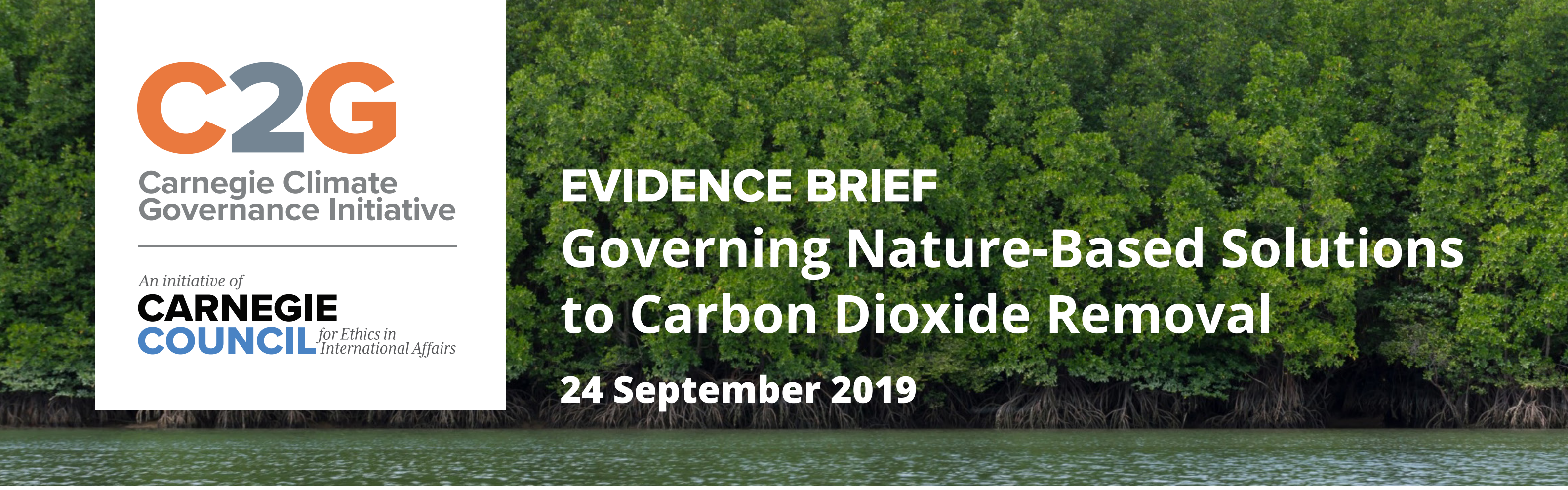


C2G Carnegie Climate Governance Initiative

An initiative of CARNEGIE COUNCIL for Ethics in International Affairs

EVIDENCE BRIEF
Governing Nature-Based Solutions to Carbon Dioxide Removal

24 September 2019

This briefing summarises the latest evidence relating to the governance of Nature-Based Solutions (NBS) to Carbon Dioxide Removal (CDR). It describes a range of techniques currently under consideration, exploring their technical readiness, current research, applicable governance frameworks, and other socio-political considerations. It also provides an overview of key instruments relevant for the governance of NBS based CDR.

Introduction

Almost four years after the Paris Agreement on climate change, recognition is growing that without a rapid acceleration in action, limiting global average temperature rise to 1.5-2 degrees Celsius will not be achieved through emissions reductions or existing carbon removal practices alone. Scientists have begun exploring the additional use of large-scale CDR techniques to limit climate impacts, including keeping temperature rise down.

CDR now features in many climate change mitigation scenarios consistent with achieving the goals of the Paris Agreement (IPCC 2018) and, in the light of the mitigation measures taken to date, carbon budgets are increasingly tight (Rogelj et al., 2015) and CDR options are increasingly being proposed as compensation for temporary overshoots (UNEP, 2017). Indeed, Fuss (2014) and Minx et al., (2017) conclude that there are now no scenarios available which can constrain warming to below 1.5°C by 2100, unless CDR is adopted at scale.

A range of approaches to CDR are under consideration and a distinction is often made between technological or natural approaches (NAS, 2019 UNEP, 2017), with the latter being increasingly referred to as 'Nature-Based Solutions' (NBS). This briefing focuses on these NBS approaches to CDR. It describes techniques currently under consideration and explores their relative strengths and weaknesses. Current applicable governance frameworks are examined and other socio-political issues pertinent to these large-scale interventions, including interrelationships with the Sustainable Development Goals (SDGs), are explored. The techniques discussed still require further research, governance dialogue and decision making, even though some are already being deployed, although not at scales capable of delivering climate scale impacts (see table 2).

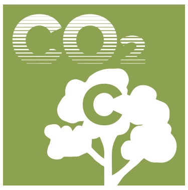
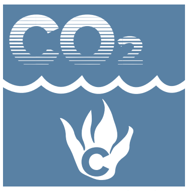
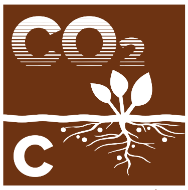
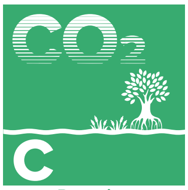
The Carnegie Climate Governance Initiative (C2G) has no position on the appropriateness of any of the techniques described here; we seek only to broaden the discourse about them and catalyse debate about the future of such techniques by providing this impartial overview. The briefing is not a comprehensive, detailed assessment of the techniques; rather it provides a description of each and a brief analysis of readiness, the research landscape, governance and socio-political issues associated with each (summarised in table 1 - table 2 indicates their CO_2 sequestration potential).

For more detailed reading please refer to the comprehensive works by the Intergovernmental Panel on Climate Change (IPCC), the Royal Society, International Union for Conservation of Nature (IUCN), McLaren and Minx et al., (IPCC, 2018, IPCC, 2019, RS/RAE, 2018, IUCN, 2016).

C2G

Table 1. Overview of evidence on NBS CDR Techniques

(Legend: Green – no significant issues; Orange – issues remain)

Techniques	Readiness	Active Research Area	Governance Framework	Social Acceptability
 Afforestation and forest ecosystem restoration	Already widely practiced. Could be deployed at scale with little further development.	Yes. Exploring gas fluxes from trees, land use change effects and albedo changes.	The United Nations Framework Convention on Climate Change (UNFCCC), Kyoto Protocol, Paris Agreement, the Food & Agricultural Organisation (FAO). Questions remain regarding social justice (i.e., land use issues). A requirement for better monitoring, verification and reporting of achieved sequestration.	Competing demands for land use need governance. A lack of financial incentives to encourage afforestation.
 Macroalgal cultivation for sequestration	Technologies are readily available. Development may be required to maximise methane and CO_2 capture and use.	Yes. Limited research underway.	Dependent on the location of cultivation, which could be within in-shore or off-shore waters. The FAO may have interests.	As an extant farming method, a proliferation of the technique will not pose insurmountable challenges.
 Carbon sequestration in soils	No significant barriers. Some have adopted the practice. Limited knowledge of the techniques in the agriculture community.	Yes. A better understanding of gas fluxes from enhanced soil is required.	The UNFCCC and Paris Agreement, the FAO and the 4p100 initiative. A requirement for better monitoring, verification and reporting of achieved sequestration.	No major social concerns.
 Restoring wetlands	Requires little new technology.	Yes. Reducing methane release and its capture.	The UNFCCC, Kyoto Protocol, Paris Agreement and FAO. Land use trade-offs. A requirement for better monitoring, verification and reporting of achieved sequestration.	A key barrier may be the lack of financial incentives to encourage land-use change.
 Building with biomass	Widely practiced.	Yes. Improving materials strength & combustion protection. Reusing materials during decommissioning.	Imported timber may, in the future, require international agreement re carbon credit allocation. Potential governance issues around land-use change.	No major social concerns. Some barriers in construction industry related to uptake.
 Biochar	A well-established technology with an evolving market.	Yes, explorations of decomposition rates and the relationship with feedstock and temperature.	State and customary law, UNFCCC and FAO. Better reporting, monitoring and verification is required. A transboundary trade in biochar may require international agreement regarding carbon credit allocation.	No major social concerns.

C2G

Background

Scope

This evidence brief is focused only on those NBS methods that are directed at the intentional capture, removal and long-term storage of CO_2. Whilst such methods often also provide other human well-being, ecosystems and biodiversity benefits, this brief only focuses on their climate change related implications. It should also be noted, that it does not explicitly cover CDR and the approaches discussed here do not include measures captured by the Convention on Biological Diversity (CBD) categorisation of 'Ecosystem-based Adaptation' (CBD, 2009) which is defined as:

> "The use of biodiversity and ecosystem services ... to help people adapt to the adverse effects of climate change" which "may include sustainable management, conservation and restoration of ecosystems, as part of an overall adaptation strategy that takes into account the multiple social, economic and cultural co-benefits for local communities."

An important caveat

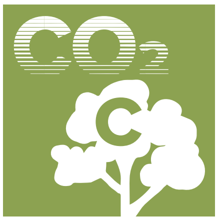
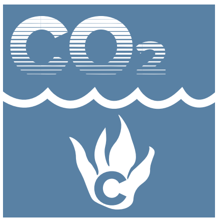
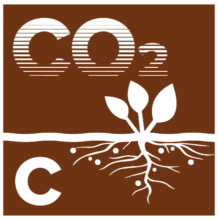
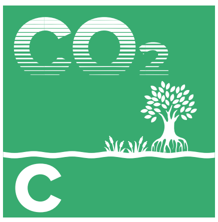
The use of the term NBS, and especially the word 'solutions', in this context, raises questions about possible moral hazard. 'Solutions' implies a certain level of effectiveness – i.e., that they can resolve the problems of climate change. This could give rise to a reduced sense of urgency among policy makers, and others, about the need to move quickly and decisively to reduce greenhouse gas emissions to avoid catastrophic climate change, this position is sometimes described as a 'moral hazard' (Lenzi 2018). Whilst, as demonstrated in this brief, NBS could, with the right policy, political and governance environment in place, make important contributions to efforts to constrain warming to below 1.5°C by 2100, they cannot provide the solution to the challenge (Griscom et al., 2017, IPCC, 2014a, Smith, 2013, Houghton, 2013, Pacala and Socolow, 2004).

Whilst 'Nature Based Approaches' might then be a more accurate descriptor of the interventions discussed in this brief, the nomenclature of NBS is used here given its wider usage. Table 2 provides a summary of the potential theoretical maximum capacity of the various techniques discussed in this brief to sequester carbon and, where evidence is available, what the potential cost of an intervention may be. The data in table 2 is drawn from peer-reviewed articles. However, there are multiple assessments of many of the techniques, for example Fuss et al., note that there are 22 papers that include technical potentials for carbon sequestration in soils and that 'none of the assessments of the area provide a systematic, comprehensive and transparent analysis rooted in a formal review methodology' (2018). These assessments should then be viewed as advisory or for guidance only.

With its focus on nature-based systems this brief does not include any coverage of the technique known as Bioenergy with Carbon Capture and Storage (BECCS). BECCS is an engineering approach to using carbon sourced from nature, rather than a nature-based technique. In brief, BECCS works from the principle that bioenergy can be produced with very low, or potentially zero CO_2 emissions. Biomass is grown as feedstock and burnt to generate energy. The gasses released from the combustion process are captured at source and sequestered permanently (e.g., in geological formations) effectively taking the emissions out of the carbon cycle. C2G intends to produce briefings about BECCS in the near future. In the meantime, Daggash et al., (2018) technology and policy assessment of BECCS is suggested for those interested in further information.

C2G

Table 2. Potential sequestration capacity and costs of NBS techniques

Techniques	Potential Sequestration Capacity	Potential Cost of Deployment
 Afforestation and forest ecosystem restoration	3 – 18 $GtCO_2$ per annum (pa) (Griscom et al., 2017).	Between $15 and $30 per ton of CO_2 (Smith et al., 2015).
 Macroalgal cultivation for sequestration	If 9% of the oceans were converted to macroalgal aquaculture it would create 12 Gt pa of bio digested methane. This could be burned as a substitute for natural gas. The biomass involved would capture 19 Gt of CO_2. An additional 34 Gt CO_2 could be captured, if the CO_2 produced by burning the methane was captured and sequestrated. (N'Yeurt et al., 2012).	Yes. Limited research underway.
 Carbon sequestration in soils	Modeling estimates suggest between 1 – 11 $GtCO_2$ pa ((Lal, 2011, Lal, 2013, Minasny et al., 2017).	A potential for profit of up to $3 per ton of CO_2 through improved productivity, in other circumstances, deployment may cost up to $12 per ton (Smith, 2016).
 Restoring wetlands	Between 0.4 – 18 tons of CO_2 per hectare pa, scaling to a global potential of approximately 1 $GtCO_2$ pa by 2030 (Bain, 2011).	Estimated in the range of $10 – $100 per ton of CO_2 (Kayranli, 2010).
 Building with biomass	Between 0.5 – 1 $GtCO_2$ pa by building with biomass in place of conventional materials (McLaren, 2012).	Not available.
 Biochar	1 ton of biochar can remove between 2.1 – 4.8 tCO_2 (Lehmann, 2015, Hammond et al., 2011). Globally biochar could theoretically remove between 1.8 – 4.8 $GtCO_2$ pa (Woolf et al., 2010).	Costs of biochar production range from $18 – $166 per tCO_2 (Woolf et al., 2010).

Natural systems and carbon

Ecosystems play a critical role in the global carbon cycle, and when adequately preserved they act as very large carbon sinks and stores (IUCN, 2016). Protected terrestrial areas contain 15% of global terrestrial carbon reserves, making a critical contribution to climate change mitigation (IUCN, 2016). Any degradation of these sinks, or outright loss of them, would result in the release of large quantities of greenhouse gases (IUCN, 2016). For example, deforestation and soil loss currently produce almost 20% of greenhouse gas emissions (IUCN, 2016).

NBS seek to use these natural carbon sink capacities to increase the natural storage of carbon. For the approach to maximise its potential, it then also follows that, in addition to the use of the approaches described below, steps also need to be taken to protect the environment's current natural sinks from degradation (IUCN, 2016).

Because biodiversity, ecosystems and human capacity may be affected by human interventions in the natural system, NBS will be an area appropriate for governance dialogue (IPCC, 2018). The natural systems that NBS would exploit, or potentially enhance, provide essential ecosystems services to Earth and humanity. They already support carbon storage as well as providing oxygen production, food and income generation, and flood and storm protection (IPCC, 2018). This suggests that any future development of NBS should be done in the context of a careful consideration of their environmental consequences. The socio-political challenges associated with changing natural systems may also be testing (Buck, 2016). The natural environment retains a special place in the culture, economy and environmental awareness of many societies (Thomas et al., 2018). It may then be the case that intentionally changing nature for the purposes of NBS will be met with hostility, as exemplified by responses to other intentional interventions in the environment (Elliot, 2019). This, coupled with important governance questions, such as: who would deploy, monitor, pay for and insure against harms of any interventions; how would they be governed; and, how might trade, food production and other resource extraction be affected (NERC, 2016), suggest a challenging governance environment which may require careful deliberation.

A range of NBS approaches are presented, and their technical or other readiness, associated research issues, any socio-political considerations and comments about their governance, are explored below.

Nature-Based Solutions CDR Techniques

Afforestation and reforestation

The principle

Afforestation and reforestation, described here collectively as 'forestation', exploits the photosynthesis process. As plants and trees grow, they absorb CO_2 from the surrounding atmosphere, storing it in their organic matter and soils. This process is driven by photosynthesis which harnesses energy from the sun. During photosynthesis, chlorophyll within chloroplasts inside plant and tree cells absorbs the light energy of the sun. Chloroplasts act as a collection point in the plant cell, storing the sun's energy until it can be used (see figure 1). This store of energy then acts upon water absorbed by the roots of the plant or tree by splitting the hydrogen from the oxygen inside a water molecule. Carbon dioxide in the atmosphere is then absorbed by the plant's leaves and paired with the hydrogen to produce sugar. The sugar is used as an energy source by the tree or plant and the extra oxygen created during this process is released into the atmosphere as a by-product. For further information, Morton (2008) provides a detailed review of photosynthesis, and its role in the environment and human civilisation.

Figure 1. The photosynthesis equation

$6CO_2$	+	$6H_2O$	+	LIGHT	→	$C_6H_{12}O_6$	+	$6O_2$
Carbon Dioxide		**Water**				**Sugar**		**Oxygen**

Forestation is the intentional planting of new trees in places where trees have not traditionally grown (afforestation), or replanting trees where they have been cropped, died or been removed by other means (reforestation). These processes of establishing or re-establishing forest areas takes up CO_2 as the trees grow. However, once a tree or forest reaches maturity, the uptake of CO_2 slows (Houghton, 2013). Once a tree's life cycle is complete it decomposes, and CO_2 is returned to the atmosphere (Read et al., 2009). However, this release of CO_2 can be avoided through forest management, with mature trees being harvested and the biomass stored in long-lived wood products (see Building with Biomass below), or with them being used for bioenergy or biochar (see below). Following harvesting, new planting and subsequent forest regrowth, or natural revegetation allows for continuing CO_2 removal.

The capacity to remove carbon through forestation is dependent on a range of factors including land availability, location, the species of tree planted, ability to manage the resource, and the long-term opportunity cost of tying up the land for forestry at the expense of other land uses, such as cropping, grazing or urbanisation (Popkin, 2019). Biophysical constraints will also play an important role, for example, soil quality, vulnerability to flood, drought, fire or disease and future effects of climate change.

The capacity for forestation to make a significant contribution to achieving global net zero greenhouse gas emissions is contested. Griscom et al., (2017) suggest the potential for forestation to remove carbon, ranges from between 3 to 18 $GtCO_2$ per year, with the variation dependent on assumptions about the land available for planting ranging from 350 to 1780 million hectares (MHa). For reference, the Earth's total land surface is 14.9 billion hectares (BHa) meaning up to 1.2% of the total available land surface of the planet would be required each year to achieve the potential, identified in this

study. A potential that would be insufficient to deliver any global cooling. In a more conservative assessment Smith et al., (2015) estimate a maximum sequestration through forestation of 12 $GtCO_2$ per annum by the year 2100. This compares to the IPCC (2018) estimated global CO_2 emissions in 2030 of 52–58 $GtCO_2$, which takes account of all the nationally stated mitigation ambitions as submitted under the 2015 Paris Agreement.

An additional 1 to 2 $GtCO_2$ per annum could potentially be sequestered if the full potential for global forestry management were achieved (Griscom et al., 2017).

The technique and its readiness

Afforestation and reforestation are already widely practiced throughout the world and there are no challenging technical constraints to overcome. However, there are several non-technical issues that remain unresolved.

Depending on how it is done, replacing other ecosystems with forests can have important biodiversity implications, with some species being marginalised whilst others may benefit. These ecosystem changes may have significant implications, both negative, or, where forestation occurs on previously degraded land, positive; for example, enhancing biodiversity, improving soils and reducing risks of flooding and erosion (RS/RAE, 2018). The type of tree that is introduced may also effect the acidity of run-off water and in turn the biodiversity of rivers (Thompson, 2019).

The locating of new forests is an important consideration. Temperature, albedo and precipitation locally and regionally can be effected by the planting of large forests, changes that, if planting is done at sufficient scale, can mitigate or enhance the effects of climate change in the affected areas (Griscom et al., 2017) and evidence suggests that such changes will not be trivial (Winckler et al., 2019, Luyssaert et al., 2018).

The cost estimates for afforestation and reforestation have been assessed at between $15 and $30 per ton of CO_2 (Smith et al., 2015) and their development will depend on the availability of land.

Current research activities

A better understanding of the balance of effects of planting trees between their carbon sequestration and warming effects is required. For example, shading by trees, particularly in higher latitudes and in mountains or dry regions, where dark leaved conifers predominate may have a negative effect. A recent modeling study of a range of European forest-management scenarios concluded that, because of the surface darkening and cloud cover changes created, any added forests would approximately eliminate their carbon-storage benefits (Luyssaert et al., 2018). More research on climate models is therefore required to better understand the full effects of changes to forestry cover (Winckler et al., 2019).

In addition, the effect of the complex chemicals that trees emit can affect their 'cooling' capability and this requires further research. For example, Pangala and Enrich-Prast et al., (2017) reported, for the first time, that trees emit around half of the Amazon's total methane. Subsequent studies have found that methane and nitrous oxide, also greenhouse gases, are emitted by trees in upland forests (Welch et al., 2019) and methane leaks from non-wetland trees in temperate forests (Covey et al., 2012).

It may be possible that forestation could, in some places, have a negative effect on the climate and research is ongoing to fully account for the impacts of forests. For example, research using very high towers in the Amazon and Siberia, and hundreds of other smaller towers globally, situated amongst various types of forest is exploring this by monitoring the carbon, water and other chemical fluxes of forests (Popkin, 2019).

Another set of key research challenges are economic and social. A better understanding of how to balance competing demands for land use, such as bio-fuel production, cropping and grazing with forestation in the most equitable, economically viable and socially acceptable way is required.

Socio-political considerations

There are different responses to proposals to plant trees globally, it is broadly welcomed in many European states, whilst in other countries, despite commitments in Nationally Determined Contributions (NDCs) to afforestation, it remains a contested space with significant issues surrounding the effects on extant ecosystems, land-tenure and equity (RS/RAE, 2018). Importantly, planting may undermine capacity for landowners to generate income in the short term, meaning they will want certainty regarding any payments that may be forthcoming to bridge the period between planting and harvest.

Natural environments have an aesthetic amenity value, which may be diminished or enhanced by forestation dependent on location and the residents' perspectives, which vary and are informed by cultural differentiation (Thomas et al., 2018). No 'one size fits all' approach can then be taken and careful consideration of local circumstance maybe important, before taking any decisions about where to afforest, or not.

Governance

Many states, including Brazil, China, India and Mexico include forestation in their NDCs under the Paris Agreement (UNFCCC, 2015). They are planned to meet 25% of all the committed mitigation under those NDCs. In addition, the Bonn Challenge (IUCN, 2011), a global effort to reforest 350 MHa of forest by 2030, has been endorsed and extended by the New York Declaration on Forests at the 2014 UN Climate Summit (UN, 2014). To date, the Declaration has been endorsed by 40 national governments, 56 companies, and more than 70 civil society and indigenous peoples' organisations.

Experiences with the REDD+ programme suggest that considerable social justice issues should be expected to arise when projects are sited (FCP, 2019). At the local level, negotiations are required between landowners, those with grazing/cropping rights and others with a material interest, including cultural, on the land under consideration for forestation (IPCC, 2018). These would normally be resolved under local law and state legislation. However, these processes will play out in the context of the wider international position regarding forestation, as exampled in the New York Declaration on Forests (2014). A position that might, in the future, include a financial mechanism to scale up forestation. In addition, in the light of the potential implications for cropping, and food supply the Food and Agricultural Organization's (FAO) Forestry Department may be a useful neutral location for transboundary governance debate.

The monitoring of rates of both afforestation and deforestation need to be improved and a precise global accounting system agreed upon. This is challenging given it must account for the complexities of monitoring, reporting and verifying gas fluxes across a sector that is, simultaneously, a sink for and source of CO_2 and other greenhouse gasses from both natural and human sources (Welch et al., 2019). Further work is required to better understand these intertwined factors to ensure global stocktaking under the Paris Agreement is robust. The FAO Forest Department, which acts as a clearing house for information on forests and their resources, may provide mechanisms to support any verification work, through; for example, the Global Forest Resources Assessment which provides a five yearly review of forest worldwide (FAO, 2017a).

Currently, carbon taxes, cap-and trade and carbon credit offsets do not fully fund sequestration at the global scale. It may be the case that a global policy, coordinated centrally, with the long-term support of central banks' monetary policy, might usefully be debated going forward.

Macroalgal cultivation for sequestration

The principle

Sometimes called 'ocean afforestation' (N'Yeurt et al., 2012), macroalgal cultivation is the proposed large-scale farming at sea of macroalgae to capture carbon through photosynthesis. The biomass would subsequently be harvested either for sequestration or bio-fuel production with carbon capture (the lack of connection to the substrate would prevent the macroalgae being sequestrated in situ (Sondak et al., 2017)). Large-scale macroalgae could potentially play a role in enhancing the biological pump, the ocean's natural biologically driven process of absorbing and circulating carbon dioxide to the deep ocean (Sigman and Haug, 2006).

The technique and its readiness

Nearshore macroalgal aquaculture for food is a well-established industry globally and in particular in China, Japan and South Korea (Pereira et al., 2013). It may already account for the accumulation of ~0.8 Mt of organic carbon annually in the Asia-Pacific region (Sondak et al., 2017). Off-shore macroalgal aquaculture has a far greater capacity. N'Yeurt et al., (2012), for example, has demonstrated that if 9% of the oceans were converted to macroalgal aquaculture they would generate 12 Gt per annum of bio digested methane. This could be burned as a substitute for natural gas. The biomass involved would capture 19 Gt of CO_2 and an additional 34 Gt CO_2 could be captured, if the CO_2 produced by burning the methane was captured and sequestrated.

Current research activities

Research is underway in China, Denmark, the United Kingdom and the United States, exploring the challenge of entrapping macroalgae in the seabed (Queiros, 2019). Other work is exploring the effect of ocean acidification on microalgae growth (Rodríguez et al., 2018), which may diminish the value of the technique if acidification continues, and the conversion of seaweed to bio-products (BMRS, 2019).

Socio-political considerations

As an extant farming method, a proliferation of the technique in the Asia-Pacific region would not raise novel socio-economic challenges (Pereira et al., 2013). Pereira also suggests diversification to other regions is likely to be practical and commercial operations are functioning on the Atlantic coastline and elsewhere. In addition to environmental benefits, the technique has economic value from sale for nutrition, energy and fertiliser, although some of these uses may mean the approach does not capture greenhouse gasses in the long term and, as such, may not qualify as CDR.

GreenWave, Oceans 2050, ClimateWorks and 3Degrees (2019) are working with industry, scientists and NGOs to design and launch a kelp carbon credit protocol for certification by international carbon credit agencies. These potential economic returns may offset the capital investment need for large processing plants and aerobic combustion and Carbon Capture and Storage (CCS) facilities. It is noteworthy that this technique would avoid the competition for land resources of other afforestation methods.

Governance

The regulation of inshore waters is a matter for individual nation states to resolve. Regimes would include those relevant to environmental protection and food safety. This creates a governance gap in terms of monitoring, reporting and verification of greenhouse gas removals (GESAMP 2018).

For waters outside exclusive economic zones (EEZ), the technique would fall under customary international law, the London Protocol and the UN Convention of the Law of the Sea (UNCLOS).

The FAO may be positioned to play a role in some aspects of the monitoring of macroalga production by building on its regular assessments of aquaculture, which include details on the global production of various types of aquatic plants (FAO, 2014).

Carbon sequestration in soils

The principle

Carbon dioxide is held within soil and provides a significant store of CO_2 within the biosphere and changes in this stock through disturbance can either mitigate or worsen climate change (Powlson et al., 2011). This approach removes CO_2 from the atmosphere; predominantly by changes in land management practices, especially in agriculture, in ways that increase soil's carbon concentrations. This is done by changing the balance between carbon loss via soil disturbance and plant respiration, and inputs, predominantly in the form of leaving materials such as roots, litter and other residues in the soil, plus the addition of manure (Lal, 2011). The Royal Society and Royal Academy of Engineering (2018), in their review of approaches to remove greenhouse gases from the atmosphere, identified a number of ways that carbon can be sequestrated in soil through crop and grassland management. These included, depending on soil type, usage and resource availability:

- improved crop varieties and changes in their rotation and cropping;
- the use of novel biotechnologies;
- managing nutrients and optimising fertiliser use though careful timing and precise applications;
- minimising tillage and maximising the retention of organic material;
- improving grasses, especially by promoting and planting those with deep roots, and grass density; and,
- improving grazing management, paying attention to feed sourcing/production and stock density.

The technique and its readiness

There are no significant barriers to taking measures to improve soil carbon sequestration, the practices are understood and in some cases already in practice in farming (RS/RAE, 2018). The practices required are broadly understood by the agricultural industry and new machinery, tools or expensive soil treatments are not required for deployment (UNEP, 2017). Also, the approaches required can be applied without any requirement to change extant land usage (Smith et al., 2010). However, whilst some are already using the required practices, considerable further support for farmers is required before the industry can achieve its full sequestration potential (Minasny et al., 2017).

Assessing the global capacity to sequester carbon in this way is complex given the diverse nature of soils, farming practices, land use and local climates. The estimates derived from modeling are therefore varied, ranging from 1 to 11 $GtCO_2$ per annum ((Lal, 2011, Lal, 2013, Minasny et al., 2017). In the longer term the capacity to store additional carbon year on year will decline as soils become saturated, after which it becomes impossible to sequester additional carbon through these types of intervention. For example, the IPCC has adopted a carbon sequestration saturation horizon of only 20 years. After which, it considers additional sequestration to be minimal (IPCC, 2013), although it is recognised that the rate at which saturation might be reached may vary and is dependent on a

range of factors. In addition to the rate of uptake by those managing land, such as latitude or soil type (Smith, 2012).

Smith (2016) suggests taking forward the required practices has the potential to create profit of up to $3 per ton of CO_2 through improved productivity. In other circumstances, dependent on soil and environmental conditions, Smith suggests deployment may cost up to $12 per ton.

Carbon sequestration in soils is not expected to negatively affect albedo (RS/RAE, 2018). Additional positive benefits are likely to arise from changes to the required land management practices. These are expected to include: improved soil fertility; enhanced land workability; increased crop yield; and, potentially, improved hydrodynamics (Keesstra, 2016).

Current research activities

There is potential for carbon sequestration to increase the release of non-carbon greenhouse gases, such as soil methane (Lal, 2011). In addition, it increases the volume of organic nitrogen levels in the soil, which could be mineralised becoming a substrate for N_2O production (Smith, 2016). Further research on these issues is warranted.

If we are to accurately quantify the volume of carbon sequestered through this approach, new ways to measure and monitor levels of activity, and their successes and failures, will be required (RS/RAE, 2018). A comprehensive method for this has yet to be resolved and requires further work before a well calibrated model will be available for global use.

Socio-political considerations

There is a lack of knowledge about the benefits of the approach among some quarters of the farming/land management community, which needs to be overcome with education and training, if deployment is to be scaled up (Minasny et al., 2017). Assuming practices do change, such that carbon saturation is reached, then a further set of motivators may be required to help ensure that the practices are maintained indefinitely, and a reversal of the sequestration is avoided.

Measures are already in play that aim to promote the method as a contributor to the climate change targets of the Paris Agreement (UNFCCC, 2015) including the '4 per 1000 initiative' (Soussana et al., 2019).

Governance

Given the broadly positive effects on crop productivity and biodiversity, and the apparent lack of potential harms, governance of this method will likely be constrained to practical issues including global monitoring and accounting, promoting the value and maintenance of the practices, and facilitating dialogue across diverse communities of interest to help develop best practices in diverse environments and communities. The method is partially captured under the reporting requirements of the UNFCCC and the Paris Agreement (see the governance section below).

The FAO may play a lead role in future dialogue about the governance of this technique. The contribution carbon sequestration in soils can make to improving crop productivity aligns with the Organisation's key objective to 'achieve food security for all' (FAO, 2019). In recognition of the importance of preserving and boosting healthy soils, in 2012 the FAO established the Global Soil Partnership (GSP) as a mechanism to improve soil governance at global, regional and national levels. That soil carbon is an important element of the GSP's work, and as such that it may have in important governance role moving forward, this is highlighted by its 2017 global symposium on soil organic carbon (FAO, 2017b).

Restoring wetlands, peatlands and coastal habitats

The principle

The IPCC (IPCC, 2014) characterisation of 'wetlands', used in this text, includes:

- inland organic soils and wetlands on mineral soils;
- coastal wetlands (such as mangrove forests, tidal marshes and seagrass meadows); and,
- constructed wetlands for wastewater treatment.

Wetlands have some of the highest biodiversity on Earth and provide a range of benefits to humanity, including: food, freshwater, nutrient removal, flood control, tourism, and shoreline stability (Maziarz et al., 2019). Wetlands comprise 9% of the global surface area, and it is estimated that coastal wetlands with peatlands store up to 71% of Earth's terrestrial based carbon (Zedler and Kercher, 2005).

Recent assessments suggest that wetlands can sequestrate 200 MtCO_2 per annum globally, storing between 50 – 90% percent of this carbon in perpetuity (Howard et al., 2017). However, these carbon reserves are vulnerable as a result of intensifying levels of human disturbance, through drainage, land use change, other forms of human exploitation, and climate change and fire. Approximately one third of global wetlands had been lost by 2009 (Hu et al., 2017), and the frequency and scale of these disturbances are accelerating globally, but in particular in Southeast Asia (Page and Hooijer, 2016).

Current estimates of the maximum long-term carbon sequestration that can be achieved through improving wetlands, indicate a potential of between 0.4 and 18 tons of CO_2 per hectare per annum, scaling to a global potential of approximately 1GtCO_2 per annum by 2030 (Bain, 2011). Carbon sequestration costs are estimated to be in the range of $10 to $100 per ton of CO_2 (Kayranli, 2010). These costs should be considered alongside the additional value that restored or new wetlands can bring through monetisable ecosystem services, such as water provision and flood management as well as the potential for tourism. These have been estimated to be as high as $14,800 per annum (Junk et al., 2013).

The technique and its readiness

The restoration of wetlands can be undertaken requiring little in the way of new technology (Zedler and Kercher, 2005). It centres on rewetting environments, normally through practices to block excessive draining including constructing dams, managing vegetation, and restocking with plants such as sphagnums and hypnoid mosses, to colonise and enhance newly wetted land (SNH, 2019). Coupled with this, measures to protect the ecosystems against further exploitation and degradation are required (Bain, 2011). Such action is normally promoted through regulatory and other local governance measures, including small scale local funding such as 'Peatland Action' (2019) in Scotland, which funds local in situ restoration activities, training and advice for volunteers and land-owners.

Current research activities

Important research questions remain to be resolved, if wetland restoration is to realise its full potential. Further work is required to establish how best to protect restored wetlands against future development or land use change and better insights into how market mechanisms might work to promote re-wetting and ongoing protection are required.

The release of methane and nitrous oxide from wetlands can be a significant source of greenhouse gas release (Montzka et al., 2011), with estimates ranging from 20% to 25% of global emissions (Whiting and Chanton, 2001). Whilst, reviews of methane mitigation technologies indicate that this may be a challenging task (Stolaroff et al., 2012, Lockley, 2012), it is known that such releases can be reduced significantly by planting of mosses and other plant coverage on wetlands. More research is required to better understand these processes and how they can be promoted and protected going forward.

A better understanding of how restored wetlands might be protected against either climate change driven drying or the effects of sea level rise are also required (RS/RAE, 2018), and, in addition, more needs to be known about the albedo change effects of restoration, where the surface darkening effects of vegetation growth may reduce the radiative forcing of the surface (Rouse, 2000) offsetting some of the benefits of the re-wetting.

Socio-political considerations

The key barriers to wide scale wetland restoration are largely financial. Frequently, the direct economic value of co-benefits that accompany restoration, such as water quality and availability improvements, and greater biodiversity, can be insufficient to offset the value of the loss of land (RS/RAE, 2018). For example, many reclaimed wetlands are used as ports or for food production, such as shrimp farming in what were mangroves. Balancing the clear opportunity costs of re-wetting such land against the less tangible benefits that would be achieved from restoration may be challenging. To address this problem new financial incentive mechanisms may be required, and, maintained over the long-term (Kayranli et al., 2009).

Challenges also remain regarding the monitoring, verification and reporting of achieved carbon sequestration, cost-effective monitoring of fluxes, and the effects, positive or negative, of land-use change (Kayranli et al., 2009, RS/RAE, 2018). Such monitoring is problematic not only because there are no governance mechanisms in place to encourage it, but also because most nations lack wetland inventories meaning any changes in the quantity and quality of the world's wetlands cannot currently be tracked adequately (Zedler and Kercher, 2005).

Restoring wetlands can have a wide range of other, non-climate related benefits, including enhancing resilience to natural disasters from flooding and the effects of storms. They can improve water quality, preserve and enhance biodiversity, and create employment and new recreational benefits including tourism – some of which would contribute to wider global sustainability goals (Zedler and Kercher, 2005).

Governance

The method is partially captured under the reporting requirements of the Kyoto Protocol and the Paris Agreement (see the governance section below). More broadly, wetlands fall under the 'Ramsar Convention on Wetlands of International Importance Especially as Waterfowl Habitat', also known as the Convention on Wetlands (UNESCO, 1971). Currently there are 170 contracting parties, and it includes over 2,000 designated sites with a combined area of 490Mha. The Convention's mission is "the conservation and wise use of all wetlands through local and national actions and international cooperation, as a contribution towards achieving sustainable development throughout the world". It calls upon contracting parties to recognise the interdependence of humans and the environment as well as the ecological functions of wetlands, including habitat, nutrient cycling, and flood control. The wide scope of the Convention's framing means that it could, potentially, provide a framework through which to respond to some of the challenges of rewetting for large-scale carbon sequestration.

Despite the views of Finlayson (2017) that the Convention has not been effective in this space, there is some evidence to suggest that the Convention is now moving in this direction. The 2016-2024 Strategic Plan, for example, puts in place arrangements for international cooperation in order to link Ramsar with global debates and processes related to carbon sinks. In addition, its strategic priority areas focus on understanding better the importance of wetlands for climate change mitigation (and adaptation), and the restoration of wetlands where relevant to climate change (Ramsar, 2016). Data collected for the COP 21 national reports (Ramsar, 2016b) show that 70% of the Parties have recently implemented restoration or rehabilitation programmes.

More broadly, other interested parties in wetlands restoration would include:

- Convention on Biological Diversity (CBD);
- United Nations Framework Convention on Climate Change (UNFCCC);
- those engaged in food production and the governance of agriculture, including the UN Food and Agriculture Organisation (FAO);
- shipping interests in coastal zones;
- Civil Society Organisations (CSOs), civic society; and,
- landowners.

Building with biomass

The principle

Plant and tree matter contain carbon, sequestered through photosynthesis. As discussed above, plants' capacity to continually take up new carbon declines as they age. This technique would harvest plants and trees with a diminished capacity to take up new carbon for use in construction. The vacated land would, ideally, then be replanted with appropriate trees and plants which would take up further carbon from the atmosphere. These harvest/grow processes could occur in either established forests, or new plantations.

The harvested materials could be used in a wide range of purposes within the building process, from providing frameworks and walls to insulation. Whilst these will not be permanent forms of sequestration (Read et al., 2009), the approach does have the potential to sequester carbon for between several decades and several hundred years. For example, a residential build in Switzerland, constructed of wood in 1287, is still in good condition and occupied (SWI, 2019). In the context of Seto et al., (2012) assessment, that only 60% of the urban areas that are foreseen to exist by 2030 have already been built. It is apparent that significant additional urban development will take place in the near future, within which timber and other plant-based materials could play an important role.

McLaren (2012) has suggested between 0.5 and 1 $GtCO_2$ per annum could be sequestered by building with biomass in place of conventional materials, whilst Oliver (Oliver et al., 2014) indicates that the approach could save between 12% to 19% of global fossil fuel use. However, to achieve this, between 34% and 100% of the Earth's sustainable wood growth would be required to service the building industry, requiring the development of a new global industrial and supply infrastructure. A positive benefit of using more timber and other plant materials in construction could be the decrease in demand for carbon-intensive steel and concrete.

How buildings constructed from plant and wood material will be decommissioned in the future is an important further consideration. To ensure carbon remains removed, the timber would need to be either combusted with CCS for power and energy creation or recycled. However, this might require careful governance and a new service industry.

The technique and its readiness

Building with timber and other natural plant-based materials is well understood and has been practiced for millennia. Increasingly novel types of engineered timber in laminate and other forms are becoming available (RS/RAE, 2018). These materials have greater strength and durability than un-changed timber and are beginning to open-up new architectural and design opportunities (Hudert and Pfeiffer, 2019). Thermal and chemical treatments are available for use on fast growing soft woods to enhance their strength and duration. Whilst the environmental implications of these treatments must be accounted for, they do mean that fewer slow growing trees are required for use in construction.

Scale up of the use of timber and other plant materials would be required in order to deliver large scale sequestration. The costs of transitioning to these materials within the building and construction industry are not considered to be prohibitive (McLaren, 2012); however, such an uptake would require a shift in crop production and land use change, raising similar issues to those flagged in the afforestation and reforestation section above.

Current research activities

Building research is undertaken globally, within state funded and independent building research institutions, corporations and universities. Some of the leading research questions in the field of building with timber and plant materials focus on establishing: whether large scale timber structures behave fundamentally differently to other buildings in a fire, how to improve timber coatings to enhance the materials strength and performance, how to ensure structural integrity under variable conditions; and, how to best use the residue material at the end of a build's lifetime. More broadly, a holistic assessment of the full environmental implications of using wood in buildings needs to be completed (Ramage et al., 2017, Gustavsson and Sathre, 2011).

Socio-political considerations

Whilst there may be some caution about the use of wood in construction, in relation to fire hazard and durability, its use is common-place in many states, including; the United States, Scandinavia and the UK, and it is suggested that there is unlikely to be any significant public reticence to overcome when seeking to expand the use of the materials in construction (RS/RAE, 2018).

In a study of business barriers to wood adoption in buildings Gosselin et al., (2017) identified a lack of timber engineering skills and expertise, meaning that new training will be required widely before widespread adoption will be possible. They also noted that the culture of the industry, perceptions about building speed, relationships with stakeholders, and adapting business models were all factors in mitigating against rapid uptake of timber in buildings.

Governance

If timber and plant material for building is imported, an international agreement about who can claim the carbon credit arising from the activity will be required, along with a mechanism to monitor the flow of materials, and the carbon storage (RS/RAE, 2018). As such, standards for crediting the national emissions inventories would be required. The IPCC guidelines for national greenhouse gas inventories (IPCC, 2006) might be adopted, under the auspices of the UNFCCC.

National and supra national building regulations may constrain the use of materials in some circumstances. However, there is evidence that these can and are changing in the light of the new potentialities of wooden structures. For example, wood building codes in Canada, China and the United States have all recently changed giving greater flexibility for the inclusion of wood in builds (Cecco, 2019).

Biochar production and deposition

The principle

Biochar is a hybrid approach to sequestering carbon in soils, as such it is not a true NBS. However, given that it involves situating organically derived carbon, once produced, within organic matter in similar ways, and with similar governance agenda associated other NBS approaches, it is included in this briefing.

Biochar is a stable, long lived form of carbon which can be stored in soil for long periods and provides not only a carbon store, but can also improve soil quality and crop yields (Lehmann, 2015), as well as water quality and nutrient levels (Smith, 2016). Biochar is formed, in a process called pyrolysis, when biomass (such as wood, manure or crop residues) is heated in a closed container, with little or no available air, to above 250ºC. In combination with sustainable biomass production, it can be carbon-negative, with potentially positive implications for the mitigation of climate change. Biochar production can also be combined with bioenergy production through the use of the gases that are given off in the pyrolysis process (RS/RAE, 2018). This energy-generation potential has been estimated by Shackley et al., (2015) to be between 5 and 14 GJ per ton of CO_2 removed. However, this energy production would itself generate carbon emissions.

It is suggested that a ton of biochar can remove between 2.1 to 4.8 tCO_2 (Lehmann, 2015, Hammond et al., 2011) and it is estimated that globally biochar could theoretically remove between 1.8 and 4.8 $GtCO_2$ per annum (Woolf et al., 2010).

Woolf et al., (2010) estimate that the costs of biochar production ranges from $18 to $166 per tCO_2 produced. Actual costs will vary depending on a range of factors, including the costs of: cultivating and sourcing biomass; feedstock preparation; storage and transport; capital and operating costs of technologies; yield engineering; post-production processing of biochar and other by-products (bio-liquids and syngas); and, the packaging, marketing and selling of those products (Shackley et al., 2011).

The technique and its readiness

Biochar is a well understood and established method and, whilst biochar products are now commercially available as soil amendments and in composting and potting mixes in Europe and the United States (for example though Wakefield BioChar (BioChar, 2019)), it is not yet widely available globally. Across much of the developing world biochar production is at the micro scale, for example, from household biochar cookstoves to village level systems. There are however a small number of larger scale units utilising agricultural waste (BIO, 2019).

Because biochar can be applied directly to current land without changing its use there are no restrictions in terms of access to suitable land for distribution (RS/RAE, 2018). However, the availability

of quantities of biomass for biochar production is an important limiting factor constraining the potential for global biochar use. In addition to source biomass constrains, additional large-scale investment in pyrolysis facilities will be required before it will be possible to scale up implementation.

Current research activities

There is a wide range of on-going biochar research activity helping to better understand what constitutes 'good' biochar in agronomic and environmental management applications, for example, at the UK Biochar Research Centre. Other areas of current research include exploring uncertainties associated with decomposition rates of the various types of biochar, depending upon the pyrolysis feedstock and temperature.

Socio-political considerations

Alexander et al., (2014) suggest there are limited economic and policy incentives currently in place to encourage investment in, and take up of, biochar and suggests that new measures to facilitate a guaranteed market for biomass or for biochar would have a positive effect on the development of a biochar industry.

In recognition of the potential of biochar, and the need for actors to work together to help address the challenges constraining up-take, academics, businesses, investment bankers, non-govermental organisations (NGOs), federal agency representatives, and representatives from policy arena around the world came together in 2006 to form the International Biochar Initiative (2019). This group seeks to play a role in the evolution of biochar by promoting research, development, demonstration, deployment, and commercialisation of biochar.

There are not expected to be major social concerns with the deployment and scale up of biochar, although there may be some concern about any effects on forests or food supply (Smith et al., 2010). It may be important for those developing infrastructure, that they be clear to the wider local community about the nature of the combustion methods and its by-products.

Governance

The monitoring, reporting and verification of the take up and use of biochar can be difficult, both at the state and international level. Improvements in this will be important in the future for carbon accounting purposes. At the EU level, a number of tools are available that may be suitable for wider consideration and it is possible that biochar will, in the longer term, become subject to international governance mechanisms such as the CBD and UNFCCC. However, currently, the main regulatory frameworks that apply are state and customary law. Were transboundary trade in Biochar to become common, certification schemes, like those associated with other bio-based products, such as forestry products, bioenergy, or palm oil might be required.

Because biochar can improve plant yields and reduce fertiliser requirements (Cowie et al., 2017), the technique is of interest to the FAO. In its role as a facilitator of dialogue, this interest in biochar may be reflected in new steps by the FAO to work through its partners to open up understandings of and debate about whether, and if so how biochar might be best brought to the field.

Governance Issues

C2G uses the IPCC definition of governance in relation to CDR, and other climate technologies - 'A comprehensive and inclusive concept of the full range of means for deciding, managing, implementing and monitoring policies and measures. Whereas government is defined strictly in terms of the nation-state, the more inclusive concept of governance recognises the contributions of various levels of government (global, international, regional, sub-national and local) and the contributing roles of the private sector, of nongovernmental actors, and of civil society to addressing the many types of issues facing the global community' (Masson-Delmotte, 2018).

It is suggested that the successful development and implementation of NBS climate policy, as with other climate related interventions, requires multi-level governance from the international, through the national to local levels (IUCN, 2016). Nation state governance may provide impetus for NBS interventions at the country level, for example by developing, deploying and coordinating public policy and allocating and managing resources. These in turn could potentially drive more localised responses, such as measures that might be taken to gain access to state resources. Because the impacts of climate change are transboundary, and some NBS effects may also cross boundaries, bilateral and multilateral cooperation may be needed, potentially requiring international agreement or treaty through the UNFCCC, or other multilateral and bilateral agreements, such as trade agreements.

Because some NBS deployments, such as afforestation, may have effects on ecosystems beyond removing CO_2, for example, diminishing biodiversity, they could give rise to contested trade-offs between multiple environmental objects. For example, protecting and enhancing biodiversity and delivering CDR to help address climate change. Such cross-boundary governance challenges my require multiple processes, such as the CBD and UNFCCC to come together, alongside other bodies like the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) to maximise benefits and minimise harms across multiple agenda.

Key governance issues

Noted in the commentary above, large scale NBS deployment may have some negative side-effects, causing environmental, economic, social and political transboundary harm requiring international governance. If large scale NBS approaches are adopted, it will be essential to have transparent monitoring, verification and reporting of achieved sequestration in place for all methods. This will be required to monitor global progress against climate change targets, and to provide accurate accounting of states' contributions and any carbon sequestration credits that may accrue (Zakkour et al., 2014). It is unclear how the international community might agree, set and stabilise, over the long-term, atmospheric carbon dioxide concentrations. Nor how this process, and the outcomes of the decisions taken, can balance the individual interests of nation states with global need. These challenges will be subject to on-going debate through the UNFCCC and its associated mechanisms (see below).

NBS raises novel challenges for carbon life-cycle accounting. These will affect not only accounting standards, but also industrial standards and practice, financial practice, and regulation. Emissions trading will also be complicated by the adoption of NBS approaches. How, for example, would timber grown in one state and used in buildings in another, be accounted in such a complex transboundary, commercial and government situation?

Current international governance

Currently, many NBS approaches lie under the scope of the UNFCCC, and its associated Protocols and Agreements. To date, the coverage for NBS is incomplete. However, given decisions taken under the UNFCCC are used in the construction of the IPCC greenhouse gas inventories, which in turn drive how anthropogenic carbon removals are reported, it is important that this is fully resolved in the future. In addition, provisions in the Kyoto Protocol, which set out how removals will contribute to achieving reduction targets, were not designed to incorporate the large-scale removals that NBS may have the potential to deliver. A brief overview of how NBS are treated under the three main international governance instruments, the UNFCCC, Kyoto Protocol and the Paris Agreement, follows. For a more detailed analysis of how CDR, including most NBS removals, are governed by these instruments, the 2018 paper, 'Governing large-scale carbon dioxide: are we ready?' is recommended (Mace et al., 2018).

The UNFCCC

Many NBS methods are captured under Article 4.1(d) of the UNFCCC, which requires all Parties to "Promote sustainable management, and promote and cooperate in the conservation and enhancement of sinks and reservoirs of all greenhouse gases not controlled by the Montreal Protocol, including biomass, forests and oceans, as well as other terrestrial, coastal and marine ecosystems" (UNFCCC, 2015). Under this article, States are required to regularly report a national inventory of anthropogenic emissions by sources and critically for the purposes of climate altering technologies, removals by sinks using comparable methods. Importantly, the Convention places different reporting obligations on developing countries. Developed states, known as Annex 1 Parties, report annually, whilst Non-Annex 1 Parties report on a four-yearly basis, using the 2006 IPCC Guidelines (IPCC, 2006), which include a requirement to report on land use, land-use change and forestry – locations within which NBS fall. Although reporting obligations for Annex 1 and Non-Annex 1 countries have moved closer to each other in recent years, the differences in these obligations continues to present a challenge for monitoring, verification and reporting of achieved sequestration, frustrating the assessment of progress toward global goals. In addition, inventory data cannot be aggregated due to a series of issues that perpetuate differentiation in the treatment of inventory data (Mace et al., 2018).

The Kyoto Protocol

Parties to the Protocol agree to reduce or limit their future emissions. In the accounting process the removal of carbon by sinks from direct human-induced land-use change and forestry activities limited, under Article 3.3 of the Protocol, to afforestation, reforestation and deforestation are included. Under Article 3.4 of the Protocol, Parties can choose to include net removals of carbon from certain additional activities, including forest management, cropland management, and revegetation. Activities that may capture many of the NBS methods discussed above, but which require clarification at this stage. This list was expanded in the second Kyoto commitment period (2013-2020) to make forest management a mandatory reporting category, and to include wetlands management as voluntary accounting area.

The Paris Agreement

Article 5 of the Agreement requires the Parties to take action to conserve and enhance sinks and reservoirs of greenhouse gases (GHGs) – a measure that would encompass forestations, carbon sequestration in soil and restoring wetlands. Parties are also encouraged to implement policies and positive incentives for conservation, sustainable management of forests and enhancement of forest carbon stocks in developing countries.

The lack of guidance about the presentation of NDCs under the Agreement, means Parties account for their Contributions in varied ways. This may be encumbering capacity to track carbon reductions from NBS and in turn may fail to encourage their adoption. Certainly, consistent reporting of NDCs would help project 2030 net-emission levels and aid future planning for NBS, and CDR more widely. Such information gaps could be addressed through the ongoing negotiating processes under the Paris Agreement.

Moving forward

There may be a risk that assumptions about the effectiveness of NBS, coupled with their inclusion in Integrated Assessment Models whose scenarios are assessed by the IPCC, will create inflated judgements about progress toward achieving the Paris Agreement targets, and disproportionately reduce the sense of urgency among policy makers, a form of moral hazard (Lenzi 2018). Currently, there has been only limited discussion about CDR, including NBS, in most subnational and international climate policy forums and more extensive discussion is required to better understand, and plan for, the risks and challenges that arise (Williamson, 2016), as well as to identify and resolve barriers to deployment (Peters and Geden, 2017). It is possible that such processes will reveal the effectiveness of NBS approaches to be less than is currently expected and as a consequence, greenhouse gas emissions will need to be mitigated and eliminated more quickly than is currently assumed in the IPCC scenarios (IPCC, 2014a) by other means (Vuuren, 2018).

Relationship with the Sustainable Development Goals (SDGs)

Given the interdependency between responding to climate change and the delivery of the SDGs (ICSU, 2017) any steps taken may help, rather than hinder, the global response to both agendas. In the case of NBS this is particularly important because they have the potential to reduce atmospheric carbon levels, and have direct positive effects on biodiversity preservation, ecosystem restoration, water quality, food security and the creation of new employment opportunities (IUCN, 2016). For example, large scale monoculture afforestation, delivered in a top-down autocratic manner could have implications for some SDGs, including, zero hunger, clean water and sanitation, responsible consumption and production, life on land and decent work and economic growth.

Alternatively, a community driven approach to afforestation, taken forward with a focus on delivering positive implications for SDG delivery could have positive effects on all these SDGs. In the future, then, the development and governance of climate related NBS may be conducted with both agenda in mind. Indeed, the European Union (2019) has argued this should be done in a planned and systemic manner.

Table 3 identifies where the NBS techniques discussed here, raise potentially challenging interactions with implementation of the SDGs and where there are risks that require new research prior to developing governance. For a more detailed analysis of the potential implications of climate technologies for the delivery of the SDGs, C2G's 2018 report is recommended (Honegger, 2018) and for an analysis of the underlying literature, Smith's (2019) annual reviews are recommended.

The interdependencies of some NBS with the SDGs mean that not only might attention be paid to the potential effects and governance of deployments, but any decision not to deploy could be assessed on the basis of effects on the climate, and its implications for the delivery of the SDGs. Moving forward, the governance debate could seek to reach balanced positions informed by the consideration of detailed, transdisciplinary assessments of all implications of NBS for the climate and SDG delivery.

Table 3. Potential NBS/SDG interactions and risks to consider when developing governance

- **Interaction:** interaction identified between NBS technique and implementation of each SDG which may require governance.
- **Risk:** potential risk(s) identified between NBS technique and implementation of each SDG that requires further research prior to developing governance.

	1 No Poverty	2 Zero Hunger	3 Good Health and Well-Being	4 Quality Education	5 Gender Equality	6 Clean Water and Sanitation	7 Affordable and Clean Energy	8 Decent Work and Economic Growth	9 Industry, Innovation and Infrastructure	10 Reduced Inequalities	11 Sustainable Cities and Communities	12 Responsible Consumption and Production	13 Climate Action	14 Life Below Water	15 Life on Land	16 Peace, Justice and Strong Institutions	17 Partnerships for the Goals
Afforestation and forest ecosystem restoration	Interaction, Risk	Interaction, Risk	Interaction			Interaction, Risk		Interaction, Risk	Interaction	Interaction			Interaction, Risk		Interaction, Risk	Interaction	
Macroalgal cultivation for sequestration	Interaction	Interaction					Interaction	Interaction			Interaction	Interaction	Interaction, Risk	Interaction, Risk			
Carbon sequestration in soils	Interaction	Interaction				Interaction		Interaction	Interaction	Interaction			Interaction, Risk		Interaction, Risk	Interaction	
Biochar		Interaction					Interaction, Risk	Interaction	Interaction				Interaction, Risk		Interaction, Risk		
Restoring wetlands		Interaction, Risk	Interaction, Risk			Interaction, Risk		Interaction			Interaction	Interaction	Interaction, Risk	Interaction, Risk	Interaction, Risk		
Building with biomass								Interaction	Interaction, Risk		Interaction, Risk	Interaction, Risk	Interaction, Risk				

Conclusions

The natural environment plays a key role in climate regulation and has been considered by many interested and affected parties to be an appropriate location in which to develop novel interventions in response to the climate change challenge. A wide range of potential techniques, ranging from scaling up well understood practices, to entirely new types of interventions have been subject to debate and research. The increasingly urgent need to address anthropogenic climate change is driving forward work, such as afforestation, that may, in the future, lead to regionally effective deployments. Moving forward, increasingly close co-operation between scientists, engineers, publics, governments, global institutions, the commercial sector and civil society organisations will be essential to deliver a safe, socially acceptable and environmentally sustainable future.

References

ALEXANDER, P., MORAN, D., ROUNSEVELL, M., HILLIER, J. & SMITH, P. 2014. Cost and potential of carbon abatement from the UK perennial energy crop market. *GCB Bioenergy*, 6, 156-168.

BAIN, C. G., BONN, A., STONEMAN, R., CHAPMAN, S., COUPAR, A., EVANS, M., GEAREY, B., HOWAT, M., JOOSTEN, H., KEENLEYSIDE, C., LABADZ, J., LINDSAY, R., LITTLEWOOD, N., LUNT, P., MILLER, C.J., MOXEY, A., ORR, H., REED, M., SMITH, P., SWALES, V., THOMPSON, D.B.A., THOMPSON, P.S., VAN DE NOORT, R., WILSON, J.D. & WORRALL, F. 2011. IUCN Commission of Inquiry on Peatlands. *The Peatland Programme*. Edinburgh, UK.

BIO. 2019. *Biochar in developing countries* [Online]. Available: https://biochar-international.org/biochar-in-developing-countries/ [Accessed].

BIOCHAR, 2019. This is a US based company retailing biochar https://www.wakefieldbiochar.com/ [Accessed 24 September 2019].

BMRS. 2019. *The conversion of seaweed to bio-products research agenda* [Online]. Available: https://www.bmrs.ie/bmrs-projects#seaweed-conversion-to-bio-products [Accessed 5 September 2019].

BUCK, H. 2016. Rapid scale-up of negative emissions technologies: social barriers and social implications. *Climate Change*, 139, 155-167.

CBD 2009. Connecting biodiversity and climate change mitigation and adaptation: report of the Second Ad Hoc Technical Expert Group on Biodiversity and Climate Change. . *In:* DIVERSITY, S. O. T. C. O. B. (ed.). Montréal, Québec, Canada. .

CECCO, L. 2019. Canadian cities take wooden skyscrapers to new heights *The Guardian Newspaper*, 22 July 2019.

CLARKE, L., JIANG, K., AKIMOTO, K., BABIKER, M., BLANFORD, G., FISHER-VANDEN, K., HOURCADE, J.-C., KREY, V., KRIEGLER, E., LÖSCHEL, A., MCCOLLUM, D., PALTSEV, S., ROSE, S., SHUKLA, P.R., TAVONI, M., VAN DER ZWAAN, B., VAN VUUREN, D. 2014. Assessing Transformation Pathways. *In*: IPCC (ed.) *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge and New York: Cambridge University Presss.

COVEY, K. R., WOOD, S. A., WARREN II, R. J., LEE, X. & BRADFORD, M. A. 2012. Elevated methane concentrations in trees of an upland forest. *Geophysical Research Letters*, 39.

COWIE, A., VAN ZWIETEN, L., PAL SINGH, B. & ANAYA DE LA ROS, R. 2017. Biochar as a strategy for sustainable land management and climate change mitigation *Proceedings of the global symposium on soil organic carbon* Rome, Italy: FAO.

DAGGASH, H., FAJARDY, M., GROSS, R. & HEPTONSTALL, P. 2018. Bioenergy with carbon capture and storage, and direct air capture: Examining the evidence on deployment potential and costs. *UKERC Technology and Policy Assessment* Imperial College Centre for Energy Policy and Technology

ELLIOT, E. 2019. History of the Environmental Movement. Chicago: Encyclopaedia Britanica.

EU 2019. Horizon 2020 Work Programme 2018-2020 Climate action, environment, resource efficiency and raw materials In: COMMISSION, E. (ed.) *Decision C(2019)4575 of 2 July 2019*.

FAO 2014. The State of the World Fisheries and Aquaculture. Opportunities and Challenges. Rome: Food and Agriculture Organization of the United Nations.

FAO 2017a. FRA 2015 Process Document. *In:* 186, F. R. A. W. P. (ed.). Food and Agriculture Organization of the United Nations.

FAO 2017b. Proceedings of the Global Symposium on Soil Organic Carbon 2017. Rome, Italy: Food and Agriculture Organization of the United Nations.

FAO. 2019. *About the FAO* [Online]. Available: http://www.fao.org/about/en/ [Accessed 7 September 2019].

FCP. 2019. *Forest Carbon Partnership* [Online]. Available: https://www.forestcarbonpartnership.org/what-redd [Accessed 20 August 2019].

FINLAYSON, C. M. 2017. Policy considerations for managing wetlands under a changing climate. *Marine and Freshwater Research*, 68, 1803-1815.

FUSS, S., CANADELL, J. G., PETERS, G., TAVONI, M., ANDREW, R., CIAIS, P., JACKSON, R., JONES, C., KRAXNER, F., NAKICENOVIC, N., LE QUERE, C., RAUPACH, M., SHARIFI, A., SMITH, P. & YAMAGATA, Y. 2014. Betting on negative emissions. *Climate Change*, 4, 850-853.

FUSS, S., LAMB, W. F., CALLAGHAN, M. W., HILAIRE, J., CREUTZIG, F., AMANN, T., BERINGER, T., DE OLIVEIRA GARCIA, W., HARTMANN, J., KHANNA, T., LUDERER, G., NEMET, G. F., ROGELJ, J., SMITH, P., VICENTE, J. L. V., WILCOX, J., DEL MAR ZAMORA DOMINGUEZ, M. & MINX, J. C. 2018. Negative emissions—Part 2: Costs, potentials and side effects. *Environmental Research Letters*, 13, 063002.

GOSSELIN, A., BLANCHET, P., LEHOUX, N. & CIMON, Y. 2017. "Main motivations and barriers for using wood in multi-story and non-residential construction projects,". *BioRes*., 12, 546-570.

GREENWAVE, O., CLIMATEWORKS AND 3DEGREES 2019. These are companies or bodies working in the agenda. Their websites are https://www.greenwave.org/ http://oceans2050.com/ https://www.climateworks.org/ https://3degreesinc.com/.

GRISCOM, B. W., ADAMS, J., ELLIS, P. W., HOUGHTON, R. A., LOMAX, G., MITEVA, D. A., SCHLESINGER, W. H., SHOCH, D., SIIKAMÄKI, J. V., SMITH, P., WOODBURY, P., ZGANJAR, C., BLACKMAN, A., CAMPARI, J., CONANT, R. T., DELGADO, C., ELIAS, P., GOPALAKRISHNA, T., HAMSIK, M. R., HERRERO, M., KIESECKER, J., LANDIS, E., LAESTADIUS, L., LEAVITT, S. M., MINNEMEYER, S., POLASKY, S., POTAPOV, P., PUTZ, F. E., SANDERMAN, J., SILVIUS, M., WOLLENBERG, E. & FARGIONE, J. 2017. Natural climate solutions. *Proceedings of the National Academy of Sciences*, 114, 11645-11650.

GUSTAVSSON, L. & SATHRE, R. 2011. Energy and CO_2 analysis of wood substitution in construction. *Climatic Change*, 105, 129-153.

HAMMOND, J., SHACKLEY, S., SOHI, S. & BROWNSORT, P. 2011. Prospective life cycle carbon abatement for pyrolysis biochar systems in the UK. *Energy Policy*, 39, 2646-2655.

HONEGGER, M., DERWENT, H., HARRISON, N., MICHAELOWA, A., & SCHÄFER, S. 2018. Carbon Removal and Solar Geoengineering: Potential implications for delivery of the Sustainable Development Goals. *In:* (C2G), C. C. G. I. (ed.) New York, US.

HOUGHTON, R. 2013. The emissions of carbon from deforestation and degradation in the tropics: Past trends and future potential. *Carbon Management*, 4, 539-546.

HOWARD, J., SUTTON-GRIER, A., HERR, D., KLEYPAS, J., LANDIS, E., MCLEOD, E., PIDGEON, E. & SIMPSON, S. 2017. Clarifying the role of coastal and marine systems in climate mitigation. *Frontiers in Ecology and the Environment*, 15, 42-50.

HU, S., NIU, Z., CHEN, Y., LI, L. & ZHANG, H. 2017. Global wetlands: Potential distribution, wetland loss, and status. *Science of The Total Environment*, 586, 319-327.

HUDERT, M. & PFEIFFER, S. 2019. *Rethinking Wood: Future Dimensions of Timber Assembly*, Birkhauser.

ICSU 2017. A Guide to SDG Interactions: from Science to Implementation *In:* GRIGGS, D., NILSSON, M., STEVANCE, A. & MCCOLLUM, D. (eds.). Paris: International Science Council.

INITIATIVE, I. B. 2019. Details about the initiative are available here https://biochar-international.org/

IPCC 2006. International Panel on Climate Change - Guidelines for National Greenhouse Gas Inventories. Task Force on National Greenhouse Gas Inventories: https://www.ipcc-nggip.iges.or.jp/public/2006gl/vol1.html Accessed 22 August 2019.

IPCC 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. *In:* [STOCKER, T. F., D. QIN, G.-K. PLATTNER, M. TIGNOR, S.K. ALLEN, J. BOSCHUNG, A. NAUELS, Y. XIA. (ed.).

IPCC 2014. 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands. *In:* HIRAISHI, T., KRUG, T., TANABE, K., SRIVASTAVA, N., BAASANSUREN, J., FUKUDA, M. AND TROXLER, T.G. (EDS). (ed.). Switzerland: International Panel on Climate Change.

IPCC 2014a. Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. *In:* EDENHOFER, O., R. PICHS-MADRUGA, Y. SOKONA, E. FARAHANI, S. KADNER, K. SEYBOTH, A. ADLER, I. BAUM, S. BRUNNER, P. EICKEMEIER, B. KRIEMANN, J. SAVOLAINEN, S. SCHLÖMER, C. VON STECHOW, T. ZWICKEL & J.C. MINX (ed.). Cambridge, United Kingdom.

IPCC 2018. International Panel on Climate Change Special report on Global Warming of 1.5 degrees *In:* IPCC (ed.).

IPCC 2019. The Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems

IUCN. 2011. *The Bonn Challenge* [Online]. Available: http://www.bonnchallenge.org/ [Accessed 20 August 2019].

IUCN 2016. Nature-based solutions to address climate change. Paris, France: International Union for Conservation of Nature.

JUNK, W. J., AN, S., FINLAYSON, C. M., GOPAL, B., KVĚT, J., MITCHELL, S. A., MITSCH, W. J. & ROBARTS, R. D. 2013. Current state of knowledge regarding the world's wetlands and their future under global climate change: a synthesis. *Aquatic Sciences*, 75, 151-167.

KAYRANLI, B., SCHOLZ, M., MUSTAFA, A. & HEDMARK, Å. 2009. Carbon Storage and Fluxes within Freshwater Wetlands: A Critical Review. *Wetlands*, 30, 111-124.

KAYRANLI, B. S., M. MUSTAFA, A. HEDMARK, A. 2010. Carbon Storage and Fluxes within Freshwater Wetlands: a Critical Review. *Wetlands*, 30, 111-124.

KEESSTRA, S., BOUMA, J, WALLINGA, J, TITTONELL, P, SMITH, P, CERDÀ, A, MONTANARELLA, L, QUINTON, JN, PACHEPSKY, Y, VAN DER PUTTEN, WH, BARDGETT, RD, MOOLENAAR, S, MOL, G, JANSEN, B & FRESCO, LO 2016. The significance of soils and soil science towards realization of the United Nations sustainable development goals. *SOIL*, 2, 111-128.

LAL, R. 2011. Sequestering carbon in soils of agro-ecosystems. *Food Policy*, 36, S33-S39.

LAL, R. 2013. Soil carbon management and climate change. *Carbon Management*, 4, 439-462.

LEHMANN, J. J., S. 2015. *Biochar for Environmental Management*, London, Routledge.

LOCKLEY, A. 2012. Comment on "Review of Methane Mitigation Technologies with Application to Rapid Release of Methane from the Arctic". *Environmental Science & Technology*, 46, 13552-13553.

LUYSSAERT, S., MARIE, G., VALADE, A., CHEN, Y.-Y., NJAKOU DJOMO, S., RYDER, J., OTTO, J., NAUDTS, K., LANSØ, A. S., GHATTAS, J. & MCGRATH, M. J. 2018. Trade-offs in using European forests to meet climate objectives. *Nature*, 562, 259-262.

MACE, M. J., FYSON, C. L., SCHAEFFER, M. & HARE, W. L. 2018. Governing large-scale carbon dioxide removal: are we ready? New York, US.

MASSON-DELMOTTE, V., P. ZHAI, H.-O. PÖRTNER, D. ROBERTS, J. SKEA, P.R. SHUKLA, A. PIRANI, W. MOUFOUMA-OKIA, C. PÉAN, R. PIDCOCK, S. CONNORS, J.B.R. MATTHEWS, Y. CHEN, X. ZHOU, M.I. GOMIS, E. LONNOY, T. MAYCOCK, M. TIGNOR, AND T. WATERFIELD 2018. Summary for Policymakers. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. Geneva, Switzerland: World Meteorological Organization.

MAZIARZ, J., VOURLITIS, G. & KRISTAN, W. 2019. Carbon and nitrogen storage of constructed and natural freshwater wetlands in Southern California. *Ecological Engineering: X*, 100008.

MCLAREN, D. 2012. A comparative global assessment of potential negative emissions technologies. *Process Safety and Environmental Protection*, 90, 489-500.

MINASNY, B., MALONE, B. P., MCBRATNEY, A. B., ANGERS, D. A., ARROUAYS, D., CHAMBERS, A., CHAPLOT, V., CHEN, Z.-S., CHENG, K., DAS, B. S., FIELD, D. J., GIMONA, A., HEDLEY, C. B., HONG, S. Y., MANDAL, B., MARCHANT, B. P., MARTIN, M., MCCONKEY, B. G., MULDER, V. L., O'ROURKE, S., RICHER-DE-FORGES, A. C., ODEH, I., PADARIAN, J., PAUSTIAN, K., PAN, G., POGGIO, L., SAVIN, I., STOLBOVOY, V., STOCKMANN, U., SULAEMAN, Y., TSUI, C.-C., VÅGEN, T.-G., VAN WESEMAEL, B. & WINOWIECKI, L. 2017. Soil carbon 4 per mille. *Geoderma*, 292, 59-86.

MINX, J., LAMB, W., CALLAGHAN, M., BORNMANN, L. & FUSS, S. 2017. Fast growing research on negative emissions. *Environmental Research Letters*, 12, 035007.

MONTZKA, S. A., DLUGOKENCKY, E. J. & BUTLER, J. H. 2011 Non-CO_2 Greenhouse Gases and Climate Change. *Nature*, 476, 43-50.

MORTON, O. 2008. *Eating the Sun: How Plants Power the Planet* Harper.

N'YEURT, A. D. R., CHYNOWETH, D. P., CAPRON, M. E., STEWART, J. R. & HASAN, M. A. 2012. Negative carbon via Ocean Afforestation. *Process Safety and Environmental Protection*, 90, 467-474.

NERC 2016. Report of Workshop on Greenhouse Gas Removal from the Atmosphere: London. Swindon: Natural Environment Research Council, UK.

OLIVER, C., NASSAR, N., LIPPKE, B. & MCCARTER, J. 2014. Carbon, Fossil Fuel, and Biodiversity Mitigation With Wood and Forests. *Journal of Sustainable Forestry*, 33, 248-275.

PACALA, S. & SOCOLOW, R. 2004. Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies. *Science*, 305, 968-972.

PAGE, S. & HOOIJER, A. 2016. In the line of fire: the peatlands of Southeast Asia. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 371, 20150176.

PANGALA, S. R., ENRICH-PRAST, A., BASSO, L. S., PEIXOTO, R. B., BASTVIKEN, D., HORNIBROOK, E. R. C., GATTI, L. V., MAROTTA, H., CALAZANS, L. S. B., SAKURAGUI, C. M., BASTOS, W. R., MALM, O., GLOOR, E., MILLER, J. B. & GAUCI, V. 2017. Large emissions from floodplain trees close the Amazon methane budget. *Nature*, 552, 230.

PEREIRA, R., YARISH, C. & CRITCHLEY, A. T. 2013. SeaweedseaweedAquacultureseaweedaquaculturefor Human Foods in Land-Based and IMTA Systems. *In:* CHRISTOU, P., SAVIN, R., COSTA-PIERCE, B. A., MISZTAL, I. & WHITELAW, C. B. A. (eds.) *Sustainable Food Production*. New York, NY: Springer New York.

PETERS, G. & GEDEN, O. 2017. Catalysing a political shift from low to negative carbon. *Nature Climate Change*, 7, 619.

POPKIN, G. 2019. The forest question. *Nature*, 565, 280-282.

POWLSON, D. S., GREGORY, P. J., WHALLEY, W. R., QUINTON, J. N., HOPKINS, D. W., WHITMORE, A. P., HIRSCH, P. R. &

GOULDING, K. W. T. 2011. Soil management in relation to sustainable agriculture and ecosystem services. *Food Policy*, 36, S72-S87.

QUEIROS, M. A., N. STEPHENS, S. WIDDICOMBE, K. TAIT, S. J. MCCOY, J. INGELS, S. R€UHL, R. AIRS, A. BEESLEY, G. CARNOVALE, P. CAZENAVE, S. DASHFIELD, E. HUA, M. JONES, P. LINDEQUE, C. L. MCNEILL, J. NUNES, H. PARRY, C. PASCOE, C. WIDDICOMBE, T. SMYTH, A. ATKINSON, D. KRAUSE-JENSEN, AND P. J. SOMERFIELD. 2019. Connected macroalgal-sediment systems: blue carbon and food webs in the deep coastal ocean. *Ecological Monographs* 89, 21.

RAMAGE, M., BURRIDGE, H., BUSSE-WICHER, M., FEREDAY, G., REYNOLDS, T., SHAH, D., WU, G., YU, L., FLEMING, P., DENSLEY-TINGLEY, D., ALLWOOD, J., DUPREE, P., LINDEN, P. & SCHERMAN, O. 2017. The wood from the trees: The use of timber in construction. *Renewable and Sustainable Energy Reviews*, 68, 333-359.

RAMSAR 2016. The 4th Strategic Plan 2016 – 2024 - The Convention on Wetlands of International Importance especially as Waterfowl Habitat – the "Ramsar Convention" Adopted by the 12th Meeting of the Conference of the Parties at Punta del Este, Uruguay, 1-9 June 2015, through Resolution XII.2

RAMSAR 2016b. Ramsar collected National Reports to the COP 21. https://www.ramsar.org/search?f[]=field_tag_categories%3A510.

READ, D., FREER-SMITH, P., MORISON, HANLEY, N., WEST, C. & SNOWDON, P. 2009. Combating climate change – a role for UK forests. An assessment of the potential of the UK's trees and woodlands to mitigate and adapt to climate change. The synthesis report. The Stationery Office, Edinburgh.

RODRÍGUEZ, A., CLEMENTE, S., BRITO, A. & HERNÁNDEZ, J. C. 2018. Effects of ocean acidification on algae growth and feeding rates of juvenile sea urchins. *Marine Environmental Research*, 140, 382-389.

ROGELJ, J., LUDERER, G., PIETZCKER, R., KRIEGLER, E., SCHAEFFER, M., KREY, V. & RIAHI, K. 2015. Energy system transformations for limiting end-of-century warming to below 1.5 °C. *Nature Climate Change*, 5, 519.

ROUSE, W. R. 2000. The energy and water balance of high-latitude wetlands: controls and extrapolation. *Global Change Biology*, 6, 59-68.

RS/RAE 2018. Greenhouse Gas Removal. London: Royal Society and Royal Academy of Engineering

SETO, K. C., GÜNERALP, B. & HUTYRA, L. R. 2012. Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools. *Proceedings of the National Academy of Science*s, 109, 16083-16088.

SHACKLEY, S., HAMMOND, J., GAUNT, J. & IBARROLA, R. 2011. The feasibility and costs of biochar deployment in the UK. *Carbon Management*, 2, 335-56.

SHACKLEY, S., HAMMOND, J., GAUNT, J. & IBARROLA, R. 2015. CostsBiochar.

SIGMAN, D. & HAUG, G. 2006. The biological pump in the past. In: Treatise on Geochemistry. *In:* HOLLAND, H. & TUREKAIN, K. (eds.). Pergamon Press.

SMITH, P. 2012. Soils and climate change. *Current Opinion in Environmental Sustainability*, 4, 539-544.

SMITH, P. 2013. How Much Land-Based Greenhouse Gas Mitigation Can Be Achieved without Compromising Food Security and Environmental Goals? *Global Change Biology*, 19, 2285-2302.

SMITH, P. 2016. Soil carbon sequestration and biochar as negative emission technologies. *Global Change Biology*, 22, 1315-1324.

SMITH, P., DAVIS, S. J., CREUTZIG, F., FUSS, S., MINX, J., GABRIELLE, B., KATO, E., JACKSON, R. B., COWIE, A., KRIEGLER, E., VAN VUUREN, D. P., ROGELJ, J., CIAIS, P., MILNE, J., CANADELL, J. G., MCCOLLUM, D., PETERS, G., ANDREW, R., KREY, V., SHRESTHA, G., FRIEDLINGSTEIN, P., GASSER, T., GRÜBLER, A., HEIDUG, W. K., JONAS, M., JONES, C. D., KRAXNER, F., LITTLETON, E., LOWE, J., MOREIRA, J. R., NAKICENOVIC, N., OBERSTEINER, M., PATWARDHAN, A., ROGNER, M., RUBIN, E., SHARIFI, A., TORVANGER, A., YAMAGATA, Y., EDMONDS, J. & YONGSUNG, C. 2015. Biophysical and economic limits to negative CO_2 emissions. *Nature Climate Change*, 6, 42.

SMITH, P., LANIGAN, G., KUTSCH, W. L., BUCHMANN, N., EUGSTER, W., AUBINET, M., CESCHIA, E., BÉZIAT, P., YELURIPATI, J. B., OSBORNE, B., MOORS, E. J., BRUT, A., WATTENBACH, M., SAUNDERS, M. & JONES, M. 2010. Measurements necessary for assessing the net ecosystem carbon budget of croplands. *Agriculture, Ecosystems & Environment*, 139, 302-315.

SNH. 2019. *Peatland Action Scottish Natural Heritage* [Online]. Available: https://www.nature.scot/climate-change/taking-action/peatland-action [Accessed 21 August 2019].

SONDAK, C. F. A., ANG, P. O., BEARDALL, J., BELLGROVE, A., BOO, S. M., GERUNG, G. S., HEPBURN, C. D., HONG, D. D., HU, Z., KAWAI, H., LARGO, D., LEE, J. A., LIM, P.-E., MAYAKUN, J., NELSON, W. A., OAK, J. H., PHANG, S.-M., SAHOO, D., PEERAPORNPIS, Y., YANG, Y. & CHUNG, I. K. 2017. Carbon dioxide mitigation potential of seaweed aquaculture beds (SABs). *Journal of Applied Phycology*, 29, 2363-2373.

SOUSSANA, J.-F., LUTFALLA, S., EHRHARDT, F., ROSENSTOCK, T., LAMANNA, C., HAVLÍK, P., RICHARDS, M., WOLLENBERG, E.,

CHOTTE, J.-L., TORQUEBIAU, E., CIAIS, P., SMITH, P. & LAL, R. 2019. Matching policy and science: Rationale for the '4 per 1000 - soils for food security and climate' initiative. *Soil and Tillage Research*, 188, 3-15.

STOLAROFF, J., BHATTACHARYYA, S., SMITH, C., BOURCIER, W., CAMERON-SMITH, P. & AINES, R. D. 2012. Review of Methane Mitigation Technologies with Application to Rapid Release of Methane from the Arctic. *Environmental Science & Technology*, 46, 6455-6469.

SWI 2019. Europe's oldest wooden house still going strong - Swissinfo.

THOMAS, G., PIDGEON, N. & ROBERTS, E. 2018. Ambivalence, naturalness and normality in public perceptions of carbon capture and storage in biomass, fossil energy, and industrial applications in the United Kingdom. *Energy Research & Social Science*, 46, 1-9.

THOMPSON, B. 2019. Do conifers make soil more acid? *The Telegraph*, 16 February 2014.

UN. 2014. *New York Declaration On Forests - Declaration and Action Agenda* [Online]. Climate Summit 2014: UN. Available: https://www.undp.org/content/dam/undp/library/Environment%20and%20Energy/Forests/New%20York%20Declaration%20on%20Forests_DAA.pdf [Accessed 20 August 2019].

UNEP 2017. The Emissions Gap Report 2017. Nairobi: United Nations Environment Programme (UNEP).

UNESCO 1971. Convention on Wetlands of International Importance especially as Waterfowl Habitat. https://web.archive.org/web/20160409053942/http://ramweb-uat.neox24.ch/about/the-ramsar-convention-and-its-mission

UNFCCC 2015. Adoption of the Paris Agreement. Paris: UN.

WELCH, B., GAUCI, V. & SAYER, E. J. 2019. Tree stem bases are sources of CH4 and N2O in a tropical forest on upland soil during the dry to wet season transition. *Global Change Biology*, 25, 361-372.

WHITING, G. J. & CHANTON, J. P. 2001. Greenhouse carbon balance of wetlands: methane emission versus carbon sequestration. *Tellus B*, 53, 521-528.

WILLIAMSON, P. 2016. Emissions reduction: Scrutinize CO_2 removal methods. *Nature*, 530, 153-155.

WINCKLER, J., LEJEUNE, Q., REICK, C. H. & PONGRATZ, J. 2019. Nonlocal Effects Dominate the Global Mean Surface Temperature Response to the Biogeophysical Effects of Deforestation. *Geophysical Research Letters*, 46, 745-755.

WOOLF, D., AMONETTE, J. E., STREET-PERROTT, F. A., LEHMANN, J. & JOSEPH, S. 2010. Sustainable biochar to mitigate global climate change. *Nature Communications*, 1, 56.

ZAKKOUR, P., KEMPER, J. & DIXON, T. 2014. Incentivising and Accounting for Negative Emission Technologies. *Energy Procedia*, 63, 6824-6833.

ZEDLER, J. & KERCHER, S. 2005. Wetland Resources: Status, Trends, Ecosystem Services, and Restorability. *Annu. Rev. Environ. Resour*, 15, 39-74.

Summarised information about the techniques and their governance is available in the
C2G Policy Brief: Governing Nature-Based Solutions to Carbon Dioxide Removal

This briefing is based on the latest literature and has been subject to independent expert review.
Please notify contact@c2g2.net of any important suggested corrections. This publication may be reproduced with acknowledgement of C2G.
Suggested citation: *'C2G (2019). C2G Evidence Brief: Governing Nature-Based Solutions to Carbon Dioxide Removal. Carnegie Climate Governance Initiative (C2G). New York. 2019'* Version 20190824.