologies (including biofuels, in particular) (Breetz, 2020) and international carbon markets (Michaelowa et al., 2019) all offer crucial lessons for the intricacies involved in navigating the specific circumstances in the socio-environmental dimensions named above. While deployment of any one CDR technology at the large scale foreseen in IAMs is unlikely, as the need for a portfolio approach is increasingly recognized, our review shows there may still be potential negative consequences at all scales of application. This means that early and ambitious political action to reduce emissions is required to lessen our reliance on CDR for a given mitigation pathway. In this context, it is critical that policy planning and governance for both emission reductions and CDR not unduly prioritize one objective over all others, but is done mindful of all SDGs.

More transdisciplinary and geographically diverse research is required on the interconnections between various CDR approaches and the delivery of SDGs. To advance international climate policy, this may also include the development of common assessment principles or metrics for judging sustainable development impacts consistently across regions. Such efforts, however, should not be misinterpreted to produce globally applicable assessments for entire categories of potential CDR approaches concerning their specific performances on the project level. Rather, common assessment metrics would allow for the conduct of assessments on a case-by-case basis, thereby offering specific insights into expected impacts for specific social, economic, and environmental circumstances and a specific activity or policy design.

Domestic CDR policies or activities should be analyzed regarding their potential risks and benefits in national contexts as part of the periodic planning processes provided for under the Paris Agreement for revising NDCs every five years or updating long-term low GHG emission development strategies. This would allow assessment of the local suitability of portfolios of CDR and emissions reductions measures holistically, avoiding the errors of omission and overlap that are all too common for parallel policy planning processes. Such policy impact analysis should build on both quantitative and qualitative approaches, as well as on a deep understanding of national circumstances, while avoiding harm to vulnerable populations and negative transboundary effects. As experiences accrue, countries may learn from one another, and with increasingly accurate bottom-up potential estimates, uncertainties around global CDR potentials would gradually be reduced. In light of the global urgency to tackle climate change, many countries will require support in this process, which international cooperation institutions might provide as they have in the past concerning mitigation policy planning. The shared benefit will be to lessen the risks of over- or underestimating mitigation effectiveness and sustainable development impacts.

Assessments of consequences of CDR for SDGs should become more explicit as to their empirical basis and increasingly include experiences of pilot activities as they start to emerge. In our review, we find that assessments often integrate findings across three empirical processes to state their findings on aggregate level SDG performance of a particular category of technologies or practices: extrapolations from present pilot activities; inference from lessons from similar technologies or practices already put in place; and inference from modelled land-, energy or material requirements. Much commentary focuses on the latter, thus overlooking the need for case-specific learning. Unfortunately, many commentators infer general claims about the (lack of) sustainability independent of scale or form of application. This can result in unfortunate generalizations and overstated certainties of outcomes, characterizing, for instance, particular approaches as unsustainable under all circumstances, when such judgment might only apply to the very large scales or particular circumstances of implementation.

More work in this space would help improve policy planning by bringing into focus a broader range of possible outcomes, contribute to alignment of climate change mitigation with established globally shared visions of sustainable development, and help overcome polarization (Thiele, 2019) that may have slowed policy attention given to CDR to date.

Note

1. Removal of non-CO_2 GHGs has so far not been addressed in the scientific literature to a significant extent.

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