Carnegie Climate Governance Initiative

An initiative of CARNEGIE COUNCIL for Ethics in International Affairs

EVIDENCE BRIEF

# Carbon Dioxide Removal and its Governance

2 March 2021


## Summary

**This briefing summarises the latest evidence relating to Carbon Dioxide Removal (CDR) techniques and their governance. It describes a range of techniques currently under consideration, exploring their technical readiness, current research, applicable governance frameworks, and other socio-political considerations in section I. It also provides an overview of some generic CDR governance issues and the key instruments relevant for the governance of CDR in section II.**


## About C2G

The Carnegie Climate Governance Initiative (C2G) seeks to catalyse the creation of effective governance for climate-altering approaches, in particular for solar radiation modification (SRM) and large-scale carbon dioxide removal (CDR). In 2018, the Intergovernmental Panel on Climate Change (IPCC) reaffirmed that large-scale CDR is required in all pathways to limit global warming to 1.5°C with limited or no overshoot. Some scientists say SRM may also be needed to avoid that overshoot. C2G is impartial regarding the potential use of specific approaches, but not on the need for their governance - which includes multiple, diverse processes of learning, discussion and decision-making, involving all sectors of society. It is not C2G's role to influence the outcome of these processes, but to raise awareness of the critical governance questions that underpin CDR and SRM. C2G's mission will have been achieved once their governance is taken on board by governments and intergovernmental bodies, including awareness raising, knowledge generation, and facilitating collaboration. C2G has prepared several other briefs exploring various CDR and SRM technologies and associated issues. These are available on our website.

# Table of Contents

# Introduction

CDR is defined by the IPCC as *'Anthropogenic activities removing $CO_2$ from the atmosphere and durably storing it in geological, terrestrial, or ocean reservoirs, or in products. It includes existing and potential anthropogenic enhancement of biological or geochemical sinks and direct air capture and storage, but excludes natural $CO_2$ uptake not directly caused by human activities'* (p544, IPCC, 2018). CDR is also known as carbon removal or carbon drawdown. Negative Emissions Technologies (NETS) and Greenhouse Gas Removal (GGR) are terms that encompass CDR, but which also include other greenhouse gases (GHGs) such as methane. It should be noted that there are currently no well-developed methods for removal of non-$CO_2$ GHGs. CDR, if ever implemented at large scale is expected to have climate cooling effects. In such circumstances, they are described as climate-altering techniques, climate engineering or geoengineering.

Four years after the Paris Agreement on climate change entered into force, recognition is growing that without a rapid acceleration in action, limiting global average temperature rise to 1.5-2 degrees Celsius (°C) will not be possible. Progress towards achieving the Paris Agreement goals has been slow. Rather than fall, prior to the COVID-19 pandemic, emissions have only risen, hitting a new high of 55.3 billion tonnes of $CO_2$ equivalent in 2018 (UNEP, 2019). Even if all the Nationally Determined Contributions (NDCs) under the Paris Agreement were implemented, the Earth is still expected to warm by 3.0°C by the end of the century (range 3.0–3.5°C with 66% probability) (UNEP, 2020).

The collective failure to adequately respond to global warming is reflected in the emission pathways in the IPCC Special Report on Global Warming of 1.5°C (IPCC, 2018). These all require the removal of $CO_2$ from the atmosphere using CDR, if warming is to be limited to 1.5°C. These scenarios indicate the need to remove up to 1,000 billion tonnes (Gigatons, or 1,000 Gt) of $CO_2$ by the year 2100, demonstrating the necessity of rapid and unprecedented action. It is in this context that CDR options are increasingly being proposed (UNEP, 2019).

This briefing encompasses all the main CDR techniques covered in the scientific literature, presenting them in alphabetical order. 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 are explored. Knowledge gaps about 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.

C2G has no position on the appropriateness of any of the techniques described here; it seeks only to catalyse the creation of effective governance 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.

# SECTION I: CDR Techniques Overview

## Introduction

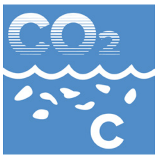
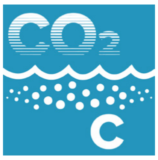
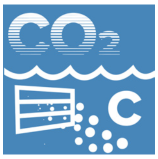
This section presents a range of CDR techniques understood to be currently under consideration, in alphabetical order. Each technique's readiness, current research, applicable governance frameworks, and other socio-political considerations are discussed. Table 1 provides an overview of the techniques discussed in the section and each techniques' potential removal capacity and costs are summarised at the end of the section, in Table 2.

Many of the techniques explored in this brief are either theoretical, or in very early stages of development. As such, considerable uncertainties remain about many of the techniques regarding, for example, their potential for carbon removal over time, any potential climate scale impacts they may have and the likely costs of deployment. These uncertainties are compounded by researchers' divergent choices regarding a complex range of factors including, for example, decisions about likely future adaptation strategies, climate change scenario choices, innovation timelines, opportunity costs and future innovation cost discounting. All of which would affect the outcomes of their assessments. Pending more research, through which more rigorous assessments may become available, this brief provides ranges for costs, carbon removal potentials and other factors for each technique, reflecting the evidence in current literature. In section these assessment issues are discussed in more depth.

**Table 1 Overview of CDR Techniques**

| Technique | | Readiness | Active Research Area | Governance Framework | Social Acceptability |
|---|---|---|---|---|---|
|  | **Afforestation and Reforestation** Planting of forests and restoration of ecosystems that result in long-term storage of carbon. | 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, reporting and verification (MRV) of achieved sequestration. | Competing demands for land use need governance. A lack of financial incentives to encourage afforestation. |
|  | **Artificial upwelling or downwelling** Pumping oceanic waters from or to deep waters to enhance carbon uptake. | Not currently practical, even in principle in engineering terms, to deliver cooling. | Very limited if any activity. | Unresolved. | Unknown. |
|  | **Biochar** Biomass burning under low-oxygen conditions (pyrolysis) creates "biochar", which is then added to the soil to enhance soil carbon levels. | A well-established technique with an evolving market. | Yes, explorations of decomposition rates and the relationship with feedstock and temperature. | State and customary law, UNFCCC and FAO. Better MRV is required. A transbounday trade in biochar may require international agreement regarding carbon credit allocation. | No major social concerns. |

| Technique | Readiness | Active Research Area | Governance Framework | Social Acceptability |
|---|---|---|---|---|
| **Bioenergy with Carbon Capture and Storage (BECCS)** Feedstock is burnt producing energy or heat. Gases released from combustion are then captured. | An established technology. | Yes, whole systems analysis and feedstock production and combustion techniques. | Unresolved. The UNFCCC, Paris Agreement and FAO. Land use trade-offs. A requirement for better MRV of achieved sequestration. | Land-use change issues may create tensions. |
| **Building with biomass** Using carbon embedded in timber in construction. | 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. |
| **Carbon sequestration in soils** Land management changes that increase soil's carbon concentration. | 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 MRV of achieved sequestration. | No major social concerns. |
| **Crop residue oceanic carbon sequestration** Crop residues are gathered and deposited into the ocean to sink. | No technical constraints to deployment. Scale up and infrastructure developments would be required. | Not an active area of research. More evidence regarding environmental impact is required. | Covered by the London Protocol and the Convention on Biological Diversity (CBD). | It is uncertain how publics would respond to this technique. |
| **Direct Air Carbon Dioxide Capture and Storage (DACCS)** Chemical processes that separate $CO_2$ from air for subsequent storage. | No technical constraints to deployment aside from scale up and energy supply/use. | Yes. Demonstrator projects improving energy, heat and water efficiency, whole systems modelling to understand scale up. | With amendments may be relevant to UNFCCC, Kyoto Protocol and Paris Agreement. | It is uncertain how publics would respond to this technique. |
| **Enhancing oceanic alkalinity** Additional alkalinity in ocean surfaces will increase the uptake of $CO_2$. | A major challenge remains to reduce the large carbon/energy footprint of manufacturing processes. | Very limited. | Would be subject to the United Nations Convention on the Law of the Sea (UNCLOS) and the London Protocol in the future, if named in annex 4. The CBD. | Limited research on broadly similar techniques suggest it is unlikely to be welcomed. |
| **Enhanced terrestrial weathering** Minerals added to the land surface which react with the atmosphere and permanently remove carbon. | No technical constraints to deployment aside from scale-up and infrastructure development. | Yes. Limited research underway. | Subject to nation state law. With amendments may be relevant to UNFCCC, Kyoto Protocol and Paris Agreement. With run-off, potentially the London Protocol. | Only limited evidence regarding how publics would respond to this technique. |

| Technique | | Readiness | Active Research Area | Governance Framework | Social Acceptability |
|---|---|---|---|---|---|
|  | **Macroalgal cultivation for sequestration** Intensive farming of microalgae. | Technologies are readily available. Further 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 in in-shore or off-shore waters. | As an extant farming method, a proliferation of the technique may pose insurmountable challenges. |
|  | **Ocean fertilisation with iron** Placing iron in ocean surface water encourages plankton growth, which takes up $CO_2$ during growth. | Technically feasible and the industrial infrastructure required is well understood. | Yes. Environmental impacts and capacity to uptake $CO_2$. | Research addressed under the London Protocol and UNCLOS. The CBD. | Limited research suggests it is not welcomed. |
|  | **Oceanic micro-nutrients, nitrogen and phosphorus fertilisation** Placing nutrients in ocean surface water encourages plankton growth, which takes up $CO_2$ during growth. | Modelling studies only to date. | Very limited theoretical and modelling research. | Research addressed under the London Protocol. The CBD. | May not be welcomed – see iron fertilisation. |
|  | **Ocean Carbon Capture and Storage (OCCS)** The chemical removal of dissolved inorganic carbon which is taken to storage sites. | The principles are well understood. Chemical engineering research is required before a viable technology becomes available for testing. | Mainly technical and economic modelling. | If conducted in Exclusive Economic Zone (EEZ) waters, OCSS would be subject to nation state terms. On the high seas, the storage of $CO_2$ beneath the seabed would be covered by the London Protocol. | There is no evidence to indicate the nature and scale of any responses. |
|  | **Restoring Wetlands** Rewetting and reclaiming of wetlands, e.g., peatlands to enhance carbon storage. | Requires little new technology. | Yes. Reducing methane release and its capture. | The UNFCCC, Kyoto Protocol, Paris Agreement the Ramsar Convention on Wetlands and FAO. Land use trade-offs. Better MRV required. | A key barrier may be the lack of financial incentives to encourage land-use change. |

## 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.

Forestation is the intentional planting of new trees in places where they have not traditionally grown (afforestation), or replanting where they have been cropped, died, or been removed by other means (reforestation). This planting results in a net uptake of $CO_2$ as the trees grow. However, once a tree or forest reaches maturity, the uptake of $CO_2$ slows (Houghton, 2013) and when a tree’s life cycle is complete it decomposes, and $CO_2$ is returned to the atmosphere (Read, 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 such as within buildings, or with them being used for bioenergy or biochar. Following harvesting, new planting and subsequent forest regrowth, or natural revegetation allows for continuing $CO_2$ removal.

Forestation’s removal capacity 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 and fire or disease. The future effects of climate change will also play a crucial role in the effectiveness of forestation and climate stability needs to be achieved quickly meaning forestation is not a substitute for urgent emission reductions (Popkin, 2019).

Forestation’s global carbon removal capacity is contested. Griscom et al., (2017) suggests the capacity ranges from between 3 to 18 gigatons (Gt) $CO_2$ per year, with the variation dependent on assumptions about the land available for planting ranging from 350 to 1780 million hectares (MHa). Whilst earlier evidence which informs the IPCC estimate indicates a global capacity of 1 to 7 $GtCO_2$ per year by 2050 (IPCC, 2018). The IPCC notes that these ranges are arrived at with limited evidence and medium agreement (IPCC, 2018). 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 this potential (Rouse, 2020). Even at this scale forestation would not remove sufficient carbon to deliver any global cooling for many years unless humanity reaches net-zero. 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 current nationally stated mitigation ambitions under the 2015 Paris Agreement.

## The technique and its readiness

Afforestation and reforestation are already widely practiced throughout the world. However, multiple issues regarding their efficiency, location and effects remain.

Replacing other ecosystems with forests can have important carbon storage and biodiversity implications, with some species being marginalised whilst others may benefit. Grasslands, for example, already play a role in the global carbon budget with studies suggesting grasslands may store up to 30% of global carbon (Anderson, 1991). In addition, they also provide important, large reserves of biodiversity, comparable in some cases to areas of tropical forest (Murphy et al., 2016). Changes to ecosystems caused by afforestation may then have significant implications, both negative, or, where forestation occurs on previously degraded land, positive; for example, enhancing or damaging biodiversity, improving or harming 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, 2019, Luyssaert, 2018).

The cost estimates for afforestation and reforestation have been assessed at between $15 and $30 per tonne of $CO_2$ (Smith, 2015) whilst the IPCC only provide abatement costs of $5 to $50 per tonne, demonstrating the considerable uncertainty regarding potential costs. However, the planting of forests will create trade-off tensions related to land use change, or future land use opportunities. Further, perverse incentives can be introduced through financial or other forestation incentives which may lead to net negative effects on biodiversity and soil carbon (Heilmayer et a., 2020). For example, a decision to plant forests in favour of crops may have negative economic and social effects such as reducing food supply and food prices increases leading to food access stresses (NAS, 2015). However, it has been suggested that agroforestry may, potentially, mitigate food supply chain challenges by combining food production and afforestation (Karki, 2019).

Given other crops will also have capacity to remove $CO_2$, if managed appropriately policy trade-offs may become important future policy and governance agenda (Hammad et al., 2020). There may also be potential for other negative social implications of afforestation such as large-scale land use driving expulsions of indigenous, possibly vulnerable people from their land (NAS, 2015).

## 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 increase longwave radiation (Lundquist et al., 2013). A recent modelling 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, 2018). More research on climate models is therefore required to better understand the full effects of changes to forestry cover (Winckler, 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 - a sum similar to emissions from the Arctic tundra or emissions from all oceans combined. Subsequent studies have found that methane and nitrous oxide, also GHGs, are emitted by trees in upland forests (Welch et al., 2019) and methane leaks from non-wetland trees in temperate forests (Covey, 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 biomass and bio-fuel production, cropping and grazing with forestation in the most equitable, economically viable and socially acceptable way is required (Rouse, 2020).

Given forests do not guarantee long-term carbon storage they may only provide a temporary climate benefit, if not managed appropriately (Crusius, 2020). Further research and related policy work may help address this important issue and, in the context of the many global efforts to reforest the need for this work is ramping up (Hammad et al., 2020).

### 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, NAS, 2015). 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). Further, forestation may, in some circumstances, create concerns about the rights of vulnerable and indigenous people. 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 (RS/RA, 2018).

### Governance

Many states, including Brazil, China, India and Mexico include forestation in their current NDCs under the Paris Agreement. They are planned to meet 25% of all the committed mitigation to 2030 under those NDCs (UNFCCC, 2015). 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 (UN, 2014).

In addition, in the light of the potential implications for cropping, and food supply and prices the Food and Agricultural Organization's (FAO) Forestry Department may be a useful neutral location for transboundary governance debate (FCP, 2019).

The monitoring of rates of both afforestation and deforestation need to be improved and a precise global accounting system agreed upon (IPCC, 2018). This is challenging given it must account for variable species uptake capability over time, the complexities of monitoring, reporting and verification (MRV) gas fluxes across a sector that is, simultaneously, a sink for and source of CO2 and other GHGs 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).

Several governance issues that are generic to many CDR techniques, including afforestation are discussed in section II.

## Artificial downwelling

### The principle

Theoretical engineering interventions would transport cold surface waters saturated in $CO_2$ into the deep ocean. At the surface, these 'down welled' waters would be replaced laterally by warmer surface waters. These would subsequently cool, taking up $CO_2$ because of enhanced solubility.

### The technique and its readiness

At the time of writing, no artificial downwelling ideas have been tested. Neither are any technologies available capable of creating oceanic downwelling at very large scales. If it were to be introduced, the oceans would sequester additional carbon, but they may further acidify. Zhou and Flyn (2005), have estimated that increasing downwelling by 1 million cubic metres per second would only increase carbon uptake in the oceans by 0.01 Gt per annum. Given the scale of the engineering challenge it is unlikely to be developed further.

### Current research activity

The technique is not currently being researched in any detail, in part due to the scale of the engineering challenges involved, the high costs and low potential carbon uptake.

### Socio-political considerations

Socio-political considerations have not been explored in the literature, potentially due to the low likelihood of further development of the technique.

### Governance

How downwelling might be governed is uncertain; however, it would likely be under the scope of the London Protocol and United Nations Convention on the Law of the Sea (UNCLOS). Importantly, the technique would not introduce new or additional materials to the oceans creating ‘dumping’ or ‘pollution’ governance issues. It may, theoretically however, if deployed at very large scale have effects on biodiversity (GESAMP, 2019).

Several governance issues that are generic to most CDR techniques, including artificial downwelling are discussed in section II.


## Artificial upwelling

### The principle

Across much of the mid and low latitude oceans, nutrients are depleted in the surface waters, limiting biological production (Moore et al., 2013). Artificial upwelling would bring deeper, nutrient-rich waters up toward the surface stimulating phytoplankton growth and the absorption of carbon. In addition, upwelled waters would be cooler than surface waters, and therefore cool the surface waters increasing their capacity for heat absorption from the atmosphere at local scales (i.e., providing ‘air-conditioning’ for coastal cities nearby). It has been estimated that the theoretical maximum carbon capture and storage of this technique would be less than 20 Gt by 2100 (GESAMP, 2019) whilst the IPCC (2019) have concluded that long-term large-scale interventions could be counterproductive in some circumstances. Unlike fertilisation techniques, upwelling would not add any new nutrients to the oceans.

### The technique and its readiness

There is no scalable technology available to date, although some field experiments, using very small scale devices have been successfully deployed for several months in Qiandao Lake, China and in one sea trial in the East China Sea (Pan et al., 2016). Other studies and field experiments (Aure et al., 2017, Fan et al., 2020) suggest a robust and efficient artificial upwelling device, utilising self-powered energy may be possible (Pan et al., 2016). Some modelling studies have demonstrated a limited potential for upwelling to draw down carbon from the atmosphere (Oschlies et al., 2010). There has not been any experimental measurement of achieved carbon sequestration.

The engineering challenges which must be surmounted to deliver meaningful carbon sequestration using this technique are substantial, including questions about the water transportation methods, and the design and construction of the tubes. If the process were stopped, the heat stored at depth could return to the surface, potentially leading to surface temperatures exceeding those previously experienced (Keller et al., 2014).

The extent of any environmental impacts of the technique are unknown but it is known that artificial upwelling would bring up high levels of dissolved $CO_2$ as well as nutrients which may affect biomass productivity (GESAMP, 2019). In addition, there may be undesirable climatic consequences, including disruption of regional weather patterns and long-term warming rather than cooling, if enhanced upwelling is deployed at large scale (Kwiatkowski et al., 2015). In addition, some simulations suggest that if artificial upwelling were stopped, surface temperatures and atmospheric $CO_2$ concentrations would rise quickly (Oschlies et al, 2010)

### Current research activity

Research is limited to modelling, laboratory scale prototyping and small-scale studies to test upwelling 'tubes. More research is required to better understand the feasibility of the large-scale engineering required, the environmental affects and the associated economics.

### Socio-political considerations

Knowledge gaps include: the economics of interventions; decisions regarding who would operate systems and why; where they would be located; monitoring and risk assessment; and social acceptability.

### Governance

Governance of upwelling interventions is unresolved; however, it would likely be within the scope of the London Protocol and UNCLOS if outside Exclusive Economic Zones (EEZs). It should be noted that, given upwelling would not require the introduction of any additional materials to the ocean, other governance mechanisms such as the London Convention are unlikely to bear on upwelling (see, for example 'Ocean Fertilisation' and Section II for a discussion of the London Protocol). It may, theoretically, however, have effects on biodiversity bringing the technique within the domain of the CBD.

Several governance issues that are generic to many CDR techniques, including artificial upwelling are discussed in section II.


## Biochar production and deposition

### The principle

Biochar would sequester carbon in soils by situating organically derived carbon, once produced, within organic matter. 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., (2014) to be between 5 and 14 GJ per tonne of $CO_2$ removed. This energy production would itself generate carbon emissions which could, potentially, be captured and sequestered.

It is suggested that a tonne of biochar can remove between 2.1 to 4.8 tonnes of $CO_2$ (Lehmann, 2015, Hammond, 2011). Looking at the full literature range, the IPCC identify that the global potential in 2050 lies between 1 and 35 Gt $CO_2$ yr−1 but notes that, given the limitations in biomass availability and uncertainties due to a lack of large-scale trials of biochar application, a lower 2050 range of 0.3–2 Gt$CO_2$ per annum may be more accurate (IPCC, 2018). In a recent White Paper on biochar, Anderson (2020) suggests up to 9.2 Gt $CO_2$ per annum may be possible when combined with savings from biochar derived energy.

Woolf et al., (2010) estimate that the costs of biochar production ranges from $18 to $166 per tonne of $CO_2$ 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, 2014).

### The technique and its readiness

Biochar is a well understood and established technique and, whilst biochar products are commercially available as soil amendments and in composting and potting mixes (for example though Wakefield BioChar, it is not yet widely available globally. Across much of the developing world biochar production is small 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 few 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 factor constraining the potential for global biochar use. In addition to source biomass constraints, 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. There is also some suggestion that biochar could potentially drive increases in methane and nitrous oxide in some specific contexts (RS/RA, 2018). 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-governmental 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 social reticence and concerns 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 MRV of the take up and use of biochar can be difficult, both at the state and international level.

How, for example, might small scale remote rural community biochar production be monitored? Improved accounting will, though, be important in the future for carbon accounting purposes 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.

Several governance issues that are generic to the majority of CDR techniques, including the use of biochar are discussed in Section II.

## Bioenergy with carbon capture and storage (BECCS)

### The principle

Biomass is grown as feedstock and burnt in generators, producing energy or heat. Gases released from combustion are then captured at source and sequestered permanently (e.g., in geological formations), effectively taking the emissions out of the carbon cycle.

### The techniques and readiness

BECCS requires a secure, regular supply of biomass, which may be grown for the purpose or derived from waste, sourced locally to minimise emissions from transport. Rapid growing, cropping, and gathering and crop replacement is required. The biomass is then transported to bespoke power generation plants where it is burnt, and the emissions captured at source (RS/RA, 2018).

Other constraints include limited energy efficiency – BECCS plants are estimated to run at up to 33% efficiency whilst gas turbines currently achieve 61% - and limited financial or other incentives (RS/RA, 2018).

The IPCC have identified literature estimates for BECCS total mitigation potentials by the year 2050 in the range 1 to 85 Gt$CO_2$ (IPCC, 2018) whilst Fuss et al., (2018) suggest that BECCS may have the potential to remove between 0.5 and 2 Gt$CO_2$ per annum by 2050. Behave et al., (2017) suggest that costs are likely to be in the range $65 to $240 per tonne of $CO_2$ whilst the IPCC notes that most cost estimates are below $200 per tonne (IPCC, 2018).

Biomass derived energy is a mature technology, whilst CCS is largely at the demonstration stage. There are currently only 19 CCS plants in operation globally. They have successfully captured and stored 250 million tonnes of $CO_2$. A further 51 are in a near ready state (CCS, 2019). If globally meaningful removals are to be achieved, a very large scale up of infrastructure will be required (RS/RAE, 2018, NAS, 2015).

BECCS at climate effecting scale will require land-use change, creating competition between BECCS and other land uses including food supply, potentially leading to increases in food prices (Hasegawa et al., 2018). In addition, fresh water and nutrients will be required to enable biomass crops to flourish potentially creating further tensions, including in relations to the Sustainable Development Goals (SDGs) (RA/RS, 2019). For example, it has been estimated that BECCS may potentially require up to 9.7 billion M3 per annum to remove 12 Gt of $CO_2$ per annum (Fajardy and Mac Dowell, 2017). Biodiversity loss because of land use changes to produce feedstock is a further potential risk of BECCS (Fajardy et al., 2019).

### Current research activity

Whole systems assessments of BECCS, to better understand the embedded carbon cycle and the wider environmental, economic and social effects are required (Fuss et al., 2018). Given the dependence on CCS in the BECCS process, collaborative work with CCS researchers is required to ensure the co-design of appropriate feedstock production and combustion techniques. To maximise the climate value of BECCS, research is exploring how required energy and CCS efficiencies may be achieved (RS/RAE, 2019).

### Socio-political considerations

Land use change issues may create tensions and policy will need to find ways to balance the demands for land to support BECCS against needs for settlements, energy, carbon removal and food. Given several countries already have national policy commitments and bioenergy and BECCS deployment strategies (RS/RAE, 2019), these, and the environmental implications need urgent resolution.

### Governance

Currently there is no international policy mechanism in place to support the implementation of BECCS, such a measure could be useful because the BECCS supply chain will be geographically dispersed, including, for example, biomass and storage import and export (Anandarajah et al., 2018). At the nation state level, Bellamy suggests that states should incentivise BECCS if whole energy systems are to be decarbonised (2018).

BECCS governance is generally considered to comprise two elements (Torvanger, 2019). Biomass production and usage and the CCS elements. The latter relates predominantly to capture MRV, as well as the safety and permanence of long-term storage. The Biomass agenda encompasses accounting for sustainability and resource use related to biomass energy production, processing and use, and interactions with the global carbon cycle. Trade-offs between BECCS biomass production and competing land and water use will also require governance attention, normally at the local level (Torvanger, 2019).

Currently, none of the existing carbon markets include negative emissions. Were this to change, BECCS operators could potentially earn a revenue for permanently storing $CO_2$, as well as from energy sales (Nemet et al., 2018).

## Building with biomass

### The principle

Plant and tree matter contain carbon, taken up through photosynthesis, although 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, 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).

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, 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, 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 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, 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 (US), Scandinavia and the United Kingdom (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 credit for the removal, along with a mechanism to monitor the flow of materials, and the carbon storage may be needed (RS/RAE, 2018). For effective international oversight, more comprehensive and consistent national accounting standards and reporting may be required.

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).

# Carbon sequestration in soils

## The principle

Carbon 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, 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 microbial 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 GHGs 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 technical barriers to taking measures to improve soil carbon sequestration, and 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, 2010). However, there may be social and economic reasons why uptake is challenging (Minasny, 2017) and, whilst some are already using the required practices, considerable further policy, financial and educational support for farmers is required before the industry can achieve its full sequestration potential (Minasny, 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, 2017) with

Fuss et al (2018) suggesting it may be possible to remove up to 5 Gt per annum by 2050. It should be noted that the IPCC combine CDR estimates for carbon sequestration in soils, the restoration of degraded land and changes in conservation agriculture management practices and do not provide an estimate for soil carbon sequestration alone (IPCC, 2018).

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 tonne of $CO_2$ through improved productivity. In other circumstances, dependent on soil and environmental conditions, Smith suggests deployment may cost up to \$12 per tonne.

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 GHGs, such as soil methane (Lal, 2011), although this may only be by a small amount (RS/RA, 2018). In addition, it increases the volume of organic nitrogen levels in the soil, which could be mineralised becoming a substrate for nitrogen dioxide ($NO_2$) production (Smith, 2016). Further research on these issues is warranted. Research is also warranted on the stability of soil carbon during global warming (Walker et al., 2018).

If we are to accurately quantify the volume of carbon sequestered through this approach, rapid and reliable methods are needed for the measurement of soil carbon (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 will need to be overcome with education and training, if deployment is to be scaled up (Minasny, 2017). Assuming practices do change, such that carbon saturation is reached, then a further set of incentives may help ensure that the practices are maintained indefinitely, and a reversal of the sequestration is avoided.

### Governance

Given the broadly positive effects on crop productivity and biodiversity, and the apparent lack of potential harms, governance of this technique will likely be constrained to practical issues including global monitoring and accounting (Smith, 2012), promoting the value and maintenance of the practices (Soussana et al., 2019), and facilitating dialogue across diverse communities of interest to help develop best practices in diverse environments and communities (Minasny, 2017). The technique is partially captured under the reporting requirements of the UNFCCC and the Paris Agreement (see the governance section below).

Measures are already in play that aim to promote the technique as a contributor to the climate change targets of the Paris Agreement including the '4 per 1000 initiative' (Soussana et al., 2019). This forms part of the Global Climate Action Plan (GCAA), adopted by the twenty-second session of the Conference of the Parties of the UNFCCC (COP 22) (UNFCCC, 2016) which commits stakeholders to transition towards productive and highly resilient agriculture, based on land and soils management with a view to creating employment and promoting sustainable development.

The FAO may play a lead role in future dialogue about the governance of this technique. The contribution that 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).

Several governance issues that are generic to many CDR techniques, including carbon sequestration in soils are discussed in section II.

## Crop residue oceanic carbon sequestration

### The principle

Ballasted bales of crop residue would be dumped into the deep ocean or off the deltas of large rivers. With suitable additional ballast, biochar, timber and other organic matter could also be deposited in the deep ocean seabed (GESAMP, 2019).

### The technique and its readiness

Crop waste (and other material) would be secured, gathered centrally and taken to appropriate ports for transport to dumping sites and having been suitably weighted, they would be dumped. There are no technological constraints to hinder the implementation of this technique (GESAMP, 2019).

Allowing for an average land transport distance of 200 km, and a combined average river and ocean shipping distance of 4,000 km, Strand and Benford (2009) suggested that 30% of global annual crop residues of 2 Gt could be available sustainably without harming soils. However, the use of such biomass to produce electricity in a power plant that captures the $CO_2$ and sequesters it in geological formations may usefully be explored as a potentially more effective option. Lenton and Vaughan (2009) suggest that an annual sequestration rate of up to 1 Gt C of material per annum, half the global annual crop residues, would only make a very modest contribution to slowing climate change.

The environmental impacts of depositing crop wastes in the deep ocean are uncertain. It is, though, known that, if deployed in shallow water (below 1,000m), its impacts on ecosystem services could be more significant, particularly on deep-sea fisheries. In addition, long-term oxygen depletion and deep-water acidification could be regionally significant given cumulative deposition in limited areas (GESAMP, 2019).

### Current research activity

This is not an area of current research interest.

### Socio-political considerations

There is no available research evidence to inform our understanding of how publics would respond to this technique. To deliver enough mass of material to the deep oceans to have a material effect a new, very large-scale infrastructure and market mechanism would need to be constructed (GESAMP, 2019). How much material would be taken, and from where would require monitoring and regulation to protect soils and crop productions as well as to inform the market mechanism (GESAMP, 2019). In addition, crop residues provide multiple services within agricultural systems. This technique might then have important, unintended, and harmful consequences for those systems; however, this has not been subject to systematic research to date.

### Governance

It would appear that the technique may be permissible subject to assessment under the Organic Material of Natural Origin category in Annex 1 of the London Protocol and the Uncontaminated Organic Material of Natural Origin category in Annex I of the London Convention (IMO, 2016). The technique could potentially come under the purview of The International Convention for the Prevention of Pollution from Ships (MARPOL), Annex V, if the Convention were to be revised in the light of a conclusion that the crop residue constituted either food waste, or a noxious substance.

Several governance issues that are generic to most CDR techniques, including this technique are discussed in section II.

## Direct Air Carbon Dioxide Capture & Storage (DACCS)

### The principle

DACCS seeks to separate $CO_2$ and other GHGs (then often referred to as Direct Air Capture and Storage (DACS)) from ambient air (the atmosphere around us) and store or use the sequestered gases in ways that will not contribute to global warming. DACCS uses chemical engineering to remove $CO_2$. Air is drawn into a chamber where a chemical separating agent releases the $CO_2$ from the air. The gas is then removed and stored for the very long term or permanently. This could, for example, be in geologic storage, in a mineralised form with the characteristics of rock. Alternatively, it may be transformed into useable products such as fuels, however, any emissions resulting from the use of those fuels would then also need to be captured if the process is to result in net $CO_2$ removal.

### The technique and its readiness

To extract $CO_2$, two approaches are used: adsorption and absorption. The first, adsorption uses solids to capture $CO_2$ whilst the second, absorption uses liquids.

Absorption is a well understood process and processes similar to those that would be used in DACCS have been used in the paper industry for over 120 years (Sanz-Pérez et al., 2016). This means the required hardware is commonly available without further development. Processes that would use absorption to remove $CO_2$ would use hydroxide-based solvents. Potassium hydroxide and calcium hydroxide have been proposed for DACCS (Daggash et al., 2019). In the processor a carbonate is formed, and the processed air, which is unchanged aside from having a lower density of $CO_2$, is returned to the environment. To isolate the captured carbon (for removal and storage) and regenerate the absorbent (for re-use), the energy that binds the $CO_2$ and hydroxide must be overcome. This requires a large energy input of heat at between 900 and 1000°C (Samari et al., 2019). This heat requirement creates a key challenge for DACCS, as discussed below.

Adsorption based DACCS would build on technologies that have been used in air purification systems in hostile environments that have no ambient air, for example, in space craft and submarines. The most cited approach to $CO_2$ adsorption is to use compounds called amines which are derived from ammonia. Amines hold $CO_2$ onto their surface without any chemical reaction taking place. To regenerate its absorbency the amine is subject to changes in temperature, pressure or humidity (Sanz-Pérez et al., 2016). However, unlike absorption, lower temperatures (approximately 120°C) are required to regenerate the adsorbent, meaning this approach has lower energy input requirements.

Currently DACCS technologies are situated between the pilot plant stage and small scale or prototype demonstration in the field. Conservative assumptions, such as Viebahan et al., (2019), suggest that DACCS is unlikely to be viable on a large-scale before 2030. However, Bill Gates recently ranked DACCS as one of ten breakthrough technologies that would be commercially available in five to ten years (Gates, 2019). Such a shift toward commercialisation may be reflected in an increasing number of DACCS related patents around the world, which include four each in the US and Canada, two in China, and one each in Croatia and Mexico. A further three European Patents (EP) and three World Intellectual Property Organization (WIPO) patents have been filed (Viebahn et al., 2019).

A key advantage of DACCS is that it directly captures emissions from the air. It is then unlike CCS technologies which separate $CO_2$ directly at the point of emission (Krekel et al., 2018). This gives DACCS an important advantage – it can capture emissions from both stationary and mobile emitters - in effect the atmosphere transports $CO_2$ from its emission source to its point of capture. Further, because atmospheric $CO_2$ is distributed around the world (Goeppert et al., 2012) the location of DACCS units would not have to be tied to GHG emitting industrial infrastructure or areas of high $CO_2$ concentration. DACCS plants could therefore, for example, be sited near renewable energy sources to power the process, and in areas that are neither environmentally sensitive nor densely populated (Fuss et al., 2018). It should be noted that DACCS is expected to be more efficient in dry air (Wang et al., 2013). However, a demand for water as part of the process suggests locating plants in arid deserts may not be suitable. Given the rate of air mixture globally is fairly efficient (Goeppert et al., 2012), it would be possible to co-locate multiple capture facilities in single locations, realising economies of scale, without having additional detrimental environmental effects (Goldberg et al., 2013).

Before the technologies can be scaled up, some outstanding issues, including energy requirements, the capacity for an longevity of $CO_2$ storage, and the natural resource requirements, require resolution (NAS, 2015, RS/RAE, 2018). It is suggested that, in the long term, DACCS has a global sequestration potential of between 0.5 and 5 Gt of $CO_2$ per annum by 2050 (Fuss et al., 2018), although the IPCC do not record any removals capacity estimates to date. In addition to the constraints of energy availability, Fuss et al (2018) suggest that the main constraints to DACCS removals capacity prior to the year 2050 may be storage capacity and unexpected environmental side-effects, as well as moderate land demand issues. The scalability of DACCS requires further research and new systematic analysis will be required as greater certainty about the technologies, their energy requirements and impacts become available (Fuss et al., 2018).

Both adsorption and absorption approaches have high heat or energy requirements and would require a reliable and secure power supply to provide an air supply through the plant, to reactivate the agents and release the $CO_2$. Water and a low-pressure vacuum are also required for adsorption DACCS.

In a meta review of DACCS energy requirements by Daggash et al., (2019) it is suggested that absorption based DACCS would require an energy input of 1500-2500 kWh for heat and a further 220-500 kWh of electricity per tonne of $CO_2$ removed. Adsorbent energy requirements have received less attention, possibly, as suggested by Daggash (2019), because the adsorbent materials are rarely specified in the literature. Climeworks (2019) have, however, provided energy and economic costs estimates including the need for 200-1000 kWh electricity and 640-1700 kWh for heat per tonne of $CO_2$. Having extracted $CO_2$, sequestration, in whatever form is chosen, will have some additional energy resource demands. For example, for transportation to, and pumping into reservoirs.

To maximise the net carbon removal potential of DACCS, the energy required would be best drawn from low-carbon, low impact sources such as solar or wind power or by co-locating plants with industrial processes that emit waste heat, such as gas power plants. However, the energy requirements for both approaches, in the context of the higher volumes of $CO_2$ removals that will be required, are high.

In 2019 global wind turbine generation was 650 Terawatt hours (TWh) (Wang, 2020). In 2018 the global solar power generation was 570 TWh (IEA, 2019). However, the electricity requirements of absorption and adsorption to capture and isolate only 1 Gt of $CO_2$ are estimated at 220 to 500 TWh and 200 to 1,000 TWh respectively, disregarding the required thermal energy (1,00-2,500 TWh and 640-1,700 TWh respectively) and additional sequestration energy costs (Daggash et al., 2019). This suggests, if large scale DACCS is to rely on renewable energy sources, greater efficiency and a step change in renewables capacity is required. Noting that global nuclear power generation was 2,563 TWh in 2018 (WNA, 2019), an uplift in total global energy provision may be required before climate-altering scale DACCS were to be deployed. In addition to the energy and heat requirements, there are other costs that require consideration, including water resources (Climeworks, 2019, Smith et al., 2016), sorbent replacement costs and other maintenance (Fuss et al., 2018) and $CO_2$ sequestration costs. Further, considerable investment will be required to scale up DACCS capability.

In Fuss et al's meta review of potential DACCS environmental costs (2018), it is suggested that the process of capturing around 1 megaton of $CO_2$ per annum may only leave a marginal positive net balance of $CO_2$ removed after the emissions 'costs' of the process are included.

Estimates of financial costs of DACCS range from \$20 to \$1,000 per tonne of $CO_2$ captured (Sanz-Pérez et al., 2016 and (IPCC, 2018)). Estimates vary depending on assumptions about processes, energy and thermal costs and sorbent regeneration. Some estimates include the costs of preparation for and long-term storage of $CO_2$, whilst others include only the costs up to the point of the production of $CO_2$.

In the light of the costs, current carbon prices and the absence of credit for CDR, DACCS, as with many other approaches to CDR, may not be commercially viable in the short term (Daggash et al., 2019).

### Current research activities

There is a wide range of ongoing DACCS or DACCS related research. Currently, the largest programmatic funding for GHG removal including DACCS is funded by UK Research and Innovation, which is committing \$44 million to the topic of CDR over five-years, commencing 2021 (UKRI, 2019).

At the Arizona State University, a Centre for Negative Carbon Emissions is researching a DACCS process based on an anionic exchange resin. Currently, the estimated costs of the technique are unknown, and the details of the engineering are not, yet, public (Sandalow et al., 2018)

The VTT Technical Research Centre of Finland has demonstrated a system based on an amine-functionalised polymer resin sorbent which is currently removing between 1 and 2 kg a day and further research is on-going (Sandalow et al., 2018)

In the US, Oak Ridge National Laboratory has demonstrated a proof-of-concept system using an aqueous amino acid solution (Brethomé et al., 2018)

Looking to the future research agenda, a number of studies have provided an overview of research gaps, or 'needs' (Goeppert et al., 2012, Koytsoumpa et al., 2018, Sanz-Pérez et al., 2016). The Innovation for Cool Earth Forum (ICEF) reviewed the key innovation steps required over the next 20 years in a roadmap for DACCS (Sandalow et al., 2018), and the National Academies of Sciences reviewed the research agenda of the wider field of negative emissions technologies in 2019 (NAS). A reading of these suggest the following are key areas for DACCS research in the future, in no order of priority:

- achieving greater energy, heat and water efficiency;
- developing a better understanding of the sustainability impacts of DACCS;
- resolving remaining carbon cycle uncertainties;
- improving the production of synthetic renewable fuels using captured carbon;
- gaining a better understanding of how to deliver environmentally neutral secure, permanent carbon storage;
- the economics and policy of a DACCS compatible carbon market;
- the social acceptability of DACCS; and,
- global carbon accounting and governance.

### Socio-political considerations

Blackstock and Low (2018) suggest that the social acceptability of DACCS cannot be assumed. Whilst there have been critical reports and analyses of CDR technologies and CCS (Anderson and Peters, 2016, Thomas et al., 2018, Hester, 2018, Lin, 2019), evidence regarding the acceptability of DACCS is thin. It has, however, been suggested that there may be some opposition to DACCS if its deployment is seen to create a form of moral hazard by delaying climate change mitigation efforts (Honegger et al., 2018) and McLaren has suggested publics may have concerns about intergenerational and intragenerational equity (McLaren, 2016).

DACCS plants are likely to have a small physical footprint, compared to medium sized industrial facilities, and they would not be expected to create any long-term threats regarding land availability, including to ecosystems services or food security (RS/RA, 2018). Further, because DACCS plants are not geographically constrained, aside from having access to energy and water supplies, facilities need not be in sensitive areas or close to populations (Goldberg et al., 2013). The locating of DACCS plants is not expected to give rise to significant social acceptability issues, aside from those that arise from the proposals for any medium-size industrial facility, such as issues regarding noise and loss of amenity (RS/RAE, 2018). In addition, because DACCS could be deployed proximate to storage facilities, including sub-surface storage, they will not, necessarily, create transport infrastructure demands (Fuss, 2018). However, it should be noted that studies of public views on CCS reveal public concerns that underground carbon storage could lead to leaks or earthquakes and general unease that it might facilitate continued fossil fuel consumption (Lin, 2019).

### Governance

DACCS installations will be situated within nation state boundaries and are not expected to cause direct environmental, economic, social and political transboundary harm requiring international governance.

If large scale DACCS were adopted, as with all CDR techniques, transparent MRV of achieved sequestration would be necessary for monitoring of global progress against climate change targets, and to provide accurate accounting of states' contributions and any carbon sequestration credits that may accrue (Zakkour, 2014). It is unclear how the international community might agree, set and stabilise, atmospheric carbon dioxide concentrations over the long-term. Nor is it clear how this process, and the outcomes of the decisions taken, can balance the individual interests of nation states with the global need to reduce $CO_2$ concentrations in the atmosphere. These challenges will likely be subject to on-going debate through the UNFCCC and its associated mechanisms.

DACCS raises novel challenges for carbon life-cycle accounting. The $CO_2$ captured by DACCS may or may not be anthropogenic and its origin will be unknown. A country may, for example, reach net-zero and be removing $CO_2$ generated by other nations, creating interesting carbon accounting governance issues. Further, $CO_2$ captured by DACCS will not necessarily be permanently stored within the capturing country's borders. These issues may affect not only accounting standards, but also industrial standards and practice, financial practice, and regulation.

Policy and financial support, in the form of subsidies, carbon pricing and support for geological storage, as well as the creation or support of nascent new markets for captured carbon, such as long-duration products or synthetic fuels, may also require multinational governance (Viebahn et al., 2019).

Several governance issues are generic to many CDR techniques, including DACCS, these are discussed in section II.

## Enhancing ocean alkalinity

### The principle

Alkalinity is the capacity of a solution to neutralise acid. Given the $CO_2$ absorbed in oceans is acidic (prominently in the form of carbonic acid), adding additional alkalinity to the surface of the ocean will decrease the relative pressure of $CO_2$ in the water and, as a result, increase the uptake of $CO_2$ by the ocean from the atmosphere. Enhancing alkalinity would also help reduce the effects of ocean acidification on the marine ecosystem (GESAMP, 2019).

### The technique and its readiness

Lime (calcium oxide or calcium hydroxide), which readily dissolves in seawater, would consume $CO_2$

in a well-known and understood process. No field trials have been undertaken, however, enhancing alkalinity would not require any novel or new technology – the raw materials are already available from cement and other industries and distribution could be from ships (RS/RAE, 2018). However, currently there is a major problem with this approach – there is a very large carbon and energy footprint in the current manufacturing processes of lime (RS/RA, 2018). If alternative methods could be developed, with a small footprint, liming may have potential as an effective CDR technique.

Other approaches include adding naturally occurring minerals to the oceans, or electrochemical enhancement of carbonate and silicate mineral weathering. These techniques can also be conducted on land (see Enhanced Terrestrial Weathering below), avoiding the costs of transport to and across the oceans. In addition, the impacts of introducing particles from these materials into the oceanic environment are unknown. Meaning the marine biogeochemical and ecological responses to alkalinity enhancement would benefit from further examination prior to implementation (GESAMP, 2019).

The IPCC do not estimate a theoretical removals capacity for chemically enchaining alkalinity (IPCC, 2018) although theoretical studies have suggested that enhancing ocean alkalinity could remove as much as 3,500 $GtCO_2$ by 2100 (Gonzalez and Ilyina, 2016). However, this study does not provide any details regarding how the addition of alkalinity to achieve such a large-scale removal could be delivered. An important limitation on attempts to estimate the removals capacity of this approach is that the likely extent of carbonate mineral formation because of any given increase in alkalinity, is basically unknown. Cost estimates range from $50 to $400 per tonne removed (GESAMP, 2019).

### Current research activity

Insufficient research has been completed to properly inform decision making about enhancing alkalinity. Further research is required to develop understanding about which minerals or other materials would deliver the best net $CO_2$ return, the likely impacts on ocean ecosystems, the longevity of any sequestration, the economics and resource efficiency of the methods and how both deployment and its effects would be monitored (GESAMP, 2019).

Currently, there is very limited research underway on delivery mechanisms and techniques for enhancing oceanic alkalinity. Work is however being undertaken to access potential risks and co-benefits of the approach (Bach et al., 2019).

### Socio-political considerations

There are questions about the public acceptability of the process. Research by Corner et al. (2014) suggests publics may not be supportive of ocean-based interventions of this nature. It is possible that the very large-scale of deployment that would be required by this technique may compound these concerns.

### Governance

The technique could fall under Annex 4 of the London Convention and London Protocol and UNCLOS.

Other interested parties may include intergovernmental or civil society organisations (CSOs) and commercial interests related to chemical engineering.

Several governance issues that are generic to many CDR techniques, including the techniques are discussed in section II.

## Enhanced terrestrial weathering

### The principle

Mineral weathering is the primary way in which $CO_2$ is removed from the atmosphere over geologic timescales. The process involves weathering of carbonate and silicate rocks, the most commonly found rocks on Earth (RS/REA 2018), which react with $CO_2$ to form carbonates, removing carbon from the atmosphere.  This climate-altering technique would artificially replicate and accelerate this process through the spreading of abundant silicate minerals on to the surface or adding them to soil used for agriculture. The added minerals would be pre-ground to increase the surface area of the substrate, maximising the reaction rate. It is estimated it would take approximately two tonnes of added rock to remove and store one tonne of $CO_2$ (RS/RAE, 2018), however, the process may be quite slow, potentially taking decades and even centuries.

### The technique and its readiness

A range of approaches to enhanced weathering have been suggested in the literature, including electrochemical enhanced weathering, dissolution of reactive silicate material (e.g., olivine) and enhanced weathering of mine wastes (see for example, the GESAMP study (2018)).

The underlying understanding of the chemistry of enhanced weathering of carbonate or silicate minerals to decrease $CO_2$ is very well understood (NAS, 2015) meaning the key barriers to deployment are questions about how to scale up, cost, possible environmental or other consequences alongside a number of governance issues. It should be noted that, if a sufficient volume of minerals could be processed, distributed and deployed at large enough scale the capacity of enhanced weathering to contribute to $CO_2$ mitigation is virtually unlimited (IPCC 2013). In addition, Smith et al (2015) have estimated that if two-thirds of all cropland were treated with between 10 and 30 tonnes of material per hectare per annum, between 0.4 and 4 Gt could be removed by enhanced weathering by 2100. However, a recent outdoor experiment into enhanced weathering has suggested that the approach, when in-situ maybe up to three times less efficient than had been previously suggested (Amann et al., 2020). An earlier IPCC review of literature suggests a range for the potential to remove carbon of 0.72 to 95 $GtCO_2$ per annum (IPCC, 2018). The IPCC, in the light of these wide uncertainties note that agreement is low due to a variety of assumptions and unknown parameter ranges in the applied modelling procedures, and that these would need to be verified by field experiments (IPCC, 2018).

A significant issue associated with enhanced weathering is the requirement to mine, grind-up, transport and spread very large quantities of material. The Royal Society and Royal Academy of Engineering (2018) have estimated that at least 7 $km^3$ per year of material would be required to remove as much $CO_2$ as we are currently emitting, assuming the mineral conversion in-situ was 100% efficient. This would be double the volume of all mined coal in 2018.

Cost estimates for the removal of $CO_2$ by enhanced weathering vary and are dependent on wide ranging assessments of costs for extraction, preparation and delivery, and the price of land or land access. Estimates per tonne of $CO_2$ removed range from between $15 and $3,460 per tonne (McQueen et al., 2020, Beerling, 2020, IPCC, 2018 and Renforth, 2011). Were the weathering process to be conducted using carbon mineralisation processes in wells or bore holes Kelemen et al., (2020) have suggested the costs per tonne of $CO_2$ could be similar to DACCS, if done at sufficiently large scale. Further, a techno-economic assessment of the use of Magnesite as the reactant mineral has indicated enhanced weathering may cost less than DACCS per tonne of $CO_2$ removed (McQueen et al., 2020). It is also suggested that enhanced weathering on the surface may have positive benefits on crop growth through changes in nutrient availability (de Oliveira, 2020). However, it may also have negative effects, from, for example, fine particulate pollution and nickel and chromium accumulation and release into aquatic and marine systems (Edwards et al., 2017).

It is expected that current mining, grinding and farm machinery technology would be capable of extracting, preparing and distributing the mineral. However, a large scale up of available machinery and infrastructure globally would be required (Florin et al., 2020).

### Current research activity

More research may help identify the best materials choice and how to economically extract, prepare, transport and deploy them (RS/RAE, 2018). Whilst the expectation is that on land enhanced weathering will have limited environmental impacts, it is suggested run off into the oceans may have potentially negative effects (GESAMP, 2019). In addition, crop effects, the longevity of sequestration and the economics and resource efficiency of the technique require further research.

Multiple research projects are exploring the challenges and recent proof of concept and very small-scale field trials have demonstrated positive results (McQueen et al., 2020 and Kelemen, 2020). In the UK, an interdisciplinary team from across four universities is working on the issues (GGREW, 2020). However, to date, results from large-scale field trials are not yet available (Henderson, 2019).

### Socio-political considerations

There has been little research about public perceptions or other social considerations related to enhanced weathering, although soil liming is an established practice. Despite low levels of understanding about the approach (Pidgeon and Spence, 2017, Wright et al., 2014) and whilst noting that what has been done has been focussed on Europe and the US, research has suggested that enhanced weathering may be seen as being too slow a response to the climate crisis, although research in well controlled conditions is likely to be acceptable (Cox et al., 2020). Cox et al., (2020) also suggest that publics require greater clarity about the processes that would be involved and would wish to see evidence that the current scientific uncertainties can be resolved. Further, the study also indicates there may be a preference for the use of mine by-products for enhanced weathering rather than the sinking of new mines to access materials.

### Governance

Given enhanced weathering on land would be conducted within the boundaries of countries, national law and other national governance norms would apply. Interested parties may include local and regional governance bodies, CSOs, farmers and landowners and other commercial interests related to chemical engineering, mining, transport and distribution (RS/RAE, 2018).

Enhanced weathering does not feature in any carbon accounting regimes. Therefore, were enhanced weathering to be deployed at a significant scale, new mechanisms for MRV, including mechanisms that account for transboundary effects of the approach would be required under the Paris Agreement.

Were materials to wash off into the oceans and become a transboundary issue then the technique may potentially be subject to the norms of customary international law and may also fall under the auspices of Annex 4 of the London Convention and London Protocol and UNCLOS.

Several governance issues that are generic to the majority of CDR techniques, including enhanced weathering are discussed in section II.

## Macroalgal cultivation for sequestration

### The principle

Sometimes called ‘ocean afforestation’ (N‘Yeurt, 2012), macroalgal (seaweed) 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 permanent connection to the sea bed would prevent the macroalgae being sequestrated in situ (Sondak, 2017)). Large-scale macroalgae could theoretically 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, 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, 2013). It may already account for the accumulation of ~0.8 Mt of organic carbon annually in the Asia-Pacific region (Sondak, 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 could potentially 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 the $CO_2$ produced by burning the methane would be captured and sequestrated. However, to date there is limited evidence about the potential for removals, risks and environmental impacts (IPCC, 2019).

### Current research activities

Research is underway in China, Denmark, the UK and the US, exploring the challenge of entrapping macroalgae in the seabed (Queiros, 2019). Other work is exploring the effect of ocean acidification on macroalgae growth (Rodríguez, 2018), which may diminish the value of the technique if acidification continues, and the conversion of seaweed to bio-products which use captured carbon in ways the sequester it for the long term (BMRS, 2019).

### Socio-political considerations

As an extant farming method, a proliferation of the growing of macroalgae in the Asia-Pacific region would not raise novel socio-economic challenges (Pereira, 2013). Pereira also suggests diversification to other regions is likely to be practical and commercial operations are functioning on the Atlantic coastline and elsewhere. Any development of a viable CDR process out of this agriculture, however, would require significant infrastructure investment and policy commitment (RS/RA, 2018). In addition to environmental benefits, the technique may have economic value from sale for nutrition, energy and fertiliser, although some of these uses may mean the approach does not capture GHGs in the long term and, as such, may not qualify as CDR (RS/RA, 2018).

GreenWave, Oceans 2050, ClimateWorks and 3Degrees (2019) are working with industry, scientists and non-governmental organisations (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 CCS facilities. It is noteworthy that this technique would avoid the competition for land resources of other afforestation methods and, dependent on location, may not be in competition for marine resources and may, potentially, enhance them (GESAMP, 2019).

### 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 MRV of GGRs (GESAMP 2018). For waters outside EEZ, the technique would fall under customary international law, the London Protocol and the 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).

Several governance issues are generic to many CDR techniques, including macroalgal cultivation and these are discussed in section II.

# Ocean carbon capture and storage (OCCS)

## The principle

The oceans contain most of the carbon on the planet (IPCC, 2019). This technique would remove the dissolved inorganic carbon from the water to be taken to long term storage sites. This removal would increase the capacity of the oceans to absorb $CO_2$ from the atmosphere driven by a natural return to equilibrium.

## The technique and its readiness

The principles underlying the technique are well understood and are used at small scale in laboratories during sea water analysis (Willauer et al., 2017). This would require scaling up, work on which is only at very early stages (GESAMP, 2019). OCCS would require a ready supply of energy. However, given the technique could be conducted at coastal locations, low carbon energy sources could be used to meet the energy demand. Estimates of the theoretical maximum efficiency of this technique are uncertain given the limited understanding of how scaling up would work.

## Current research activity

Technical and economic modelling is underway (Eisaman et al., 2018) exploring cost and infrastructure challenges of OCCS. Many critical research issues remain, most importantly the feasibility of large-scale engineering development of OCCS and the associated costs and whether a scaled-up system would be suitable for climate mitigation (GESAMP, 2019). There have been no environmental impact studies. There is no co-ordinated programme of investment in this area.

## Socio-political considerations

It is unclear what incentives would be required to encourage up-take were a technology proven. Which institutions would develop this and why is unknown? It is also unknown where the captured carbon would be stored and at what opportunity cost, nor whether the technique would be socially acceptable.

## Governance

If conducted in inshore waters, OCCS would be subject to nation state regulation, customary law and wider governance dialogue. In international waters, the governance frameworks are uncertain. Currently, it is unclear how sequestration and the rates of natural carbon up-take would be monitored.

Further information about governance issues that apply to this, and other techniques can be found in section II.

# Ocean fertilisation with iron

## The principle

Photosynthesis by plankton in the ocean removes around 40 Gt $CO_2$ per annum from the ocean surface and transports it downward to the deep ocean (RS/RA, 2018). This so-called 'biological pump' is limited by the abundance of photosynthesising life which in turn is constrained by the supply of nutrients, required in relatively large amounts (macro-nutrients), such as nitrate and phosphate, and small amounts (micro-nutrients), such as iron (for a review of the biological pump, see Passow and Carlson, (2012). There are some parts of the ocean where macronutrients are available, but micronutrients are lacking. Iron ocean fertilisation seeks to address this shortfall by introducing additional micronutrients.

## The technique and its readiness

Distributing iron into the oceans is technically feasible and the industrial infrastructure required is well understood (GESAMP, 2019). Some 12 experimental fertilisations have been carried out in several areas with variable results in terms of both the characteristics of the plankton blooms created, and the carbon sequestrated (Boyd et al., 2013). Modelling suggests that the subarctic Northern Pacific, Eastern Equatorial Pacific and Southern Ocean would be the most suitable locations for deployment, with the latter the most promising for net carbon sequestration (Bopp et al., 2013). Williamson suggests that further research assessment of carbon transfer in large-scale experiments is required (2012).

Estimates for the capacity for ocean iron fertilisation to remove and store $CO_2$ are extremely uncertain, and the models used to predict removals are varied. This is reflected in the range of removals estimates found in the literature. For example, the IPCC estimates a range of 15.2 kilotons (kt) for small interventions to 44 Gt per annum, (IPCC, 2018) whilst another authoritative study, by the Royal Society and the Royal Academy of Engineering, adopts an estimate of 3.7 $GtCO_2$ per annum (RS/RA, 2018). Cost estimates for this technique also vary and contain significant uncertainty. The IPCC, for example, estimate a cost range of between $2 and $457 per tonne of $CO_2$ removed (IPCC, 2018).

Some potential side-effects have emerged during testing, including population increases of toxic species of single-celled algae diatoms (Silver et al., 2010 and Trick et al., 2010). There is also limited evidence of increased concentrations of methane and nitrous oxide during the decomposition of the sinking particles (Law, 2008). Release of such gases would reduce the climatic effectiveness of the $CO_2$ uptake. If iron fertilisation is carried out over large areas, there may be reductions as well as increases in productivity, affecting fisheries and potentially nutrient robbing from downstream regions, potentially with geopolitical and economic implications (GESAMP, 2019).

### Current research activity

Ocean iron fertilisation is an area of active research interest. Oceaneos, a marine research organisation in the US has proposed research on nutrient enrichment techniques in waters off Peru. The stated purpose of the work is to understand how to 'increase wild fish populations at a local scale, through targeted ocean fertilisation focused on rehabilitating the human-impacted marine ecosystem' (Oceaneos 2019). However, the project will also likely inform understanding of iron fertilisation.

### Socio-political considerations

The Haida Gwaii 2012 project provides an example of how socio-political reactions to iron fertilisation can play out. The small remote community off Prince Rupert Columbia became subject to global news after the Guardian newspaper headlined a story 'World's Biggest Geoengineering Experiment 'Violates' UN Rules' (Lukacs, 2012). The Haida Salmon Restoration Corporation had released 120 tonnes of iron sulphate into an ocean eddy 400km offshore. This was flagged to the media when ETC Group alerted the press to the project (Lukacs, 2012). This coincided with the UN CBD COP 11 in India, in which the ETC Group were presenting a case for a test ban on 'geoengineering' (ETC, 2012). Contiguous with the Haida experiment, the governing body of the London Protocol tasked its Ocean Fertilisation Working Group to develop options for providing a control and regulatory mechanism for ocean fertilisation and, on 18 October 2013 the Protocol Parties, added a new article (6bis), 2 new annexes and consequential amendments to Articles of the London Protocol (LC&P, 2015) (see 'governance' below).

Research suggests that the public, at least in the UK, are broadly unaware of the technique, and when informed about it they view it negatively describing concerns about pollution and other deleterious environmental consequences (Corner et al. 2014)

### Governance

The technique falls under Annex 4 of the London Protocol, which was accepted as an amendment to the Protocol on 18 October 2013 (IMO 2013) which is not yet in force and, since 2008, the CBD (CBD, 2008). Other interested parties could include civil society and commercial interests.

Several governance issues are generic to many CDR techniques, including ocean fertilisation with iron, these are discussed in section II.

## C Ocean fertilisation with macro-nutrients, nitrogen, and phosphorus

### The principle

The underlying principle of this technique is the same as for iron fertilisation (above), the enhancing of organisms that photosynthesise, removing $CO_2$ that is subsequently transported to the deep ocean. It simply uses different substances.

### The technique and its readiness

Nitrogen and/or phosphorus would be added to nutrient-impoverished waters. The evidence is based on both modelling studies and limited field work (GESAMP 2018a). It has been suggested that nitrogen fertilisation, when additional costs including manufacture, transport and distribution by vessels on the ocean are included, is potentially a more efficient means of sequestration than iron fertilisation (Harrison 2017 and Matear and Elliot 2004). However, further research is required to clarify these claims in the light of new knowledge gained from further development of the techniques and their potential deployment mechanisms.

The CYCLOPS study which fertilised an area in the Eastern Mediterranean Sea with phosphorus demonstrated that half of the added phosphate was taken up biologically (Rees et al., 2006).

Research is still required to understand the viability of this approach and the supply chain infrastructure and market mechanisms that would be required to underpin deployment. However, Harrison (2017) suggests that the technique has a theoretical capacity to offset up to 15% of annual global $CO_2$ emissions (as at 2017).

### Current research activity

Academic research on macro-nutrients has declined in recent years, appearing to peak in the period 2004-2008 when some of the limitations of the technique were realised. However, in the commercial world, the Ocean Nourishment Corporation Pty Ltd ('ONC') (ONC 2019) is pursuing research to develop what it calls 'Ocean Nourishment' technology. Funded by the Ocean Nourishment Foundation, it works in partnership with academic institutions focussing on how carbon transfers to and is stored within the ocean.

### Socio-political considerations

These are broadly the same as for iron fertilisation. An additional key challenge relates to the availability of phosphorus. It is not a renewable resource and stocks are in decline with concern about the future capacity to fertilise crops raising questions about the ethics of the approach were it to harmfully effect food supply or prices. The geo-politics of phosphorus are also important: it is not evenly distributed with large mines only in Morocco, Russia, China and the US. Prices are highly volatile, leading to stockpiling. Its large-scale use for ocean fertilisation could then create significant tensions competing with food production at the same time as population increase outstrips capacity to supply enough food (GESAMP, 2019).

### Governance

The technique falls under Annex 4 of the London Protocol. Other interested parties would include intergovernmental or CSOs, and commercial interests, especially those associated with food production and mining/minerals.

Ocean fertilisation with nutrients gives rise to several governance issues that are in common with other techniques. These are explored in section II.

# Restoring wetlands, peatlands and coastal habitats

## The principle

Degraded or lost wetlands or coastal habitats are restored to improved or prime condition, enhancing natural capacity for $CO_2$ uptake and long-term storage.

## The technique and its readiness

The restoration of these environments requires little in the way of new technology (Zedler, 2005). It centres on rewetting or re-establishing environments, normally through practices to block excessive draining including constructing dams, managing vegetation, and restocking with plants such as sphagnums, hypnoid mosses and sea grasses, to colonise and hence, through enhanced photosynthesis enhance the carbon capacity (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.

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,
- iconstructed 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, 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, 2005). Coastal blue carbon is assessed by the IPCC (2019) as being capable of offsetting less than 2% of current emissions.

Recent assessments suggest that coastal wetlands can sequestrate 0.2 $GtCO_2$ per annum globally, storing between 50–90% of this carbon over the long term (Howard et al., 2017). However, these carbon reserves are vulnerable because 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, 2017), whilst, globally, around 25–50% of vegetated coastal habitats have been lost or degraded due to coastal agricultural developments, urbanisation and other human disturbance during the past 100 years (McLeod et al. 2011). Further, the frequency and scale of these disturbances are accelerating globally, but in particular in Southeast Asia (Page, 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 tonnes of $CO_2$ per hectare per annum, scaling to a global potential of approximately 1Gt$CO_2$ per annum by 2030 (Bain, 2011). Coastal ecosystem restoration could theoretically remove 0.2 Gt$CO_2$ per annum (Griscom et al., 2017). However, this would be challenging, because of the semi-permanent and on-going nature of most coastal land-use change, including human settlement, conversion to cropping, shoreline hardening and port development (Li et al., 2018). Carbon sequestration costs in freshwater wetlands have been estimated to be in the range of $10 to $100 per tonne of $CO_2$ (Kayranli, 2010) and estimates for the costs of mangrove, salt marsh and seagrass restoration range from $2,508 to $383,672 per hectare (Bayraktarov et al., 2016)  These costs should be considered alongside the additional value that restoration may bring through monetizable 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 per hectare (Junk, 2013).

## Current research activities

Despite the useful review of the mitigation potential of coastal wetlands prepared by the IPCC (2019), if wetland restoration is to be fully understood and any potential for CDR fully realised, more research is required. For example, to establish how best to protect restored wetlands against future development or land use change and gain better insights into how market mechanisms might work to promote re-wetting and ongoing protection are required (RS/RA, 2018).

The release of methane and nitrous oxide from wetlands can be a significant source of GHG release (Montzka, 2011, Al-Haj and Fulweiler, 2020), with estimates ranging from 20% to 25% of global emissions (Whiting, 2001). Whilst reviews of methane mitigation technologies indicate that this may be a challenging task (Stolaroff, 2012, Lockley, 2012), it is known that such releases can be reduced significantly by planting of mosses and other plant coverage on wetlands, although this mediation is not available in coastal contexts. More research could help improve understandings of these processes, the extent to which methane release may offset achieved carbon uptake (Al-Hay and Fulweiler, 2020) 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 (Gattuso et al., 2018), and, in addition, the effects of albedo change, 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, may be useful.

## Socio-political considerations

The key barriers to large-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, 2009).

Challenges also remain regarding the MRV of achieved carbon sequestration, cost-effective monitoring of fluxes, and the effects, positive or negative, of land-use change (Kayranli, 2009, RS/RAE, 2018). Such monitoring is problematic not only because there are no governance mechanisms in place to encourage it, but also because many nations lack wetland inventories meaning any changes in the quantity and quality of the world's wetlands cannot currently be tracked adequately (Zedler, 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, 2005). For a detailed discussion of these non-climate benefits see (IPCC, 2019).

### Governance

The technique is partially captured under the reporting requirements of the Kyoto Protocol and the Paris Agreement. 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 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 and farming, such as the UN Food and Agriculture Organisation (FAO);
- shipping interests in coastal zones; and,
- CSOs, civic society and landowners.

Several governance issues are generic to many CDR techniques, including wetland restoration, these are discussed in section II.

## Table 2 Summary of estimates of theoretical sequestration capacity and cost of CDR techniques[1]

| Technique | Estimated ranges of theoretical maximum annual sequestration capacity (Per Annum)[1] | Estimated cost ($) per tonne sequestered $CO_2$ | Permanency of sequestration |
|---|---|---|---|
| AFFORESTATION AND REFORESTATION | 1 – 18 Gt. | 15 to 30 although the IPCC give a range of $5 to $50, but only for abatement. | Medium term. |
| ARTIFICIAL DOWNWELLING | 0.01 Gt. | Unknown. | Long term. |
| ARTIFICIAL UPWELLING | Potentially counterproductive in some circumstances – and no more than a maximum 20 Gt. | Unknown. | Long term. |
| BIOCHAR | 0.3 to 35Gt. | 18 to 166. | Long term. |
| BIOENERGY WITH CARBON CAPTURE AND STORAGE (BECCS) | 1 to 85 Gt. | 65 to 240, although most costs are below $200. | Dependent on location – potentially permanent. |
| BUILDING WITH BIOMASS | 0.5 to 1 Gt. | Not available. | Medium term. |
| CARBON SEQUESTRATION IN SOILS | 1 to 11 Gt. | 12. | Medium to long term. |
| CROP RESIDUE OCEANIC CARBON SEQUESTRATION | Up to 1 Gt. | Uncertain. | Long term. |
| DIRECT AIR CAPTURE WITH CARBON STORAGE (DACCS) | 0.5 to 5 Gt (by 2050). | 20 to 1000. | Dependent on location – potentially permanent. |
| ENHANCING OCEAN ALKALINITY | 3,500 Gt. | 50 to 450. | Permanent. |
| ENHANCHED TERRESTRIAL WEATHERING | 0.72 TO 92 Gt. | 15 to 3,460. | Permanent |
| MACROALGAL CULTIVATION | With 9% global coverage 12 Gt pa of bio digested methane could be captured. If burned for power, with gas capture, a maximum of 34 Gt equivalent may be captured. | Not Available. | With robust CCS, potentially long-term. |
| OCEAN CARBON CAPTURE AND STORAGE (OCSS) | Uncertain. | Not available. | Long term. |
| OCEAN FERTILISATION | IPCC include estimates up to 44 Gt whilst other later assessments suggest 3.7 Gt. | 2 to 457. | Long term. |
| OCEAN FERTILISATION WITH MACRO-NUTRIENTS | Uncertain. | 20. | Long term. |
| RESTORING WETLANDS | 1.2 Gt | 10 to 100 although costs per tonne of saltwater restoration are unavailable . | Medium term. |

Key: Medium term – Multi Decadal, Long term – Multi Century

1 There is considerable uncertainty regarding potential removal capacity and costs reflecting a wide range of model and theoretical deployment assumptions (IPCC, 2018). This information should be treated with caution pending more rigorous comparative assessments which may become available if understandings of the techniques mature. Uncertainties in assessments is explored in Section I.

# SECTION II: Governance

## Introduction

C2G uses the IPCC's definition of governance:

> *'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 recognizes 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' (IPCC 2018).*

There has been considerable generic debate about the governance of various approaches to intentionally altering the climate over the past 10 years. Of this, techniques that aim to have a global effect have been a central topic. This section briefly explores several generic governance issues cutting across all the techniques discussed in section I above, and then reviews existing legal instruments and some key non-binding principles or codes of conduct. The purpose of this is to highlight the most important provisions, but not to analyse them in depth. Hubert, (2020), Reynolds (2018), Scott (2013 and 2015) and Redgwell (2011) have produced in-depth descriptions of international law and governance relevant to climate-altering techniques for those who wish to explore further. An overview summary showing where the CDR governance literature suggests various governance instruments are expected to apply, may apply or are not expected to apply to each technique discussed in this brief is given in table 3.

## Research governance

The technique summaries in Section I reveal considerable uncertainty regarding the likely costs, future potential removals capacity over time and the possible effects of those removals on both the climate, but also ecosystems, economies, equity and the SDGs. For example, the literature presents a confused picture of how much $CO_2$ CDR techniques may be able to remove in any given timeframe, because there are no common methods nor reporting (Fuss, 2018). Such consistency would, for example, help inform decisions about which, if any CDR techniques should be deployed, when and by how much to achieve any cooling or atmospheric $CO_2$ targets that may be agreed by policy makers.

Whilst uncertainty is unlikely to ever be resolved (Stirling, 2008, see Blue and Davidson (2021) for an overview of uncertainty in technology and innovation), further CDR research may help reduce some uncertainty, easing some of the governance challenges described (Mace, 2018). Addressing this research need is a governance challenge in its own right, for example, it is unclear how knowledge gaps will be identified, research agenda set and funding will be secured and provided to appropriate researchers.

It has been suggested that high-quality integrated assessments of CDR will be a key tool in addressing some of the CDR uncertainties (Fuss, 2018). However, these are lacking and whilst over 200 CDR review articles were published by 2017 (Minx et al., 2017) and a number have sought to asses a portfolio of techniques (e.g., RS/RA 2018, NAS 2015, Fuss 2018, McLaren 2012) these assessments have been fragmented with each selecting a different set of techniques and assessing them against different metrics. Such reviews have not consistently combined the technique assessments with Integrated Assessment Models (IAMs) (Minx, 2018, Fuss, 2018). Neither, Fuss (2018) argues have they adopted a comprehensive and transparent analysis rooted in a formal review methodology which would facilitate the reproduction of studies to address key questions such as different CDR technique's removals capacities, climate and other effects and risks and costs. In a discussion of the need to address these shortcomings, Fuss (2018) has identified three research gaps:

- the need for integrated portfolios of CDR in IAMs – including evaluations of interactions with other mitigation options and the effects on the Sustainable Development Goals (SDGs);
- enhanced knowledge about the geo-physical constraints of techniques and their implementation in IAMs; and,
- whilst recognising mitigation decisions will be made under conditions of uncertainty, an analysis of deployment dynamics in a risk management framework.

CDR research may cause harms. For example, field trials may harm local biodiversity and demonstration scale DACCS infrastructure may impact on water resources availability (for a review of potential CDR harms see Dooley et al (2020)). As such, not only does the research and science policy process require and have implications for governance, but project level governance will also require governance consideration. Reflecting this, a number of non-binding codes of conduct have been developed, such as the Oxford Principles (Rayner et al., 2013), the Asilomar Principles for Research into Climate Engineering Techniques (Asilomar, 2010), the Code of Conduct for Responsible Geoengineering Research (Hubert, 2017) and the Academic Working Group on Climate Engineering Governance (AWG, 2020). These principles or codes all encompass all forms of climate-altering techniques. They recognise that transparency in decision-making, public participation, and open publication of research results are key to ensuring maximum public engagement with, and confidence in, the governance of research. However, although such codes encourage researchers to act in measured responsible ways, given they are voluntary and have no forfeiture available, they may not deter a committed researcher.

Other important elements of the CDR research governance include the underpinning processes informing the flow of funds to and from, public or private, funders (Genus, 2018), and the provision of and access to data or research resources including infrastructure. Whilst such governance processes play out in all areas of research, as a novel and growing domain of activity, attention to CDR's research governance may be warranted.

## Monitoring, Reporting and Verification (MRV)

It is suggested that the MRV of removals will require a global accounting system (Honegger, 2020) and that, given the range of approaches to CDR and the variation with which they remove and store carbon, and the challenges associated with permanency and leakage, any future MRV will have to function in the context of considerable uncertainty (Honegger, 2020). This uncertainty is demonstrated, for example, in the challenges of MRV of gas fluxes across many techniques that are, simultaneously, a sink for and source of GHG (Welch et al., 2019). It is then, unclear how the international community may resolve the environmental, policy and research challenges that remain for MRV, and whether and how this might be done within the context of existing frameworks (Florin, 2020).

## '*Moral hazard*' or '*mitigation deterrence*'

Geden (2018), McLaren (2016), Wagner (2019) and others have discussed the issue of moral hazard – the idea that the use of CDR and its potential cooling effect could provide stakeholders with an excuse to either fail to ramp up efforts to reduce emissions or to continue using fossil fuels at current, or even accelerated rates. It is suggested that this could also happen because of theoretical modelling, if the promise of any CDR techniques identified in studies deters near-term emissions reductions, by reducing the perceived future social cost of carbon (Geden, 2018).

In the context of the modelled emissions scenarios that meet the Paris Agreement goals, including large scale deployment of CDR and the delivery of net-zero emissions (IPCC, 2108), it is apparent that any indications that mitigation deterrence, in the form of moral hazard, may occur could create an important governance consideration (Florin, 2020).

The extent, nature and scale of any mitigation deterrence are uncertain, as are the nature of measures to mitigate the thinking and behaviours that might lead to and drive it (Florin, 2020). It may also be true that moral hazard could, in some circumstances, be acceptable. For example, if SRM were safely keeping climate change within acceptable levels, despite a degree of moral hazard generating slightly higher GHG emissions (Florin, 2020).

## Risk-risk trade-offs

Risk-risk trade-offs, which apply to all CDR techniques to some extent, characterise both emergent governance and policy design choices, as well as how research is conducted and communicated. They involve risk-risk trade-offs in terms of both outcomes as well as governance choices (Honegger, 2020).

Within the policy context, risk trade-offs identified by Honegger (2020) include: effective governance versus governance efficiency, at the local, regional and global level; transboundary effects of CDR approaches as challenges to sovereignty of domestic policies; achieving the most effective mitigation verses securing and maintaining the benefits of sustainable development; and, balancing centralised and polycentric governance.

In relation to research, it is suggested that potential trade-offs include: balancing academic and innovation knowledge with lay and cultural knowledge and understandings, particularly in relation to nature based approaches (NBA) to CDR; research driven mitigation deterrence set against mitigation stalling or potentially cessation; limited international research co-operation and dialogue undermining capacity for governance cooperation; and, unbalanced research capabilities, both in terms of resources and underpinning infrastructure generating significant power differentials (Honegger, 2020).

To date how to resolve these trade-offs is uncertain, however in his comprehensive analysis of the issues, Honegger (2020) suggests, in relation to policy-design, the strengthening of capacities for international inter-agency collaboration; improving understanding of how specific governance challenges match particular international agencies' mandates; and, conducting policy assessments in the context of national mitigation policy planning. In relation to trade-offs related to research Honegger (2020) suggests enabling more diverse, transdisciplinary research; the exchange of expertise; science-policy conversations; and, conducting research on potential interlinkages in the context of the SDGs.

## Incentives

It is unclear how the international community might agree, set and stabilise, over the long-term, atmospheric $CO_2$ concentrations and other mitigation measures (Honegger, 2020). Neither is it clear how this process, and the outcomes of the decisions taken, can balance the individual interests of nation-states with the global need to reduce $CO_2$ concentrations in the atmosphere (Honegger, 2020). These policy challenges may warrant some incentivisation, but to date it is uncertain how that might evolve (Florin, 2020).

It is also unclear how the required scale and speed of implementation implied by the IPCC's Special Report (IPCC, 2018) might be achieved and it is suggested that the incentives to secure this rapid change, in terms of new financial and policy options do not yet exist (Florin, 2020). Gross (2018) has suggested some incentive measures, such as support for basic, strategic and applied research, alongside focussed efforts to guarantee the permanency of carbon storage. However, in the light of innovation literature, which demonstrates long time lags and complex social challenges in the innovation chain toward reducing environmental impacts and poverty (Hall et al., 2014) these research investment measures alone may not be sufficient.

## Sequestration and permanency

Some techniques described do not have the capability to sequester captured carbon durably or permanently (as noted in Section I and summarised in table 2). If large quantities of $CO_2$ were to re-enter the atmosphere, due to storage failure or leakage, this would reverse the gains from achieved CDR. This issue creates important research, engineering and governance challenges, as identified by the National Academy of Engineering (NAS, 2020), including, for example: the long-term management of sequestered carbon over century timescales; the prevention of leakage from hard to reach or challenging environments; and, financing or incentives (NAS, 2020). Currently, aside from agreements relating to sub-sea storage (see the Convention on the Prevention of Marine Pollution and the London Protocol below), these issues have not been resolved.

## Other remaining governance challenges

In addition to the technique specific and generic governance issues noted in this Brief, a recent a review of CDR governance challenges (Mace, 2021) identifies three further topics of relevance to CDR governance.

Mace (2021) suggests that new safeguards for sustainable development may be necessary, dependent on the scale, context and implementation strategy of CDR techniques, noting, for example, that the potentials for BECCS and afforestation to effect food security and biodiversity explored in this Brief may require 'strong governance' (for more information about the potential implications for CDR on sustainability see Honegger et al (2020) and Brack and King (2020) and in relation to biodiversity, Dooley et al., 2020)).

Secondly, Mace (2021) also argues that large-scale CDR gives rise to challenges relating to attribution of responsibility and ethical questions around implementation, in addition to those of moral hazard noted above. Specifically, to date, neither the Parties to the UNFCCC or the Paris Agreement have assigned or acknowledged responsibility for the development and deployment of CDR options, or considered how the financial, land and other burdens of CDR identified in the literature (e.g., Minx et al, 2018 and Fyson et al., 2020) should be shared among the global community. Further, the first nationally determined contributions to the Paris Agreement do not include reference to the CDR necessary to reach the Paris goals, leaving open more questions about whom might be responsible for CDR (Pozo, 2020).

Finally, were CDR interventions to cause transboundary harm or loss, new mechanisms maybe required to both identify liability and make redress (Mace, 2021). These mechanisms would be in addition to the MRV governance agenda previously discussed and might require amendments to existing instruments, or the creation of new mechanisms. In the context of the deep uncertainties associated with the potential effects of most CDR techniques, and the heterogeneity of the techniques and their potential effects, as described in this brief, this issue may be complex to resolve (Meadowcroft, 2013).

## International law and frameworks

A range of international frameworks and are relevant to CDR and, following a review of how customary international law is relevant to CDR, the following instruments are now discussed:

- UN Framework Convention on Climate Change (UNFCCC) (UN 1992);
  - Paris Agreement 2015 (UNFCCC 2015);
  - Kyoto Protocol;
- Convention on Biodiversity (CBD) (CBD 2008);
- London Convention 1972 and the 1996 London Protocol (IMO 2016);
- the International Convention for the Prevention of Pollution from Ships, 1973 as modified by the Protocol of 1978 (MARPOL, 1978); and,
- UN Convention on the Law of the Sea (UNCLOS) (UN 2009).

## Customary International Law

The general norms of customary international law as it relates to international environmental law would apply to CDR. Customary international law is important in that it applies to everyone and all human activities. For a detailed review of how customary international law may apply to CDR, and other approaches to climate engineering see Hubert (2020). In brief, customary international law that would apply to CDR would include the duty to prevent transboundary harm, duties of international cooperation to undertake transboundary impact assessments and to consult and notify and the precautionary principle.

## Table 3 Summary of governance instruments relevance to techniques[2]

| | UN Framework Convention on Climate Change (UNFCCC) | The Convention on Biodiversity (CBD) | The Paris Agreement 2015 | Kyoto Protocol | London Convention 1972 and the 1996 London Protocol | International Convention for the Prevention of Pollution from Ships, 1973 (MARPOL) | United Nations Convention on the Law of the Sea (UNCLOS) |
|---|---|---|---|---|---|---|---|
| AFFORESTATION AND REFORESTATION | Instrument explicitly applies | Instrument explicitly applies | Instrument explicitly applies | Instrument explicitly applies | Will not apply | Will not apply | Will not apply |
| ARTIFICIAL DOWNWELLING | May apply with clarification or revision | Instrument explicitly applies | May apply with clarification or revision | May apply with clarification or revision | Instrument explicitly applies | Will not apply | Instrument explicitly applies |
| ARTIFICIAL UPWELLING | May apply with clarification or revision | Instrument explicitly applies | May apply with clarification or revision | May apply with clarification or revision | Instrument explicitly applies | Will not apply | Instrument explicitly applies |
| BIOCHAR | May apply with clarification or revision | Instrument explicitly applies | Will not apply | Will not apply | Will not apply | Will not apply | Will not apply |
| BIOENERGY WITH CARBON CAPTURE AND STORAGE (BECCS) | May apply with clarification or revision | Instrument explicitly applies | May apply with clarification or revision | May apply with clarification or revision | Will not apply | Will not apply | Will not apply |
| BUILDING WITH BIOMASS | May apply with clarification or revision | Instrument explicitly applies | May apply with clarification or revision | May apply with clarification or revision | Will not apply | Will not apply | Will not apply |
| CARBON SEQUESTRATION IN SOILS | May apply with clarification or revision | Instrument explicitly applies | Instrument explicitly applies | Instrument explicitly applies | Will not apply | Will not apply | Will not apply |
| CROP RESIDUE OCEANIC CARBON SEQUESTRATION | May apply with clarification or revision | Instrument explicitly applies | May apply with clarification or revision | May apply with clarification or revision | Instrument explicitly applies | May apply with clarification or revision | Instrument explicitly applies |
| DIRECT AIR CAPTURE WITH CARBON STORAGE (DACCS) | May apply with clarification or revision | Will not apply | May apply with clarification or revision | May apply with clarification or revision | Will not apply | Will not apply | Will not apply |
| ENHANCING ALKALINITY WITH TERRESTRIAL WEATHERING | May apply with clarification or revision | Instrument explicitly applies | May apply with clarification or revision | May apply with clarification or revision | Instrument explicitly applies | Will not apply | Instrument explicitly applies |
| MACROALGAL CULTIVATION | May apply with clarification or revision | Instrument explicitly applies | May apply with clarification or revision | May apply with clarification or revision | Instrument explicitly applies | Will not apply | Instrument explicitly applies |
| OCEAN CARBON CAPTURE AND STORAGE (OCSS) | May apply with clarification or revision | Instrument explicitly applies | May apply with clarification or revision | May apply with clarification or revision | Instrument explicitly applies | May apply with clarification or revision | Instrument explicitly applies |
| OCEAN FERTILISATION | May apply with clarification or revision | Instrument explicitly applies | May apply with clarification or revision | May apply with clarification or revision | Instrument explicitly applies | May apply with clarification or revision | Instrument explicitly applies |
| OCEAN FERTILISATION WITH MACRO-NUTRIENTS | May apply with clarification or revision | Instrument explicitly applies | May apply with clarification or revision | May apply with clarification or revision | Instrument explicitly applies | May apply with clarification or revision | Instrument explicitly applies |
| RESTORING WETLANDS | Instrument explicitly applies | Instrument explicitly applies | Instrument explicitly applies | Instrument explicitly applies | Will not apply | Will not apply | May apply with clarification or revision |

Legend:
Instrument explicitly applies.
May apply with clarification or revision
Will not apply.

2 Allocations to the categories are drawn from work by Hubert (2020), Reynolds (2018), Scott (2013 and 2015) and Redgwell (2011).

## United Nations Framework Convention on Climate Change (UNFCCC)

Adopted in 1992 the UNFCCC provides an overarching framework to intergovernmental efforts to tackle climate change, its objective is to achieve the '*stabilisation of GHG concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system*' (UN, 1992) Given 'removals' of GHGs has been present in the UNFCCC since 1992 it is likely to play a significant role in the global governance of CDR. However, what that role might be is unclear at this time. Three key elements of the Convention in this context are:

- Preamble (para. 21) - *"Affirming that responses to climate change should be coordinated with social and economic development in an integrated manner with a view to avoiding adverse impacts on the latter, taking into full account the legitimate priority needs of developing countries for the achievement of sustained economic growth and the eradication of poverty".*

- Article 2 - *"The ultimate objective of this Convention and any related legal instruments that the Conference of the Parties may adopt is to achieve, in accordance with the relevant provisions of the Convention, stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner."*

- Article 4(1)(d) - *"Promote sustainable management, and promote and cooperate in the conservation and enhancement, as appropriate, 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".*

Article 4 (1) (d) may play a key role given it requires Parties 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 country Parties, 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 a number of CDR approaches fall.

Although reporting obligations for Annex 1 and Non-Annex 1 Parties have moved closer to each other in recent years, the differences in these obligations continues to present a challenge for MRV 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 combination of these creates a challenge to the provision of adequate governance of CDR measures globally which C2G suggest requires further consideration.

It should be noted that DACCS is not covered directly by the UNFCCC. It could, were the technologies to evolve sufficiently to warrant reporting, be incorporated through changes to Article 4.1(d), or by other amendments to the Convention. However, amending the Convention requires a three-fourths majority vote and may be difficulty to secure (Article 15, UN, 1992). If DACCS were to be incorporated within the Convention, it is expected to create difficulties in establishing appropriate reporting guidelines where a country has achieved net-zero emissions given it would be removing $CO_2$ from other states (RS/RAE, 2018). To be rigorous, the reporting framework would likely be based on the best available science and include a level of detail comparable to those for other processes, such as agricultural emissions.

In addition, any new reporting guidelines will need to address any long-term risks of DACCS, including leakage from storage (RS/RAE, 2018).

## The Paris Agreement 2015

Adopted in December 2015 the Paris Agreement is an agreement within the UNFCCC. The key purpose of the Agreement is to strengthen the global response to the threat of climate change by keeping a global temperature rise this century well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5°C. The Agreement requires Parties to communicate a nationally determined contribution (NDC) every five years, setting out planned domestic mitigation efforts. Each successive NDC is required to demonstrate a progression and represent highest possible ambition.

In an analysis of the Agreement, Craik and Burns (2016) have identified four ways in which it is expected to influence the future direction CDR, as detailed below.

- CDR may arise directly out of the Agreement's objectives, building on the inclusion of 'removals' that have been present in the UNFCCC since 1992. The objectives are only achievable with recourse to 'climate engineering' (scenarios that deliver the 2°C limit are underpinned by a mixture of emission reductions and 'CDR technologies' (GESAMP 2018).
- CDR techniques fall within the scope of Article 4, which includes $CO_2$ removals as a contribution to the mitigation commitments expected via the Parties' voluntary NDCs.
- The inclusion of CDR techniques in NDCs will raise legal questions about technological readiness and equity implications.
- The Agreement's institutions and mechanisms provide a basis for future deliberations about market incentives which will be required to allow scaled-up deployment of CDR.

In addition, Article 5 of the Agreement requires the Parties to take action to conserve and enhance sinks and reservoirs of GHG – a measure that would encompass forestation, carbon sequestration in soil, and restoring wetlands, all CDR approaches. 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 achieved through CDR and in turn may encumber CDR research and uptake (Fyson and Jeffery, 2019). Certainly, consistent reporting of NDCs would help project 2030 net-emission levels and aid future planning for CDR. Further, whilst under the guidance agreed in Katowice in 2018, Parties are to provide information on the approaches and assumptions used to account for emissions and removals in their NDCs, this guidance stops short of indicating which approaches should be used (Fyson & Jeffery, 2019).

Article 10 of the Agreement commits parties to work collaboratively (under the UNFCCC Technology Mechanism) to collaborate on research and development of new technologies and to facilitate access to technologies in the early stages of their development. DACSS would likely be encompassed by this commitment and may then be expected to be included in the 2023 global stocktake required under Article 14 (2) and any new measures that arise from that.

In addition, the Agreement includes reference to “response measures” needing to be assessed both in terms of their potential impact on human rights, and any implications of future actions for the SDGs. Given some forms of CDR, for example BECCS, may have implications for food supply or price, access to water resources and biodiversity. These considerations may be reflected in evolving CDR governance. For a more detailed analysis of the UNFCCC and CDR see Fyson and Jeffery (2019).

## The Kyoto Protocol

Parties to the Protocol agree to reduce or limit their future GHG 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. 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. However, the Protocol would not encompass other CDR techniques discussed above including DACCS and oceanic fertilisation or enhanced weathering and the provisions were not designed for the scale of removals required for the Paris Agreement’s long-term temperature goal.

## The United Nations Convention on Biodiversity (CBD)

The 1992 CBD has three main goals:

- to conserve biological diversity;
- the sustainable use of biodiversity; and,
- the fair and equitable sharing of benefits arising from genetic resources.

The CBD is one of the few conventions to have discussed ‘geoengineering’ directly. The initial focus was on ocean fertilisation activities when, at its 9th conference, it adopted decision IX/16 C that urged signatories *‘to ensure that ocean fertilization activities do not take place until there is an adequate scientific basis on which to justify such activities, including assessing associated risks, and a* *global, transparent and effective control and regulatory mechanism is in place for these activities; with the exception of small scale scientific research studies within coastal waters'*. (CBD, 2008, p.7).

In 2010, with a view to protecting biodiversity, the CBD went further when it invited Parties and other Governments, as well as relevant organisations and processes to consider its guidance (X/33(8)(w)) that '*no climate-related geo-engineering activities that may affect biodiversity take place, until there is an adequate scientific basis on which to justify such activities and appropriate consideration of the associated risks for the environment and biodiversity and associated social, economic and cultural impacts.....*' (CBD, 2010, p.5). It should be noted however that the CBD recommendation did not include small-scale scientific research studies undertaken in controlled settings that would help identify the potential impacts on the environment. Subsequently, the COPs XI and XIII reaffirmed this decision.

In 2016, at the 13th Conference of Parties additional guidance was agreed in Decision XIII/4 which states that '*more transdisciplinary research and sharing of knowledge among appropriate institutions is needed in order to better understand the impacts of climate-related climate engineering on biodiversity and ecosystem functions and services, socio-economic, cultural and ethical issues and regulatory options*'.

Whilst the CBD position appears strong and sends a governance signal, it is not binding, country participation is not universal (e.g. the US has signed but not ratified) and it only relates to the conservation of biodiversity, the sustainable use of biological resources and the fair and equitable sharing of benefits arising from genetic resources. The CBD's own Technical Series 66 publication states "*The 2010 CBD decision on geoengineering is not legally binding. However, the decision is important for a global governance framework because of the consensus of the 193 Parties it represents and the political signal it sends*." (CBD, 2012). The CBD evocation of the Precautionary Principle may, however, be an important demonstration of the willingness of parties to international law to take such measures in time. However, the limitations of the CBD also highlight that individual extant protocols and conventions as currently constructed could only form an incomplete basis for global regulation, which forms an important element of governance, because they each apply to discrete, specific topics and issues whereas some CDR interventions would operate at scale, across treaty boundaries.

## Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (the London Convention) 1972 and the 1996 London Protocol

Known as the London Convention, the Convention on the Prevention of Marine Pollution by Dumping of Wastes or Other Matter was adopted in 1972 and came into force in 1975. The London Protocol 1996 came into force in 2006. The two instruments operate in parallel and when the Protocol was adopted, parties agreed no further amendments would be made to the Convention and the Protocol will eventually supplant the Convention. The purpose of the Protocol is to protect and preserve the marine environment from all sources of pollution, and from the dumping of wastes and other at sea. The Protocol directly addresses CDR, and it is evolving in the context of the debate about marine 'geoengineering'. Marine geoengineering is defined in the protocol as: *'a deliberate intervention in the marine environment to manipulate natural processes, including to counteract anthropogenic climate change and/or its impacts, and that have the potential to result in deleterious effects, especially where those effects may be widespread, long lasting or severe.'*

Article 3.1, which requires parities to *"...apply a precautionary approach to environmental protection from dumping of wastes or other matter...",* and this article drives the on-going evolution of protocol's approach to marine 'geoengineering' activities.

Importantly, Parties to the Protocol are developing the first legally binding framework for the governance of marine 'geoengineering' (Hubert, 2020). This seeks not only to protect the marine environment, but also seeks to be adaptable in response to technological and research progress.

The Parties firstly discussed CCS in 2004 and subsequently turned to CDR issues in June 2007 when an ocean fertilisation experiment was being proposed (Brahic, 2007).

In 2006, the Parties amended Annex 1, paragraph 4 of the Protocol to establish a legal basis to regulate permanent CCS in sub-seabed geological formations. This amendment means that Parties may issue permits for $CO_2$ storage or 'dumping' if either the disposal is into a sub-seabed geological formation, or the disposal consists overwhelmingly of $CO_2$ and no additional materials are disposed of in the reservoir. Two sets of technical guidelines for $CO_2$ operations have also been adopted by the Parties. The Risk Assessment and the Management Framework for $CO_2$ Sequestration in Sub-seabed Geological Structures (LP, 2006) the Specific Guidelines for the Assessment of Carbon Dioxide for Disposal into Sub-seabed Geological Formations (LP, 2012).

Subsequently, in 2008, resolution LC-LP.1(1) decided that ocean fertilisation activities other than legitimate scientific research were contrary to the aims of both instruments.

In 2009, an amendment to Article 6 provided an exception that allows for the export of $CO_2$ for the purposes of geologic sequestration, where an agreement has been reached by the countries concerned.

In 2010, the Parties adopted an Assessment Framework for Scientific Research Involving Ocean Fertilisation (OFAF) (resolution LC-LP.2(2)). Whilst neither resolutions were legally binding, in 2013 amendments to regulate ocean fertilisation activities by resolution LP.4(8) were adopted, giving the Parties power to regulate CDR activities within the scope of the Protocol after two thirds of the Contracting Parties have deposited their instruments of acceptance. To date, only five have ratified (Hubert, 2020).

In 2013, resolution LP.4(8) established a *'science-based, global, transparent and effective control and regulatory mechanism'* in the form of a 'General Assessment Framework' for marine geoengineering activities listed in Annex 4. This created the principle that marine geoengineering must be assessed in the context of concerns about the risks of ocean fertilisation and other climate related interventions.

## The International Convention for the Prevention of Pollution from Ships, 1973 as modified by the Protocol of 1978 (MARPOL)

Developed by the IMO to minimise pollution of the oceans and seas, the Convention focusses on dumping, oil and air pollution from ships. It came into force in 1983 and 156 states are party to the Convention. Reviews of international governance mechanisms pertinent to CDR have generally not discussed the Convention, although Talberg et al., (2017) does mention MARPOL in relation to ocean fertilisation. Dependent on how food wastes and noxious liquid substances (under Annexes V and II respectively) are interpreted by the IMO and signatories in the future, crop dumping for the purposes of CDR could potentially become subject to the Convention. However, what that role might be is unclear.

## United Nations Convention on the Law of the Sea (UNCLOS)

UNCLOS was adopted in 1982 and amended in 1994 and 1995. Part XII - 'Protection and Preservation of the Marine Environment' and Part XIII 'Marine Scientific Research' cover the relevant environmental protection obligations under the Convention that apply to marine CDR activities. The key articles are:

- Article 192 States have a responsibility to protect and preserve the marine environment.
- Article 194 requires States to take measures to prevent, reduce and control pollution of the marine environment. This includes pollution from greenhouse gases and marine 'geoengineering' activities.
- Article 195 prohibits the transfer, directly or indirectly, of hazards or pollutants from one area into another.
- Article 204 (2) requires States to monitor activities which they permit to determine if they may cause pollution.
- Article 206 requires States to assess potential effects of their activities if there are grounds to believe activities may cause pollution/harm.
- Article 210 (6) requires compliance with the London Convention/Protocol regarding dumping.
- Article 240 (d) requires States ensure that marine scientific research, whether conducted in or under their areas of jurisdiction or on the high seas complies with the marine environmental protection provisions of UNCLOS.
- Article 257 gives States and competent international organisations the right to conduct marine scientific research in seas beyond the limits of the EEZ (i.e., within the global commons).
- Article 263 makes States and competent international organisations responsible for ensuring research is conducted in accordance with the Convention.

Articles 257 and 263 raise interesting questions about: who decides what is and is not legitimate science; who and by what mechanisms do States keep control of science when equipment, funding and information is broadly available; and, how can deployment and research be disentangled for the purposes of the Convention, by whom and to what effect? The potential importance of UN negotiations for a new international agreement under UNCLOS is an evolving Convention and an intergovernmental process is in progress that will lead to an international legally binding instrument under the Convention on the conservation and sustainable use of marine biodiversity of areas beyond national jurisdiction (Hubert, 2020).

In 2017, the General Assembly convened an Intergovernmental Conference to consider the recommendations of a Preparatory Committee for a proposed international legally binding instrument under UNCLOS regarding the conservation and sustainable use of biologically diverse marine environments in areas beyond national jurisdiction (UN, 2020). As this process evolves, it may develop importance for the future governance of marine CDR.

## Other fora

In addition to those described above, other fora or processes may also be involved in the governance of CDR including, for example, the UN Environment Assembly, the UN General Assembly, the UN Fish Stocks Agreement, the Convention on the Conservation of Antarctic Marine Living Resources, nation states, regional bodies such as the Arctic Council and the European Union, research groups, CSOs, commercial business interests and publics.

## Publics and their role in governance

Given that the techniques described in this brief are accompanied by questions about risks, benefits and uncertainties and are politically and economically complex, and because they may all cause some environmental damage with differential effects on communities, as well as positive gains, it is suggested (Buck, 2019) that citizens' perspectives on how these techniques move forward should be drawn into the processes of governance deliberation at the earliest stage in a mode of co-production.

Evidence suggests this can improve the innovation process (Genus and Stirling, 2018) and may also generate new knowledge about how the technologies and techniques can affect vulnerability and resilience to climate change on community and regional scales (Buck, 2019). It is suggested by Buck (2019), then that opportunities to engage citizens in the evolution of CDR planning should be considered a key part of the process.

## Conclusions

If the global warming is to be limited enough to achieve the Paris Agreement goals, IPCC scenarios (IPCC, 2018) clearly imply that CDR techniques will have to be adopted as part of the response. This briefing has explored the technical readiness, current research, applicable governance frameworks, and other socio-political considerations of the range of CDR options commonly addressed in the literature. Further, an overview of key instruments relevant for the governance of the techniques is offered. It is clear from this analysis that further research and debate about the techniques, and how they might be best governed will be important before any final decisions about their deployment and long-term management can be taken.

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Summarised information about the techniques and their governance is available in the
**C2G Policy Brief: Governing Large-Scale Carbon Dioxide Removal**

This briefing is based on the latest literature and has been subject to independent expert review.
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