Greenhouse gas removal

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In 2017 the Royal Society and Royal Academy of Engineering were asked by the UK Government to consider scientific and engineering views on greenhouse gas removal. This report draws on a breadth of expertise including that of the Fellowships of the two academies to identify the range of available greenhouse gas removal methods, the factors that will affect their use and consider how they may be deployed together to meet climate targets, both in the UK and globally.

The Royal Society and Royal Academy of Engineering would like to acknowledge the European Academies' Science Advisory Council report on negative emission technologies (easac.eu/publications/details/easac-net), which provided a valuable contribution to a number of discussions throughout this project.

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Cover image Visualisation of global atmospheric carbon dioxide surface concentration by Cameron Beccario, earth.nullschool.net, using GEOS-5 data provided by the Global Modeling and Assimilation Office (GMAO) at NASA Goddard Space Flight Center.

Erratum: The first edition of this report incorrectly listed the area of saltmarsh in the UK as 0.45 Mha, which is instead 0.045 Mha. This error has been corrected in the UK scenario on p96 and the corresponding GGR for habitat restoration adjusted. The conclusions of this report and the UK net-zero scenario remain unchanged.

Contents

List of abbreviations

BECCS – bioenergy with carbon capture and storage

C – carbon

CCS – carbon capture and storage

CO_2 – carbon dioxide

CO_2e – carbon dioxide equivalents. A measure used to compare warming levels between CO_2 and other greenhouse gases

DAC – direct air capture

DACCS – direct air capture with carbon storage

kJ/MJ/GJ/EJ – kilojoules/megajoules/gigajoules/exajoules

GGR – greenhouse gas removal

ha – hectare

IPCC – Intergovernmental Panel on Climate Change

NDC – nationally determined contributions

pa – per annum

ppm – parts per million

SDGs – United Nations Sustainable Development Goals

SRM – solar radiation management

TRL – technology readiness level

TWh – terawatt hours

tCO_2/$MtCO_2$/$GtCO_2$ – tonnes/megatonnes/gigatonnes of carbon dioxide, where literature cites values in terms of carbon (tC/MtC/GtC) these have been converted to CO_2 by multiplying by 3.7

$ – currency throughout the report is presented in USD unless stated otherwise.

Greenhouse gas removal (GGR) methods

Forestation – Growing new trees and improving the management of existing forests. As forests grow they absorb CO_2 from the atmosphere and store it in living biomass, dead organic matter and soils.

Habitat restoration – Restoration of peatlands and coastal wetlands to increase their ability to store carbon. This also prevents carbon release through further degradation, often providing a number of other co-benefits.

Soil carbon sequestration – Changing agricultural practices such as tillage or crop rotations to increase the soil carbon content.

Biochar – Incorporating partially-burnt biomass into soils. Biomass is grown and burned in the absence of oxygen (pyrolysis) to create a charcoal-like product which can stabilise organic matter when added to the soil.

Bioenergy with carbon capture and storage (BECCS) – Utilising biomass for energy, capturing the CO_2 emissions and storing them to provide life cycle GGR.

Ocean fertilisation – Applying nutrients to the ocean to increase photosynthesis and remove atmospheric CO_2.

Building with biomass – Using forestry materials in building extends the time of carbon storage of natural biomass and enables additional forestry growth.

Enhanced terrestrial weathering – Ground silicate rocks spread on land react with CO_2 to remove it from the atmosphere.

Mineral carbonation – Accelerating the conversion of silicate rocks to carbonates either above or below the surface to provide permanent storage for CO_2.

Ocean alkalinity – Increasing ocean concentration of ions like calcium to increase uptake of CO_2 into the ocean, and reverse acidification.

Direct air capture and carbon storage (DACCS) – Using engineered processes to capture atmospheric CO_2 for subsequent storage.

Low-carbon concrete – Altering the constituents, the manufacture, or the recycling method of concrete to increase its storage of CO_2.

Foreword

There is overwhelming scientific evidence that the human release of greenhouse gases is changing the Earth's climate. At Paris, countries from around the world committed to limiting the damage caused by this change, agreeing to keep warming to under 2°C.

The role of rapid emissions reduction in meeting this target is widely understood. But it is increasingly clearer that reducing emissions is not enough – we must also actively remove greenhouse gases from the atmosphere. New technologies have emerged that show promise in removing CO_2 from the atmosphere but these are not well understood and mostly unproven at large scale.

This report brings together the expertise of the Royal Society and Royal Academy of Engineering to outline how much we know now about each of these methods and, for the first time, to consider how they might be deployed alongside each other to meet climate goals in the UK and internationally.

The two scenarios in this report identify the suite of technologies that together can help us get to a carbon neutral future in the UK by 2050, and globally by the end of the century. They are a sobering reminder of how much work there is to do to secure the wellbeing of our planet.

The challenge ahead is not insurmountable, but it requires the full weight of the world's research community. Scientists and engineers of all types will need to pull together with social scientists, economists, the public and policymakers to develop, deploy and manage methods that range from planting trees to engineering the direct removal of CO_2 from the air.

This remains a developing field and much will change over the coming decades, but as this report shows, action must begin now.

Top
Professor Dame Ann Dowling, President of the Royal Academy of Engineering.

Bottom
Venki Ramakrishnan, President of the Royal Society.

Executive summary

In 2015, governments from around the world met to agree a framework that would minimise the negative consequences of climate change. The Paris Agreement sets a goal to limit global average temperature increase to 'well below 2°C above preindustrial levels', and to 'pursue efforts' to limit it to 1.5°C.

This is an ambitious task requiring rapid decreases in emissions and, by the second half of the century, net-zero emissions. In some sectors, notably agriculture and aviation, greenhouse gas emissions will be difficult to eliminate entirely, so we will need technologies to compensate by removing greenhouse gases from the atmosphere. Modelling of future energy systems suggests this removal would need to be at a large scale, with removal of about one quarter of present annual emissions each year.

Greenhouse gas removal (GGR) methods involve two main steps: the removal of greenhouse gases from the atmosphere and their storage for long periods. The process is best established for carbon dioxide (CO_2) removal. Removal is achieved through a wide variety of approaches, involving either biology, accelerating natural inorganic reactions with rocks, or engineered chemical processes. The carbon is then stored in land-based biomass, sub-surface geological formations, the oceans, or the built environment.

GGR methods require resources, like land, energy or water, placing limits on the scale and location of their application, and leading to resource competition between them and with other human activities, such as food production. Some GGR methods also provide co-benefits that could assist, or even be the primary reason for, deployment; these can include crop productivity and biodiversity enhancements.

Achieving the desired level of GGR will be best achieved by using a suite of approaches. Increased forestation and bioenergy with carbon capture and storage (BECCS) are often considered as major routes to deploy GGR, but they are limited by available land area, resource requirements and potential impacts on biodiversity and social equity. Deployment of these as part of a suite of methods would decrease likely environmental and social impacts anticipated at large scale.

Some GGR methods are already in use today, while others require significant development and demonstration before they can remove emissions at scale. When considered at the scale required, none of the methods have been fully evaluated across their life cycle.

GGR methods impact the environment in different ways. As such, their development will require careful assessment of environmental implications, during demonstration pilot studies, ramp-up, and full deployment. These sustainability issues will be among those that influence public perception of GGR, which ranges widely depending on the method and location, and may place constraints on their applicability.

Early deployment of GGR methods and their rapid ramp-up would make it easier to achieve climate targets, and help to avoid a damaging climate 'overshoot'. Biological approaches for land carbon storage can be applied quickly, but these will saturate after some decades so other GGR methods are expected to become critical later in the century.

To be economic and, therefore, to be pursued at adequate scale, most GGR methods require a price for carbon or other incentive system. Future projections of carbon prices of $100 per tonne of CO_2, if realised, would make many GGR methods economically feasible.

This report considered two GGR scenarios; achieving net-zero emissions in the UK in 2050; and limiting the global temperature rise on pre-industrial levels to 1.5°C as of 2100.

UK net-zero in 2050

In the UK, reducing greenhouse gas emissions to the greatest degree considered feasible would leave remaining emissions of around 130 $MtCO_2$ pa by 2050. Offsetting these emissions with GGR to reach 'net-zero' for the UK is possible, but very challenging. It involves deployment of many different GGR methods, and import of biomass. To achieve this level of GGR requires a ramp-up of forestation, habitat restoration and soil carbon sequestration now, research and development of currently unproven but promising GGR methods, and establishment of substantial infrastructure and capacity for carbon capture and storage (CCS).

Global cumulative GGR compatible with 1.5°C by 2100

Integrated assessment models provide evidence that a cumulative GGR of around 810 $GtCO_2$ is expected to be required from now until 2100 to limit the rise in temperature to 1.5°C on pre-industrial times. This is the equivalent to about 15 years of 2017 greenhouse gas emissions. The large land area available globally for potential GGR deployment make this global target achievable, but still highly challenging. Many natural sinks will become saturated in this time frame, requiring a diversity of GGR approaches. Monitoring and maintenance will be required to prevent carbon being released from storage. Trading schemes could help action to be taken in the most effective and economical locations.

Considering a global response enables significant potential for GGR but action across national borders would likely require a political solution.

Key actions for UK net-zero

- Pursue rapid ramp-up of forestation, habitat restoration, and soil carbon sequestration, across large UK land-areas.
- Establish an incentive or subsidy system to encourage changes of land practice, particularly for soil carbon sequestration. This could form part of the framework put in place to replace the EU Common Agricultural Policy.
- Encourage changes in building practice to use wood and concrete manufactured with carbonated waste (while recognising overall limited potential for GGR of these approaches).
- Develop monitoring and verification procedures and programmes to track the effectiveness of GGR delivered by each method.
- Grow and import sustainable biomass at large scale to meet the need for both energy and GGR demands.
- Pursue research into the GGR potential of enhanced weathering and biochar in UK agricultural soils, and into BECCS and DACCS for longer term deployment. This should include assessment of the co-benefits, social and environmental risks, monitoring and evaluation, and include field-based pilot demonstrations.
- Capitalise on UK access to suitable reservoirs for CCS, and relevant engineering and industry expertise, to establish substantial infrastructure for transport and storage of CO_2.

Recommendations

Greenhouse gas removal (GGR) from the atmosphere will be required to fulfil the aims of the Paris agreement on climate change. This report recommends the following international action to achieve this GGR:

RECOMMENDATION 1

Continue and increase global efforts to reduce emissions of greenhouse gases. Large-scale GGR is challenging and expensive and not a replacement for reducing emissions.

RECOMMENDATION 2

Implement a global suite of GGR methods now to meet the goals of the Paris Agreement. This suite should include existing land-based approaches, but these are unlikely to provide sufficient GGR capacity so other technologies must be actively explored.

RECOMMENDATION 3

Build CCS infrastructure. Scenario building indicates that substantial permanent storage, presently only demonstrated in geological reservoirs, will be essential to meet the scale required for climate goals.

RECOMMENDATION 4

Incentivise demonstrators and early stage deployment to enable development of GGR methods. This allows the assessment of the real GGR potential and of the wider social and environmental impacts of each method. It would also enable the process of cost discovery and reduction.

RECOMMENDATION 5

Incentivise removal of atmospheric greenhouse gases through carbon pricing or other mechanisms. GGR has financial cost at scale and so will require incentives to drive technological development and deployment of a suite of methods.

RECOMMENDATION 6

Establish a framework to govern sustainability of GGR deployment. Undertake rigorous life cycle assessments and environmental monitoring of individual methods and of their use together.

RECOMMENDATION 7

Build GGR into regulatory frameworks and carbon trading systems. In the UK, as an example, active support for GGR implementation (soil carbon sequestration, forestation, habitat restoration) should be built into new UK agricultural or land management subsidies.

RECOMMENDATION 8

Establish international science-based standards for monitoring, reporting and verification for GGR approaches, both of carbon sequestration and of environmental impacts. Standards currently exist for biomass and CCS, but not for GGR methods at large.

Image
Hellisheidi Power Plant.
Photo Arni Saeberg © Carbfix.

Introduction

The 2015 Paris Agreement, signed by 194 countries and the European Union, demonstrated international recognition of the challenges imposed by climate change and the need for action to limit its impacts on humanity and our planet. The agreement seeks to limit future warming to well below 2°C above pre-industrial temperatures, and to attempt to keep it below 1.5°C.

To reach these targets, it states: "Parties aim to reach global peaking of greenhouse gas emissions as soon as possible, recognizing that peaking will take longer for developing country Parties, and to undertake rapid reductions thereafter in accordance with best available science, so as to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century, on the basis of equity, and in the context of sustainable development and efforts to eradicate poverty[1]."

Even with reductions in emissions at the maximum rate deemed reasonable it is challenging, or impossible, to meet this aim of 'net-zero' emissions – by balancing sources and removals – on the required timescale, and so too the temperature targets. Notably, some industries, including air travel and agriculture, produce emissions that can be reduced, but not likely eliminated completely. To counteract these emissions will require enhancing the 'sinks' of greenhouse gases through the implementation of greenhouse gas removal (GGR). In practice this will mainly be carbon dioxide removal but we use the more general term GGR for completeness.

One way in which future emissions are evaluated is through so-called integrated assessment models. These consider future energy demands and provide scenarios for potential energy systems – including mixes of different forms of energy and deployment of different technologies – given different sets of economic, environmental, social and industrial constraints. Of the integrated assessment model scenarios considered at the time of the Paris Agreement, 87% of those that expect to achieve 2°C, and all those that expect 1.5°C, involved GGR as well as emissions reductions. Subsequent models have supported this view. Only very dramatic and rapid emissions reduction will allow the 2°C target to be met without GGR, and there are no recognised routes to achieve 1.5°C without GGR.

The need for GGR, in addition to rapid emissions reductions, makes assessment and development of viable approaches to large-scale GGR important. This importance has been acknowledged at national level in many countries, including in the UK, where the government's Clean Growth Strategy (October 2017) recognises the need to develop diverse approaches to GGR, and to go beyond its present commitments under the Climate Change Act[a] to, "legislate for net-zero at an appropriate point in the future".

The scale of GGR required is large. Most global scenarios indicate that several hundred $GtCO_2$[b] must be removed by the end of the century to meet 2°C, and close to a thousand $GtCO_2$ for 1.5°C. This compares to current annual CO_2 emissions of c. 40 $GtCO_2$, indicating the scale of the activity required to achieve sufficient GGR. These scenarios also indicate that GGR will need to commence now and ramp-up rapidly in subsequent decades (Figure 1).

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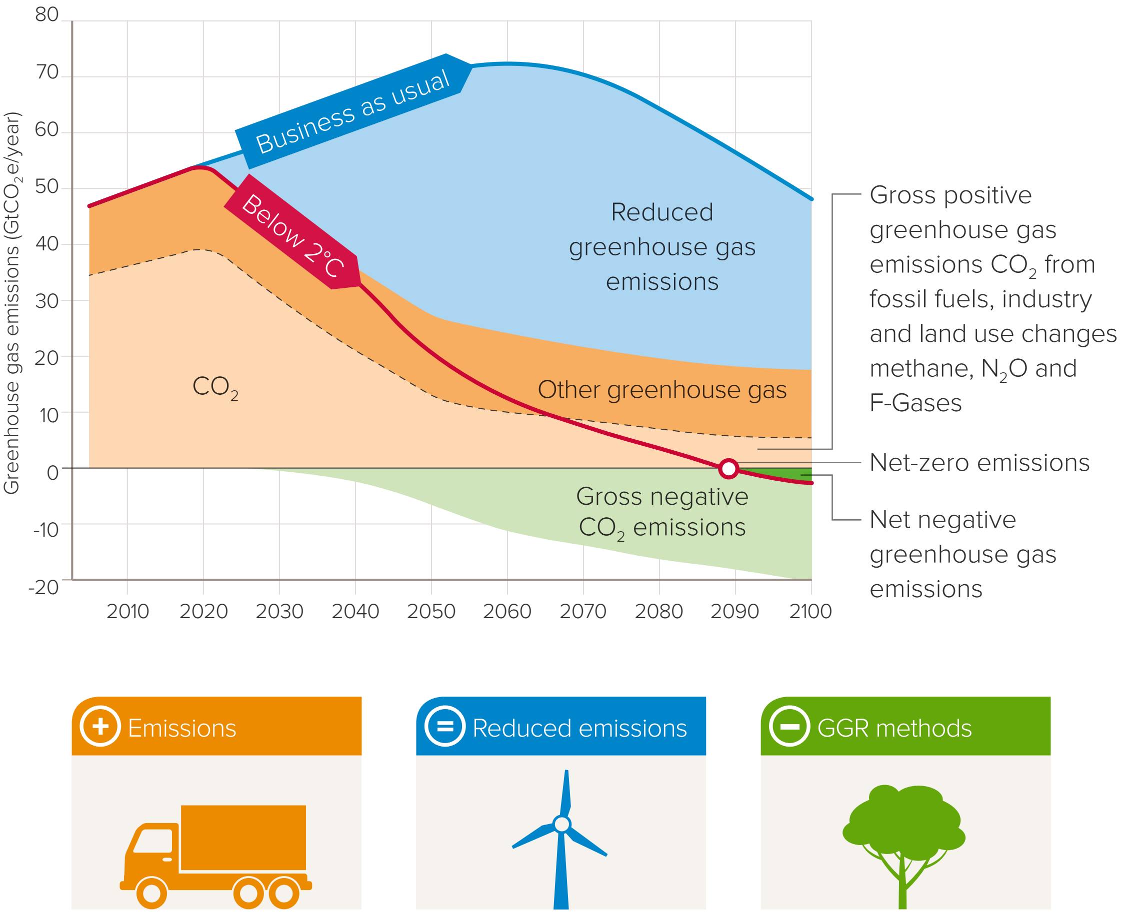
[a] The Climate Change Act (2008) commits the UK to reduce national greenhouse gas emissions by at least 80%, relative to 1990 levels, by 2050, and provides the legally-binding framework to achieve that commitment.

FIGURE 1

Future emissions and removals of greenhouse gases. To meet the 2°C goals of the Paris Agreement requires rapid and dramatic decreases in emissions (in blue), but also active removal of greenhouse gases from the atmosphere (in green), commencing in the next decade.



Source: UNEP Emissions Gap report 2018.

Many models have assumed that the required GGR will be met by growing of forests and the use of bioenergy coupled to carbon capture and storage (BECCS). But there are a wide range of other approaches to GGR, which rely on biology, accelerating natural inorganic reactions, or engineered industrial approaches. Assessing what a viable suite of GGR methods might comprise requires consideration of the potential, constraints and risks of all of these various approaches, and is the overall goal of this report.

The report is structured in three parts:

GGR methods: a description of each method, under set subheadings that capture critical issues, such as scalability, cost, and environmental risk.

Cross-cutting issues: a summary of the issues (resource, economic, societal and others) involved in establishing a suitable suite of GGR methods.

Scenarios: development of two example GGR scenarios; for the UK to achieve net-zero emissions by 2050, and to maintain global temperatures below 1.5°C in 2100.

Limitations of this report

The report is limited to GGR approaches that have global potential on the $GtCO_2$ scale. This limits the inclusion of some technologies that make use of the carbon extracted from the atmosphere. Some of these technologies, notably building with wood and low-carbon concrete, have been suggested as significant for GGR and are considered here. Others (such as production of liquid biofuel or chemical feedstocks) are not presently able to achieve GGR at scale and are not considered, although future developments may allow such technologies to become important for global CO_2 budgets[2,3]. Many of the methods discussed in this report provide both GGR and emissions reduction or avoidance, but the benefits discussed are limited to those from GGR unless stated otherwise.

This report does not consider carbon capture and storage (CCS) in detail. Availability of CCS is important for the pursuit of several GGRs and therefore it is mentioned throughout the report, but the scientific, technical or economic issues relating to CCS have been addressed in a wide range of other forums[4] and such discussion is not repeated here.

In addition, this report does not consider solar radiation management (SRM) as a form of climate control. SRM and GGR have sometimes been considered together under the title geoengineering[5], but are very different approaches to mitigate climate change with different risks and outcomes. This report only discuses GGR approaches, and is motivated by the need to pursue GGR to meet the goals of the Paris Agreement.

Chapter one
Greenhouse gas removal

Left
Pine forest in Oregon.
© franckreporter.

1.1 The carbon cycle

A number of gases in the atmosphere alter the energy balance of the Earth to cause the so-called greenhouse effect. Human activity has increased the concentration of several of these greenhouse gases, with the rise in the level of carbon dioxide (CO_2) being the most significant cause of anthropogenic climate change[6]. Nearly all proposed approaches to remove greenhouse gases from the atmosphere focus on removal of CO_2.

GGR must be performed at a large scale if it is to prove useful in limiting future climate change. Fossil-fuel use and industry released an average of 34 ± 2 billion tonnes of carbon dioxide equivalent ($GtCO_2$) per annum (pa) for the decade 2007 – 2016, and is projected to have released 37 $GtCO_2$ in 2017[7]. This CO_2 is ultimately derived from geological materials, with 94% due to burning of fossil fuels (coal, oil, gas) and 6% from limestone during production of cement. An additional 5 $GtCO_2$ pa was released due to anthropogenic land-use change (primarily deforestation) in the decade 2007 to 2016.

Anthropogenic CO_2 becomes incorporated in the global carbon cycle. This cycle is complex, with a large number of components and feedbacks (see Figure 2). It was finely balanced in pre-industrial times, and resulting atmospheric CO_2 concentrations remained within 10 parts per million (ppm) of 280 ppm for at least two thousand years before 1850[8]. In present day, atmospheric concentrations of CO_2 have reached over 400 ppm. A significant body of research has quantified the natural carbon cycle and how it has been altered by anthropogenic CO_2 release[9].

Carbon exists in four main environments (see Figure 2):

i. As living or dead organic material on land.

ii. In rock, as limestone or ancient organic material, such as coal, oil, gas.

iii. In the ocean.

iv. In the atmosphere.

Living vegetation on land contains a similar amount of carbon as the atmosphere, while soils and permafrost together contain about five times more carbon, derived from dead vegetation. The fluxes – or exchanges of carbon gases – between the atmosphere and land-vegetation are large, with photosynthesis absorbing, or removing, and respiration returning about 400 $GtCO_2$ pa in the pre-anthropogenic cycle. Since then, changing climate and rising atmospheric CO_2 have increased the net rate of plant growth and natural CO_2 sinks. The enhanced natural land sinks have led to a net removal of CO_2 from the atmosphere to the land of 11 ± 3 $GtCO_2$ pa in the decade 2007 to 2016, which is the equivalent to 33% of all human emissions in that time. This enhanced removal is partially offset, however, by the 5 ± 3 $GtCO_2$ pa released by anthropogenic land-use change – such as deforestation[10].

In addition to being the source of anthropogenic emissions when used as fossil fuels, geological materials play a significant role in the natural carbon cycle. The mass of carbon contained in rock is very large, but the rates of exchange with the atmosphere by natural means (due to volcanoes, weathering and sediment formation) are very much slower than for other forms of carbon with a global flux of less than 1 $GtCO_2$ pa. Nevertheless, it is the balance between degassing – or release – of CO_2 from volcanoes, and the reaction of atmospheric CO_2 with silicate rocks during weathering, that ultimately stabilises climate on geological timescales over millions of years[11].

The ocean contains far more carbon than the atmosphere or land reservoirs, with about 65 times as much carbon as the pre-industrial atmosphere, mostly in the form of the stable bicarbonate ion (HCO^{3-}). As with land vegetation, pre-industrial fluxes between the ocean and atmosphere were large but balanced, with cold waters absorbing and warm waters degassing around 290 $GtCO_2$ pa.

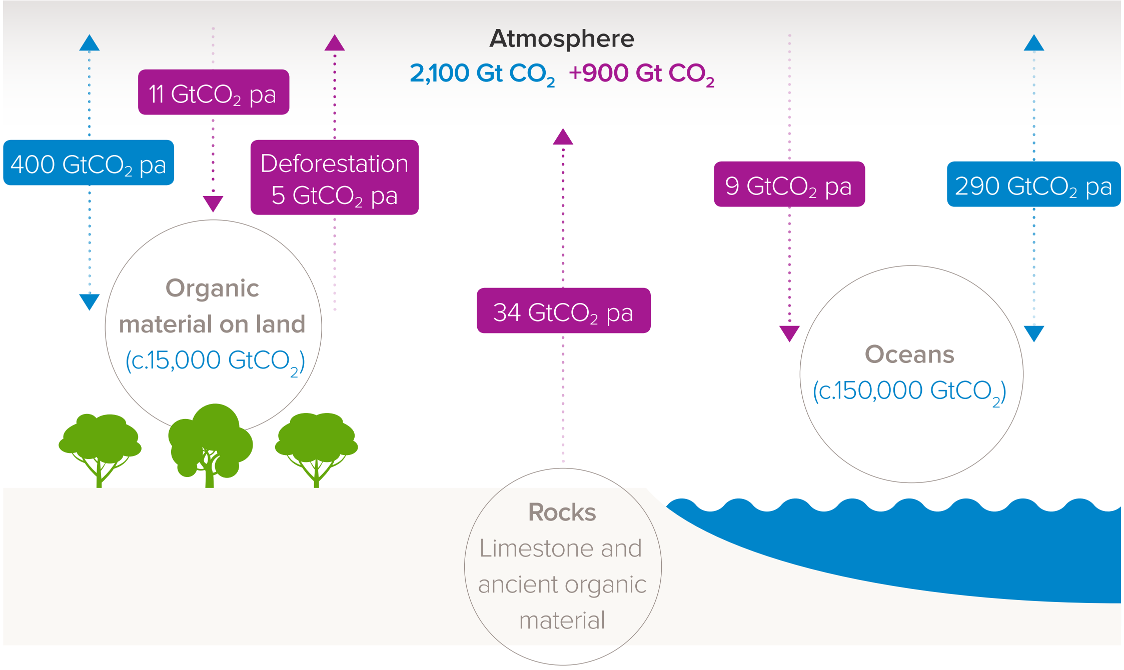
Since then, increased atmospheric CO_2 has led to net uptake of CO_2 by the ocean. In the decade 2007 to 2016, this imbalance was 8.7 ± 2 $GtCO_2$ pa, equivalent to 25% of human emissions. This uptake occurs only at the ocean surface and the slow overturning and mixing of the oceans (c. 1000 years) means that most of the deep ocean has not yet responded to increased atmospheric CO_2. In addition to these inorganic CO_2 fluxes, carbon is taken up by photosynthesis by marine plants, especially plankton, at the ocean surface. As on land, much of this is respired to CO_2 almost immediately, but some of the organic matter settles downward to be respired in the deeper ocean. This respired carbon is returned to the surface to balance biological removal.

Absorption and re-emission of light and heat by gases and clouds in the atmosphere causes a natural greenhouse effect that makes the surface of Earth about 30°C warmer than it would be otherwise. CO_2 is the most significant driver of this surface warming[b].

CO_2 concentrations have been increased by more than 40% by human activities – from 280 ppm in 1850 to 407 ppm in 2017. Regardless of the source of CO_2, once in the atmosphere it is fairly well mixed so that concentrations are similar almost everywhere. Successful application of GGR, therefore, would influence atmospheric CO_2 everywhere (as does mitigation of CO_2 emissions) and could in principle be carried out anywhere, a feature that is exploited by most of the technologies described in this briefing.

FIGURE 2

A simple depiction of the cycle of CO_2, showing the masses of CO_2 in each of the four environments, and the fluxes between these environments. Blue values and arrows reflect the natural pre-anthropogenic system; purple are human perturbations to the carbon cycle (values are for the decade 2006 – 2017).



Source: Values from IPCC and Le Quere *et al* (2017).

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[b] Water has a larger role in the overall greenhouse effect, but the atmospheric water content is controlled by saturation and responds to climate change rather than driving it.

1.2 Removal and storage

GGR must involve two processes:

i. Intentional capture and removal of a greenhouse gas from the atmosphere.

ii. Storage of that greenhouse gas in a form that prevents it from returning to the atmosphere for an extended period of time.

Some GGR approaches combine these processes, resulting in direct incorporation of the greenhouse gas within the carbon cycle. Others do not and produce CO_2 that must then be stored by a separate activity.

There are three broad approaches that can be used for removal of greenhouse gas from the atmosphere: (1) increasing biological uptake, (2) increasing inorganic reactions with rocks, or (3) engineering direct capture from the atmosphere (Table 1). The key features of each of these are as follows:

(1) Enhancing biological uptake is superficially attractive but may alter ecosystems in undesirable ways. Furthermore, the requirement for long-term storage of carbon means that significant land area must be dedicated to permanent forest, or the carbon captured must be stored in some other environment or medium. Such storage may be in soils (for example biochar), in the deep ocean (ocean fertilisation), or in the built environment. Alternatively, plant material can be burned to produce energy with the resulting CO_2 captured and stored (BECCS), again requiring viable CO_2 storage infrastructure.

(2) Natural inorganic reactions involved in weathering of rocks might be accelerated for GGR. This is challenging at large scale because these processes are naturally very slow. Approaches to accelerate weathering involve spreading fine-grained minerals over large areas of land, or use of waste products from industry. Resulting storage of carbon would be in stable carbonate minerals at the earth surface, or as stable bicarbonate ions in the ocean.

(3) Engineered removal involves passing large volumes of air over a chemical or material that adsorbs CO_2 (direct air capture or DAC), followed by release of the separated and more concentrated CO_2 and its subsequent storage. These approaches therefore also require viable CO_2 storage infrastructure, unless it can be used for example in the production of cement for the built environment. In this report capture and storage (or use) are covered by the term direct air capture with carbon storage (DACCS).

FIGURE 3

Diagram of CO_2 capture and storage for each GGR method.

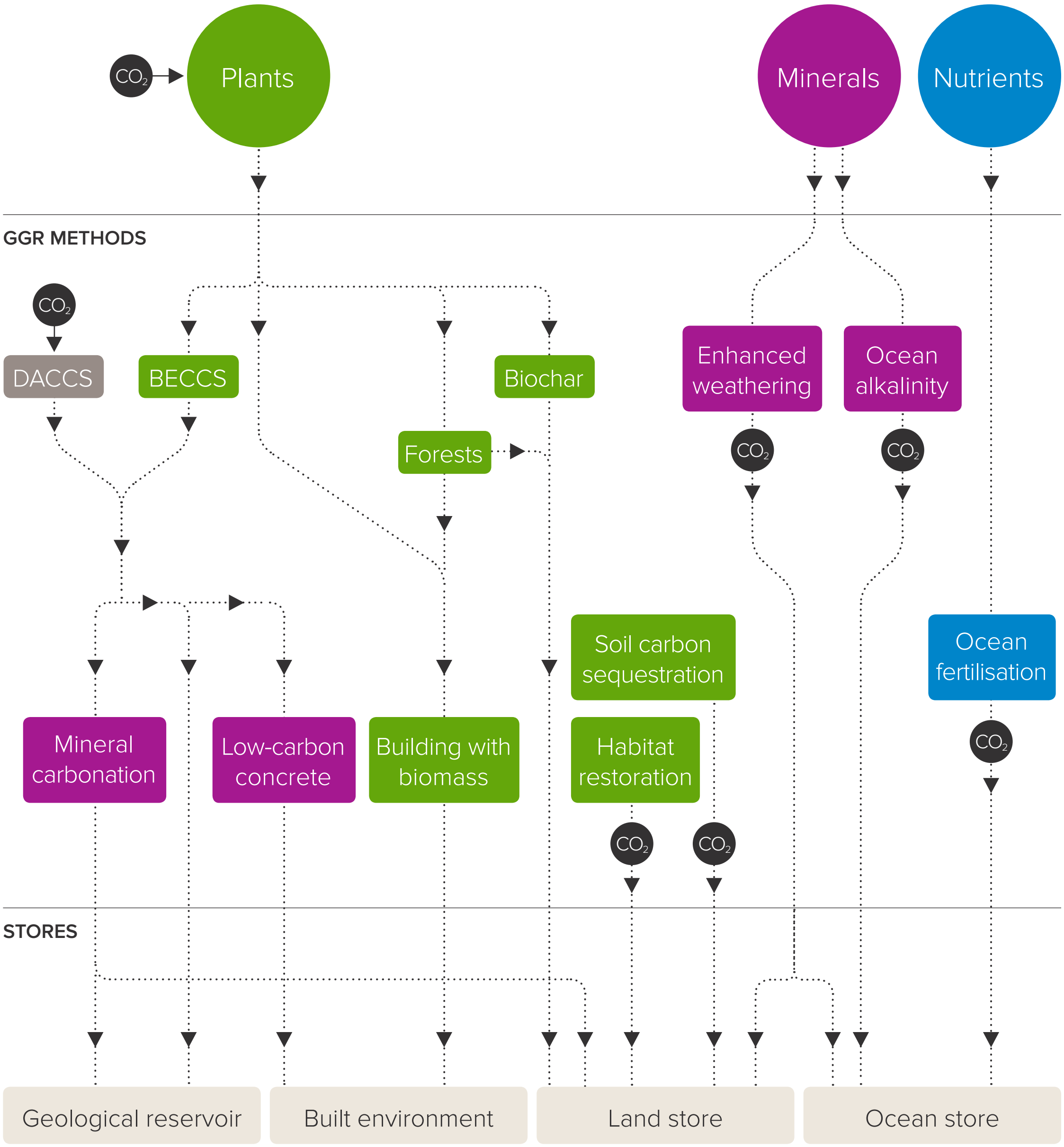

TABLE 1

GGR methods categorised by their removal and CO_2 storage mechanisms. Methods with integrated storage are highlighted in green and those requiring a separate storage mechanism in blue.

		Greenhouse gas removal method		
		Increased biological uptake	Natural inorganic reactions	Engineered removal
Storage location	Land vegetation (living)	Afforestation, reforestation and forest management; Habitat restoration;		
	Soils and land vegetation (dead)	Soil carbon sequestration; Biochar	Enhanced terrestrial weathering	
	Geological	BECCS	Mineral carbonation at surface	DAC + geological storage DAC + sub-surface mineral carbonation
	Oceans	Ocean fertilisation	Ocean alkalinity	DAC + deep ocean storage
	Built environment	Building with biomass		Low-carbon concrete

Chapter two
GGR methods

Left
Marshland in Florida.
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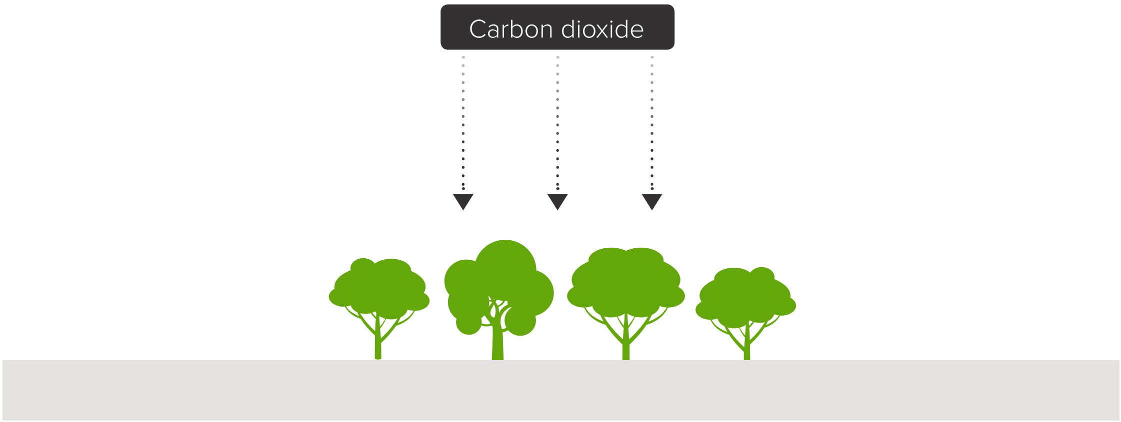
2.1 Afforestation, reforestation and forest management



Basic principle of operation

As trees grow they absorb CO_2 from the atmosphere and store it in living biomass, dead organic matter and soils. Afforestation and reforestation – sometimes referred to collectively as 'forestation' – facilitate this process of carbon removal by establishing or re-establishing forest areas. Once a forest reaches maturity the net uptake of CO_2 slows, though additional gains can be made through forest management, such as by optimising thinning and improved rotation. Once mature, forest products can be harvested and the biomass stored in long-lived wood products (see 2.7), or used for bioenergy or biochar. Consequent forest regrowth then allows continuing CO_2 removal.

Technology readiness

Afforestation, reforestation and forest management are already widely practiced throughout the world.

Storage potential and longevity of storage

The potential for carbon removal varies depending on assumed land availability, location, forest type and management as well as economic and biophysical constraints. Most estimates typically restrict land-use change to safeguard future food, fibre and to some extent habitat systems. Potentials for GGR from forestation vary from 3 to 18 $GtCO_2$ pa, depending mostly on assumed constraints to land availability (350 to 1780 Mha)[12]. By 2100 a maximum removal of 12 $GtCO_2$ pa has been estimated, or just 4 $GtCO_2$ pa with a more conservative estimate[13].

Potentials for improved forest management alone are estimated at 1 to 2 $GtCO_2$ pa by 2030[14].

It takes forests approximately 10 years to ramp-up to the maximum sequestration rate and depending on the species, the trees will reach maturity after around 20 to 100 years, then saturating in terms of CO_2 removal, after which they no longer result in net GGR. Carbon can be stored in forests indefinitely, but the permanence of this storage could be reduced by resumption of deforestation, or by natural disturbances that may be further affected by climate change – for example, fire, disease or drought.

Natural resources required

The main resource limitation is land area as forestry competes with other social and economic land uses. Significant amounts of land are required to achieve substantial CO_2 capture, with land intensity of forestation estimated at around 0.1 ha per tCO_2 pa over 100 years[15]. The energy requirement for these GGR methods is relatively low. For example, a life cycle study of forestation on reclaimed mining land showed emissions of 5.7 tCO_2 per ha over a 34 year span, 2% of the cumulative 334 tCO_2 sequestered over that period[16,17]. Forests are not typically irrigated so water requirements are also often low.

Image
© Empato.

Environmental benefits and challenges

The environmental impacts of afforestation and reforestation depend on many factors, including planting, thinning and other management activities. A particularly significant issue is the use of the land that is being replaced. For example, replacing natural forests or other natural ecosystems with faster growing or higher biomass tree plantations could reduce biodiversity. On the other hand, replacing cropland or degraded land with forests could enhance biodiversity and have other positive environmental impacts, such as improved soil quality and reduced flooding, erosion and eutrophication[c]. Forest management activities could lead to various environmental impacts on a life cycle basis, from planting through to harvest and use. These include the impacts from the use of fuels, fertilisers and pesticides, and emissions of volatile organic compounds.

Large-scale forestation can directly affect temperature and precipitation locally, regionally, and in faraway places through physical changes that may enhance or mitigate CO_2-induced climate change. The choice of location is important, as planting forests in snow-covered boreal areas can reduce albedo[d] and, therefore, enhance local or regional-scale warming[18]. Tropical forests, on the other hand, result in local cooling and rainfall recycling and act as air and water filters.

Scalability and engineering challenges

A key challenge for scale-up is in the identification of suitable locations for implementation. Further to this, even where suitable land has been identified, land owners may not be easily convinced to implement tree planting if this means replacing another more immediate income-generating activity.

Generally, projects deliver the greatest benefits if they are implemented on degraded land or land that was previously forested and for which no other economic or social activity has been planned. In particular, competition for land with agriculture could potentially infringe on food security, although this could be addressed through agroforestry systems that can combine tree planting with agricultural production, maximising efficiency and other co-benefits.

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[c] Eutrophication is the over enrichment of a body of water with minerals and nutrients which causes excessive growth of plants and algae.

[d] Albedo refers to the reflectiveness of the land surface.

While initial costs of establishing plantations can be high, the costs of regeneration and management are low. There is the potential to sequester 1.2 $GtCO_2$ for under \$30 per tCO_2 and 0.4 $GtCO_2$ pa at less than \$3 per tCO_2[19]. Future cost estimates for afforestation and reforestation range from \$15 to \$30 per tCO_2 for the year 2100[20].

Risks to implementation

The main risks to deployment of new forest are the availability of land, competition with other land uses, and the comparatively long time from planting to maturity. The latter point is particularly pertinent to land owners who would require certainty around longevity and security of payments to bridge the time until trees are able to be used for sustainable timber products. Issues around impermanence, including natural disturbances (for example, forest fires) that may increase in frequency due to climate change, may present a further risk.

Monitoring and evaluation

The inclusion of forestry in greenhouse gas inventories has been challenging due to the complexities of monitoring, reporting and verifying greenhouse gas fluxes in the land sector. This is because the land is simultaneously a source and sink of CO_2, due to a combination of both natural and anthropogenic factors. Human driven ‘direct’ changes in land cover and management happen at the same time as the ‘indirect’ effects of climate change on plant growth and decomposition and as the effects of natural disturbances such as fires and disease. There is no single best method to disentangle these effects and a range of approaches are used by those modelling global pathways[21]. These differences need to be better understood to ensure credibility and transparency under the Paris Agreement’s global stocktake, which will assess the global progress to meeting the 2°C target.

Social factors

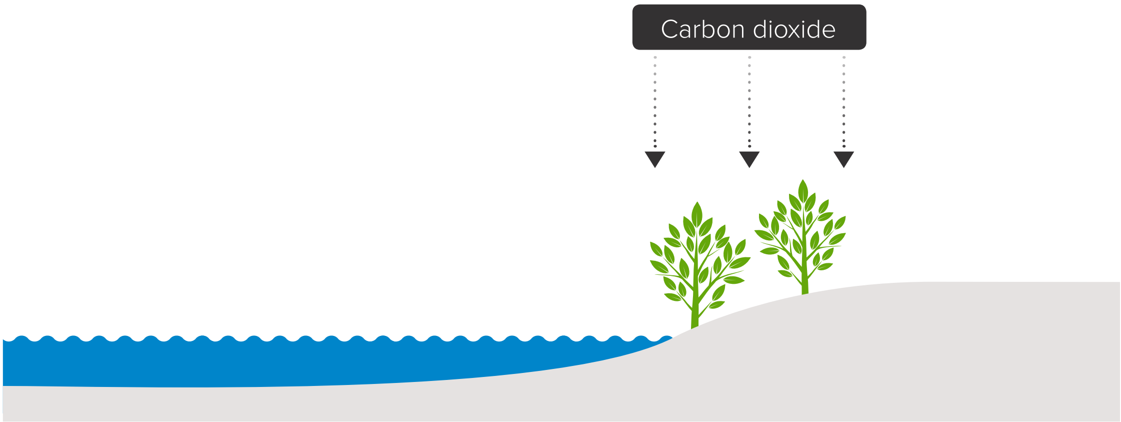
The UK public generally have a positive attitude towards forests, but may be opposed to replacing natural forests with plantations of non-native species. In developing countries there are major socio-economic issues around land-tenure, equity and the multitude of existing uses of ecosystems[22,23]. In addition, land owners and farmers usually need to generate an income from their land and may therefore prefer to put it to a more productive use than tree planting without exploitation.

Policy factors

Many countries have already included forestation or forest management in their Nationally Determined Contributions under the Paris Agreement. Forests and avoided deforestation are expected to meet a quarter of the total pledged mitigation, demonstrating the established nature of this GGR method. Examples include Brazil (0% illegal deforestation by 2030 in Amazonia), Mexico (0% deforestation, afforestation for wetland protection), China (increase forest stock volume by 4.5 billion m^3), and India (enhancement of carbon sequestration annually by about 100 $MtCO_2$). This international effort is also reflected in the Bonn challenge, which aims to restore 350 Mha of deforested and degraded land by 2030. Since 2011, 47 national commitments have been made, reaching 160 Mha of land restored or planned for restoration[24].

In the UK, the Forestry Commission is implementing the Woodland Carbon Code, which accounts for CO_2 sequestration by forestry projects. As of September 2017, validated forestry projects covering an area of 5000 hectares in the UK were projected to achieve sequestration levels of about 2.5 $MtCO_2$ over their lifetime[25].

2.2 Wetland, peatland and coastal habitat restoration



Basic principle of operation

Wetland, peatland and coastal habitat restoration rely on the restoration or construction of high-carbon-density ecosystems as a mechanism of sequestering CO_2 from the atmosphere. Examples of such ecosystems, as listed by the Intergovernmental Panel on Climate Change (IPCC), include "inland organic soils and wetlands on mineral soils, coastal wetlands (such as mangrove forests, tidal marshes and seagrass meadows), and constructed wetlands for wastewater treatment"[26]. These solutions are henceforth referred to collectively as wetlands. Peatlands and coastal wetlands have been estimated to store 44% to 71% of the world's terrestrial biological carbon[27]. While the carbon stocks in peatlands and coastal wetlands are now vulnerable to release as a result of degradation, drainage and exploitation[28], these ecosystems also have significant future carbon sequestration capacity[29]. Restoration of wetlands and peatlands usually centres on rewetting the ecosystems by blocking drainage, among accompanying measures.

Technology readiness

Since wetlands and peatlands have been managed by humans for many years, there is a high level of knowledge and readiness to implement restoration measures. Current implementation of wetland restoration techniques has resulted in significant learning over the past decade, though a number of questions remain on maximum feasible scale, cost, land-use trade-offs, and permanence in the face of climate change.

Storage potential and longevity of storage

Restoring habitats often acts to both actively sequester new carbon and prevent further loss through degradation. Although only the former is GGR, both are clearly of value. Assessments of long-term global GGR potential from wetland restoration range from 0.4 to 18 tCO_2 per ha pa. In addition to this sequestration, restoration can also reduce emissions from peatlands and coastal wetlands, with a global impact on the order of 1 $GtCO_2$ pa by 2030[30].

The UK has 0.45 Mha of salt marsh, 0.8 Mha of freshwater wetland and 9% to 15% of Europe's peatland area, 2.7 Mha, of which 80% is considered to be in poor condition, thus providing restoration opportunities[31].

As for forestation, restored habitat also faces the risk of impermanence if disturbed by human activity or natural disasters. Sea-level rise may impact the permanence of salt-marsh storage, unless this habitat is allowed to migrate landward as levels rise. As with other habitats, wetlands will eventually reach a carbon equilibrium, although over a longer period of time than soil.

Natural resources required

Compared to forests and other terrestrial ecosystems, the carbon density and slow biomass decomposition rate of wetland ecosystems can result in lower land requirements for similar levels of GGR[32]. Ecosystem restoration has negligible energy requirements and variable water requirements.

Environmental benefits and challenges

Wetland restoration has the potential to contribute to other global sustainability goals, such as improved water quality, flood protection, ecosystem restoration, biodiversity preservation, and job creation. Restoring habitats can provide additional environmental benefits by providing protection from natural disasters; for example, salt marshes acting as flood defences or mangroves providing protection from tropical storms[33]. However, depending on the previous land use of restored land, wetland restoration could either improve or diminish the heat-reflecting capabilities of those areas, possibly providing an additional benefit or detriment for climate-change mitigation. This is particularly true for wetlands that have surface vegetation of mosses, grasses, and shrubs, rather than forested wetlands like mangroves[34].

Scalability and engineering challenges

Compared to afforestation and reforestation, much less is known about wetlands. Additional research around verification of carbon storage, life cycle accounting, cost-effective monitoring of fluxes, and indirect land-use change is needed to ensure that wetland restoration can be an effective GGR strategy[35].

Direct CO_2 removal costs for peatland restoration are in the range \$10 to \$100 per tCO_2[36] suggesting potential low-cost options for projects on wetlands. Beyond carbon sequestration, wetlands can also generate valuable, potentially monetisable ecosystem services, such as water provision, flood management, soil and water quality and, in some places, cultural services, like tourism in natural areas. These could be higher than those of other terrestrial ecosystems, such as forests[37,38]. Estimates of the average annual value of wetlands, reflecting these services, range from \$3000 to \$14,800 per ha pa[39,40].

Roughly one-third of global wetland ecosystems had been lost by 2009[41], suggesting a set of locations and volumes where restoration work can begin. However, while some sites may be suitable for early remediation, others have been converted to ports, industrial sites, and other high-value capital assets, which limits the extent to which they can be used for CO_2 removal. For these high-value uses, the current barriers to implementation are largely financial as the direct economic value of co-benefits that accompany restoration (for example, biodiversity, water remediation, recreation) are often not high enough. Therefore, a change in land-management practices would need to be predicated on incentives for a long-term conversion and maintenance of the wetland ecosystem. Wetlands and other habitats will be impacted by future climate change, not least sea-level rise. Their maintenance, and potential spread inland, would then need to adapt accordingly.

Risks to implementation

Production of non-CO_2 greenhouse gases represents a substantial risk. Although wetlands represent a significant sink for CO_2, they have also historically been a significant source of methane, with estimates ranging from 20% to 25% of global emissions[42]. Restoring some wetlands could induce a short-term net warming effect, due to increased emissions of methane and N_2O. Dedicated and sustained research is needed to resolve or reduce these uncertainties. Further, future climate change or management practices could threaten the sink capacity, with some peatlands being vulnerable to changes in temperature and precipitation as well as renewed drainage[43].

A further risk is that, in some cases, restoration projects can fail. Competition for land with food and energy generation could lead to the displacement of these activities leading to indirect land-use change emissions[44].

Monitoring and evaluation

Monitoring is required to determine the longevity of storage created by restoration. Monitoring changes in carbon sequestration in wetlands is more difficult than in soils, because the organic layers are often deep and carbon stocks are large, meaning that small changes are measured against a large background. However, since wetlands are often restored by rewetting, monitoring the water table as an indicator of the carbon sequestering practice is straightforward and could be remotely sensed. Similarly, vegetation is being monitored as a proxy of the carbon sequestration status of peatlands[45].

Image
Lochan na h-Achlaise.
© JoeDunckley.

Social factors

In most cases, restoration of degraded wetlands is likely to attract public support due to conservation benefits. However, there may be concern regarding the replacement of ‘hard’ flood defences with floodable wetlands. There will also be opportunity costs, particularly where the degraded wetland is being used for food production, as in the cultivated boreal peats in Scandinavia, tropical peatlands in South East Asia, or mangrove swamps used for seafood production. Removal of these activities could displace food production and threaten livelihoods.

Policy factors

International and national conservation and biodiversity policies are likely to enhance implementation of wetland restoration. However, as economic growth and food security policies incentivise wetland drainage and destruction (particularly in poor countries with food security issues), extra efforts will be required in these instances.

2.3 Soil carbon sequestration

Basic principle of operation

Soil carbon sequestration is the process of removing CO_2 from the atmosphere by changing land management practices in such a way as to increase the carbon content of soil. The level of carbon in the soil is determined by a balance of carbon inputs (for example, from litter, residues, roots, or manure) and carbon losses (mostly through respiration, increased by soil disturbance). Therefore, practices that either increase inputs or reduce losses can promote soil carbon sequestration. A large number of land management practices are used to increase total soil carbon on a decadal timescale[46,47].

For croplands these include:

- Crop management: improved varieties and their rotation, use of 'cover crops', perennial cropping systems, agricultural biotechnology.
- Nutrient management: optimised fertiliser type, application rate, timing, precision application.
- Reduced tillage intensity and residue retention.
- Improved water management: including drainage of waterlogged mineral soils.

For grasslands, measures includes:

- Vegetation management: improved grass varieties, deep rooting grasses, increased productivity, and nutrient management.
- Animal management: stocking density, improved grazing management, improved animal feed production.
- Fire management.

The specific practices applicable to an individual land area will depend on a number of factors, including region, use, maturity and resource availability.

Image
Tractors with liquid manure spreader.
© Bestgreenscreen.

Technology readiness

Soil carbon sequestration is ready for implementation and many of the practices are already used in some places. The agricultural and land-management practices required are generally well known by farmers and land managers and mostly do not require additional machinery or infrastructure[48].

Storage potential and longevity of storage

Rates for soil carbon sequestration vary considerably, depending on land-management approaches, soil type, and climate region[49]. When scaled globally, the technical potential for soil carbon sequestration is estimated between 1.1 and 11.4 $GtCO_2$ pa, with more conservative estimates suggesting an upper limit of 6.9 $GtCO_2$ pa[50,51,52,53,54]. Estimates for the UK potential for soil carbon sequestration are 1 to 31 $MtCO_2$ pa[55].

However, these rates of carbon sequestration will not be sustainable indefinitely, with saturation expected after as little as a decade or two as soils approach a new, higher, equilibrium carbon concentration. After that point, additional sequestration decreases to zero. Moreover, sequestration is reversible, and practices need to be maintained indefinitely, incurring yearly costs. The length of time to reach saturation depends on the sequestration methodology, soil type and climate zone (slower in colder regions)[56]. The IPCC use a default saturation time of 20 years.

Natural resources required

Soil carbon sequestration approaches can be applied to all managed land without changing its current use[57]. It is typically considered to require no additional energy overall. Some practices, such as reduced or zero tillage, may save energy by reducing the energy input to farm operations while others, such as pumping irrigation water, may incur an energy cost. However, activities such as improved rotations or residue management are close to current practice and so will require little change to energy requirements. Except for processes involving increased irrigation, there is no significant use of water[58].

Environmental benefits and challenges

Increasing soil organic carbon content confers a number of environmental, economic and social co-benefits, contributing to a number of the UN Sustainable Development Goals (SDGs). These can include improved soil fertility, workability, increased crop yield and yield stability, improved water holding capacity and improved structure, depending on the practices used[59,60]. Additionally, soil carbon sequestration has no impact on albedo[61].

However, increasing soil organic matter through carbon sequestration may also increase other greenhouse gas emissions. While soil carbon sequestration is expected to have only small or negligible impact on soil methane emissions[62], it does increase organic nitrogen levels in the soil. Increased soil nitrogen could be mineralised to become a substrate for N_2O production, though the effect is difficult to quantify[63].

Scalability and engineering challenges

Since soils have been managed for millennia, knowledge of practices is widespread and readiness for adoption is high. Current barriers to implementation include lack of knowledge of the benefits among farmers and land managers, resistance to change, and lack of policy or financial incentives to encourage practices leading to soil carbon sequestration.

Costs of implementation on croplands and grazing lands range from a saving of $12 per tCO_2 to a cost of $3, suggesting revenues and cost savings from some of these practices. GGR through soil carbon sequestration at a rate of 2.6 $GtCO_2$ pa globally would save $7.7 billion, comprising savings of $16.9 billion and costs of $9.2 billion before saturation[64].

For the UK specifically, implementation to remove 1 to 31 $MtCO_2$ pa could save $0.04 billion or could incur a cost of up to $0.34 billion[65].

Assuming unit costs are limited to between $5 and $25 per tCO_2, global carbon emission mitigation potentials of soil carbon sequestration range between 1.5 and 2.6 $GtCO_2$ pa for a period of 10 to 20 years[66,67].

Risks to implementation

The main risk for soil carbon sequestration is the reversibility of carbon storage, which could be particularly acute once the sink is saturated.

Monitoring and evaluation

Monitoring, reporting and verification can be difficult because the changes in soil carbon stocks are small relative to the large background level. While it is challenging to measure changes in soil carbon, practices that lead to soil carbon sequestration can be monitored at the activity level. If coupled with field measurements, well-calibrated models could assist in the monitoring and evaluation process[68].

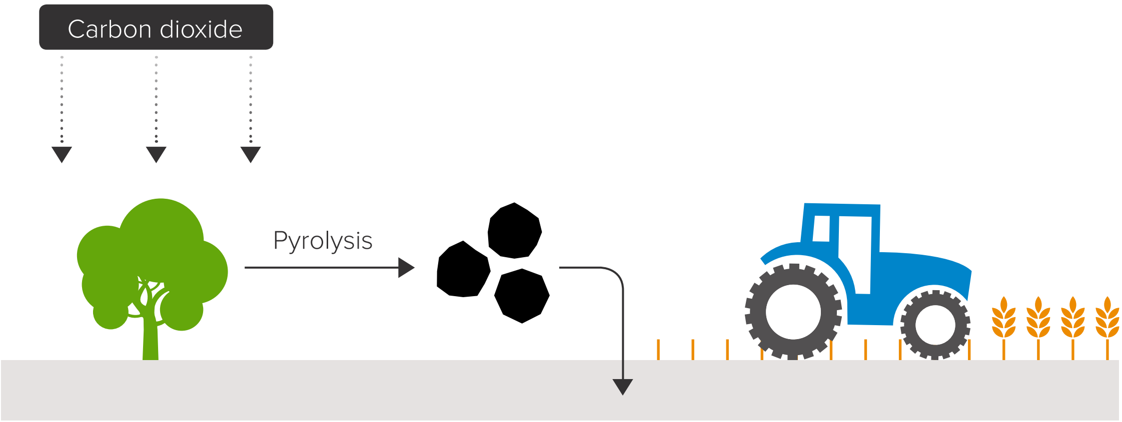
Social factors

There are likely to be few public perception barriers to soil carbon sequestration since it entails ‘good practice’ soil management and provides a range of economic, societal and environmental co-benefits[69].

Policy factors

Concerns about sink saturation and reversibility, and perceived difficulties and costs of monitoring, reporting and verification, have hindered policy action in the past. However, a large number of non-climate policies globally have promoted soil carbon sequestration for other purposes, largely to promote soil health and quality, to prevent degradation and to improve soil fertility and productivity[70,71,72]. Soil carbon sequestration can also benefit from recent international initiatives, such as the ‘4 per 1000 Initiative: Soils for Food Security and Climate’. This has begun to promote soil carbon sequestration as a GGR option to contribute toward the ambitious climate change targets in the Paris Agreement[73].

2.4 Biochar



Basic principle of operation

Biochar is produced by thermal decomposition of biomass in the absence of oxygen – known as pyrolysis – into a stable, long lived product like charcoal. Biochar stores original biomass carbon in a form that is relatively resistant to decomposition[74] and that can stabilise organic matter added to soil[75]. In this manner carbon can be stored in the soil for an extended period, while also providing a range of soil fertility and soil quality co-benefits. Examples include improved water and nutrient retention, and higher crop yields (though this effect may be limited to the tropics[76]).

Technology readiness

Biochar is an established GGR method, but it is not yet widely applied, in part due to costs and the limited availability of pyrolysis facilities. However, readiness for implementation at large scale is anticipated within a decade[77].

Storage potential and longevity of storage

It is estimated that, on a life cycle basis, biochar produced from different crops can remove between 2.1 to 4.8 tCO_2 per tonne of biochar[78,79]. This takes into account crop cultivation, biochar production by pyrolysis, carbon sequestration by biochar used as a soil improver and system credits for electricity generation by pyrolysis.

While biochar can be applied at high per-area application rates, the overall benefits are likely to be higher if applied at low rates, after enhancement through co-composting or nutrient addition[80]. Biochar is considered to be more stable than soil organic matter, so should persist longer. However, there are uncertainties associated with decomposition rates of the various types of biochar depending upon the pyrolysis feedstock and temperature. The efficacy and potential for GGR through biochar is still debated, but has been estimated globally at between 1.8 and 4.8 $GtCO_2$ pa[81,82]. For the UK, this is limited by domestic biomass resource resulting in an estimated potential for biochar of 6 to 41 $MtCO_2$ pa[83].

Image
Biochar. Credit: Oregon Department of Forestry. creativecommons.org/licenses/by/2.0

In addition to its use as a soil improver, biochar can be utilised as activated carbon in waste treatment processes or as a fuel. However, the storage times are much shorter and may result in net greenhouse gas emission on a life cycle basis.

Natural resources required

Biochar requires land firstly to grow the biomass feedstock and secondly for spreading. Biomass cultivation for biochar does lead to land competition issues, however, as biochar can be applied alongside other activities spreading does not. Biochar can also be produced from waste biomass, eliminating the need for additional land, and giving value to waste materials, although again there is competition for use of this waste from various GGR methods.

Given that biochar is less easily decomposed than soil organic matter, and that application rates to soil can be as high as 30 to 60 t per ha, GGR per ha can be much greater than for soil carbon sequestration, giving land requirements for biochar of <1 ha per tCO_2. Application rates of 50 t biochar per ha and removal of 2.6 (constrained) and 4.8 (maximum theoretical) $GtCO_2$ pa would lead to land footprints for biochar spreading of 14 and 26 Mha, respectively[84]. At this rate, biochar could be applied to current land without changing its use.

Models for feedstock to produce biochar vary, but a biochar sequestration potential of 2.6 $GtCO_2$ pa could include 1.1 $GtCO_2$ pa sequestered by dedicated biomass crops. These dedicated crops would require 40 to 260 Mha, of which half could be produced on abandoned, degraded cropland that is not used for other purposes[85,e].

Making biochar produces energy in the pyrolysis process, which could be used as heat or to produce electricity. Assuming energy contents of the feedstock of 16.4 to 35.3 MJ per kg[86], and 10% and 20% energy cost and energy loss in pyrolysis plants, respectively[87], the energy- generation potential of biochar is estimated at 5 to 14 GJ per tCO_2 removed. Globally, biochar removing 2.6 $GtCO_2$ pa could produce 14 to 35 EJ pa net energy. At maximum theoretical removal of 4.8 $GtCO_2$ pa, biochar could produce up to 65 EJ pa energy.

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e. If yields were lower on this degraded land than predicted, the area required would increase proportionally.

Water is not used in quantity in the production of biochar (with the exception of biochar made from hydrothermal carbonization[88]). It is widely accepted that adding biochar to soil improves its water-holding capacity, though the scale of this impact is difficult to quantify[89,90]. However, water is used (with chemicals) to scrub the polluting gases from the pyrolysis process and this also generates wastewater that must be treated, in turn requiring additional energy.

Environmental benefits and challenges

Biochar applied to soils can have soil fertility and soil quality benefits. However, as biochar material tends to be dark and can be applied in large quantities, it can darken the soil surface. Biochar application at 30 to 60 tonnes per ha to soil has been found to decrease surface reflectivity over the crop season by up to 40% relative to controls, which in turn increases soil temperature[91]. These albedo reductions, and related warming of the atmosphere, may reduce the beneficial effect on climate change of CO_2 sequestered by biochar[92].

Biochar also has quantifiable impacts on non-CO_2 greenhouse gas emissions. Studies on rice paddy soils show significant increases in methane and decreases in N_2O emissions when biochar is added[93]. Other studies in pasture systems show the opposite effect (increased N_2O and decreased methane[94]) and others no effect[95]. Where biochar is produced from biomass that might otherwise have naturally decayed, emissions of methane and N_2O are avoided, contributing to the greenhouse gas emission reduction delivered by biochar[96]. Biochar can also stabilise heavy metals and stop them entering food chains[97]. The effects of biochar on non-agricultural plant species are not yet fully understood[98].

Because biochar can be burned to generate energy, it could partially substitute for fossil fuels in energy generation. However, using biochar as fuel releases carbon back to the atmosphere and this must be taken into account when estimating the removal potential. Additionally, depending on the processes used, life cycle emissions from the biochar system can be greater than those removed. For example, a study considering switchgrass as a feedstock for the production of biochar showed that the net emissions could be as high as 0.12 tCO_2 per tonne of biochar[99]. Furthermore, using biochar for other applications, such as activated carbon, can also increase the net emissions to up to 11 tCO_2 per tonne of biochar[100].

Scalability and engineering challenges

The quantity of biomass available for biochar production is a key factor limiting the global potential for this GGR method. Additional pyrolysis facilities will also be required for large-scale implementation with associated capital expenditure and operational costs. Since biomass can also be used as a fuel, its conversion to biochar and burial forgoes some of the potential energy available. The practice of storing and spreading the biochar may also prove challenging.

Predicted costs for biochar range between \$18 and \$166 per tCO_2[101]. Assuming UK conditions (with different assumptions), estimates for costs of production to application of biochar vary from \$230 profit to \$330 cost per tCO_2[102]. Economic benefits from biochar application could offset some of the costs[103], but the benefits differ by region.

Risks to implementation

Although the risks of reversibility and difficulty of monitoring are lower than for soil carbon sequestration, some barriers remain, such as limited knowledge of practice or policy support. Other risks include increased environmental pollution from pyrolysis facilities and generation of liquid and solid waste, although if chemicals were extracted from the waste they may have secondary uses.

Monitoring and evaluation

Monitoring, reporting and verification can be difficult since the changes in soil carbon stocks are small relative to the large background level. While it is challenging to measure changes in soil carbon directly, the practices themselves can be monitored and, if coupled with field measurements, well-calibrated models could also assist[104,105].

Social factors

The production of biochar requires biomass feedstock (unless waste is used), so is likely to share the negative perceptions associated with the bioenergy part of BECCS. Specifically, if biomass is sourced from forests, concerns may centre on woodland loss or degradation and, if sourced from dedicated energy crops, on competition for land used for growing food[106].

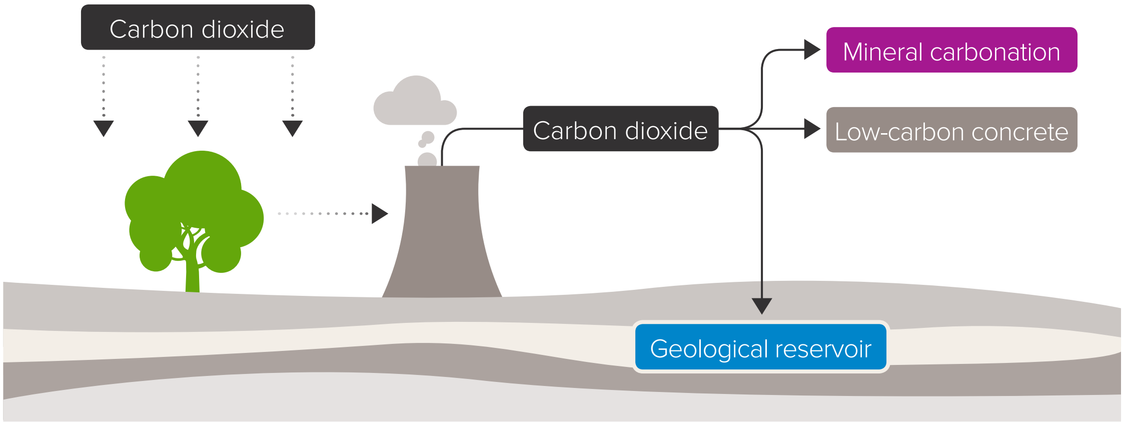
Further concerns include negative public perception of pyrolysis facilities, which for many represent ‘incineration in disguise’ and are therefore, likely to be denied public ‘licence to operate’. This is a particularly sensitive issue in the UK, but it may be less so elsewhere where incineration is used more commonly.

Policy factors

There is a lack of economic and policy incentives and guaranteed markets for biomass or biochar, which has limited the growth of dedicated biomass in the UK[107]. Some of the policy barriers are similar to those for the bioenergy component of BECCS.

Within the UK, the Environment Agency has issued guidance on low risk waste activities that allows the spreading of up to 1 tonne per ha pa of biochar from specific source materials on land without the need for an environmental permit. However, this is much lower than the suggested application rate of 50 tonnes per hectare.

2.5 Bioenergy with carbon capture and storage



Basic principle of operation

BECCS is the combination of two mitigation options: biomass combustion to generate energy –typically in the form of power, but potentially also as heat or liquid fuel – and carbon capture and storage (CCS). Biomass includes both dedicated energy crops and waste, such as those from forestry, agricultural and municipal sources. These can be used as the single fuel source for power generation (dedicated use) or in combination with other conventional fossil fuels, such as coal and gas (co-fired generation).

CCS refers to the suite of technologies that:

- capture CO_2 from the exhausts of power stations or other industrial sources
- handle and transport CO_2; and
- store the CO_2 (for example by injection in deep geological formations).

The combination of bioenergy and CCS achieves GGR by taking atmospheric CO_2 temporarily locked in plants and storing it permanently in geological formations, while using the biomass to generate electricity. Currently, the power is perceived as the main product and the carbon removed and stored as a by-product, although this perception may be reversed in the long run.

A number of related technologies also exist whereby the output of BECCS plants is either heat or an alternative energy carrier, such as bio-hydrogen or other liquid or gaseous fuels. In the case of alternative energy carriers, a thorough life cycle analysis, including emissions from fuel combustion, would be required to determine if a net removal of greenhouse gases is achieved.

Technology readiness

Bioenergy from biomass based power plants is a mature technology, while CCS is largely at the demonstration stage with examples including the Boundary Dam project in Canada and Petra Nova in Texas[108]. A number of different BECCS configurations have been reviewed and are currently at the stage of being demonstrated in an operational environment. Some have a low level of technology readiness, while there is higher maturity for established technologies, such as co-firing with amine scrubbing of CO_2 and combustion with pure oxygen.

Storage potential and longevity for storage

BECCS has been estimated by some to have a global CO_2 removal potential of c.10 $GtCO_2$ pa (mean of IPCC WGIII AR5 scenarios[109]), and 20 to 70 $MtCO_2$ pa in the UK[110]. The storage potential and longevity for BECCS are aligned with that of CCS. Global estimates of CCS potential indicate a storage capacity of the order of 900 $GtCO_2$, which would not limit application of BECCS[111]. For the UK, a verified total storage potential of 1 $GtCO_2$ offshore has been estimated[112]. There is a much larger probable UK storage potential (including saline aquifers), possibly of the order of 20 $GtCO_2$[113].

Natural resources required

Depending on the feedstock used, the land and water requirements can be significant, ranging from 0.03 to 0.06 ha per tCO_2 removed for land, and 60 m^3 per tCO_2 of water. There may be additional water requirements for the CCS process[114]. Implemented effectively, BECCS is a net energy generator, producing 0.8 to 10 GJ per tCO_2 removed from energy crops[115].

Environmental benefits and challenges

Biomass production, combustion, capture, and storage involve different environmental challenges. For example, land-use change associated with growth of dedicated energy crops, as well as the process of cultivation and harvest, will have an impact on the local environment. At this stage, fresh water and nutrient use will be required and there may be impacts on albedo[116]. These challenges are similar to those of any other biomass-based mitigation measures and depend on the nature of the feedstock. The production of dedicated crops presents a potential conflict with food and feed production and with the SDGs. In addition, the widespread implementation of BECCS is also expected to have a significant impact on the global nitrogen cycle.

The capture technologies used in CCS are expected to mitigate some air-quality issues from combustion, especially sulphur dioxide emissions. However, amine-based CCS may need additional mitigation to avoid emissions of degradation products (for example, nitramines and nitrosamines). Control of particulates and NOx emissions from the combustion stage will also be required.

Further environmental impacts will be generated across the life cycle of BECCS, including during feedstock cultivation, processing and collection as well as for CCS activities. They have yet to be quantified, as most life cycle assessment studies have so far focused on the CO_2 removal potential of BECCS. While most such studies show overall net removal[117,118], one study has demonstrated that BECCS can also result in net carbon emission, depending on management strategies and land-use change[119].

Scalability and engineering

The implementation of BECCS faces two scalability issues – ramp-up of biomass production that involves overcoming land limitations (acknowledging that imports could fill the gap for an individual nation) and ramp-up of CCS infrastructure. Previous analysis indicates that, in the UK specifically, the annual increase of capacity during the first decade of ramp-up would be between 2 and 8 $MtCO_2$ pa[120]. These values are based on earlier estimates of CCS deployment but, from a technical and supply chain point of view, developments at these rates should be possible.

Engineering challenges include improving energy efficiency relative to conventional power generation and CCS. Typical electrical efficiencies of BECCS plants are estimated at 22% to 33%[121] but with potential to improve to around 38%[122]. This contrasts with typical current figures of 35% to 41% (coal-fired power plant), 49% to 61% (combined-cycle gas turbines). While these efficiencies would reduce to 33% to 36% and 47% to 50%, respectively, with the addition of CCS, gas power is still significantly higher than the potential BECCS efficiency.

Cost estimates for BECCS are in the range \$140 to \$270 per tCO_2 captured and are highly sensitive to the assumptions on biomass cost, electricity sales price, plant lifetime and efficiency[123]. However, these estimates do not include the long-term monitoring cost.

Risks to implementation

Given the widespread deployment of bio-based power generation and the demonstration of CCS[124], the main risks are those associated with the less-mature CCS side of the system. These include risks associated with impurities in flue gas from biomass burning, with the transport of CO_2 at high pressure (demonstrated safely in several pipelines in the USA), with integrity of CO_2 storage. Other risks include direct and indirect land-use change associated with energy crops and related competition with food production.

Monitoring and evaluation

There are two key elements in the BECCS system that would require effective monitoring: environmental impacts from feedstock production, including greenhouse gas emissions, and the integrity of CO_2 storage. The former could be dealt with using certification schemes similar to those associated with other bio-based products, like forestry products, bioenergy, or palm oil, while the latter forms part of the core activities of CCS, usually known as ‘measuring, monitoring and evaluation’[125].

Furthermore, if feedstock crosses national boundaries and is then used for BECCS, standards for crediting the national emissions inventories would have to be established. IPCC guidance is available[126] for this purpose and versions have been adopted in some countries.

Image
Bioenergy crop ripe for harvest. © Jon McCalmont.

Social factors

As BECCS feedstocks are lignocellulosic (materials like wood, Miscanthus, switchgrass and agricultural residues), they are less likely to compete with food supply. However, there are still issues associated with land-use change, particularly if energy crops are grown on agricultural land or existing woodland is used for biomass supply.

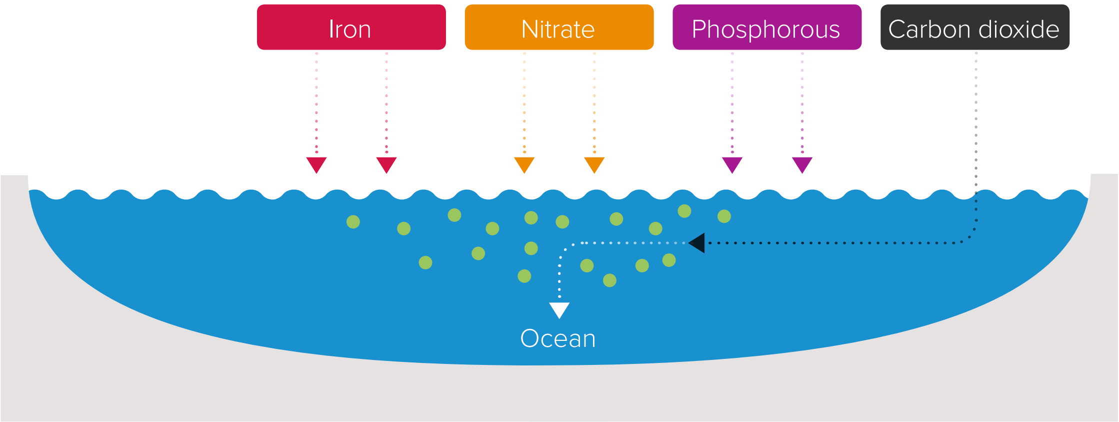
Bioenergy feedstock is traded globally, meaning that monitoring and reporting of sources and imports is crucial to ensure social and environmental sustainability of the resource. In many countries, bioenergy has created serious socio-economic problems regarding land tenure and loss of ecosystem services, and BECCS could experience similar problems especially in developing countries and areas inhabited by indigenous communities. These issues could also generate opposition to BECCS in the UK, for instance if people perceive that vulnerable communities are being treated unfairly, or if BECCS is creating problems for biodiversity.

Disruption brought about by the planning and construction of large scale infrastructure for CO_2 transportation may create public opposition, particularly where the CCS plants are located along the shoreline. Perceptions may also vary depending on whether storage is on- or off-shore.

Policy factors

Bioenergy is already supported in many national policy frameworks. However, the balance of this support with food production and other land use forms might create pressure at high levels of deployment. CCS has received variable levels of policy support over recent decades and, given the significant investments required, would likely need political support for delivery.

2.6 Ocean fertilisation



Basic principle of operation

Photosynthesis in the ocean removes around 40 $GtCO_2$ pa from the surface ocean and transports it downward to the deep ocean – a process termed 'the biological pump'[127]. In the natural system, this downward flow is approximately balanced by return of respired carbon from the deep ocean by vertical mixing and upwelling. The abundance of photosynthesizing life, like plankton, in the surface ocean, and so the magnitude of the biological pump, is limited by the supply of either micronutrients, such as iron, or macronutrients (nitrates and phosphates).

The principle of ocean fertilisation is to achieve GGR by adding additional nutrients to increase the magnitude of the biological pump, therefore removing carbon from the surface and moving it into the deep ocean, which in turn leads to additional ocean uptake of CO_2 from the atmosphere to compensate.

Technology readiness

Both nitrate/phosphate and iron fertilisation are currently technically feasible, but both face considerable challenges. Scientific experiments to fertilise patches of ocean with iron have been carried out in several areas with variable results[128]. While plankton blooms can clearly be stimulated by fertilisation, the transfer of extra carbon to the deep ocean varies significantly between experiments, making the general GGR potential of iron fertilisation questionable. Further assessment of carbon transfer would be needed involving sustained addition of iron over larger areas (thousands of square kilometres)[129]. In addition, to be practicable at the $GtCO_2$ pa scale, nitrate (or phosphate) fertilisation would require very large quantities of expensive and scarce material[130] (nitrate has to be manufactured, and phosphate is already in short supply), making wide-scale adoption unlikely. In contrast, iron fertilisation would require much smaller quantities of material at lower cost[131].

Storage potential and longevity of storage

Estimates suggest that the upper limit for ocean iron fertilisation is a CO_2 sink of not more than 3.7 $GtCO_2$ pa[132], with a total ocean sequestration capacity until the end of this century of 70 to 300 $GtCO_2$, assuming continuous iron fertilisation of all suitable areas of the ocean. Carbon successfully transported to the deep ocean (roughly to depths of 1000m or more) could potentially be retained for centuries to millennia. Although this carbon is eventually returned to the surface, continued iron fertilisation of the surface would lead to a long-lived increase in the carbon content of the deep ocean and therefore long-term GGR. Nevertheless, the balance between transport of carbon to depth and upward return flux limits the overall magnitude of GGR that might be achieved. The utility of iron fertilisation is challenged by questions about the depth of initial downward carbon transport and studies indicating significant upward return of carbon[133].

Natural resources required

Ocean fertilisation requires a supply of the fertiliser and transport and distribution to the open ocean. Iron fertilisation would need energy and raw materials for iron sulphate production, and energy and infrastructure for production, transport and distribution (chemical plants and ships). The resources required for nitrate/phosphate fertilisation would be much greater. Little land or freshwater would be required in either case. However, water requirements for the production of nitrate could be significant.

Environmental benefits and challenges

The ecological impacts of ocean fertilisation on the marine food web and fisheries, and the downstream effects on nutrient supply, productivity and food web dynamics are extremely difficult to predict. Ocean fertilisation, whether by iron or other nutrients, involves a major modification of the plankton community and the carbon sequestration is a small side effect. Producing an additional carbon sink of 3.7 $GtCO_2$ pa would likely require global ocean plankton production to be increased greatly[134]. The types of plankton stimulated by addition of nutrients cannot be controlled and would depend on other factors, such as the availability of other nutrients necessary for some species. Some iron fertilisation experiments have demonstrated that toxin-producing algae may be stimulated, leading to ‘harmful algal blooms’ that can be toxic to wildlife and humans[135]. Unintended effects on ocean biogeochemistry may also influence the production and fluxes of trace greenhouse gases, such as methane and N_2O that could reduce the benefits derived from increased uptake of CO_2[136]. Environmental impacts of the production and distribution of nutrients could also be significant but there are no estimates at present.

Scalability and engineering challenges

Ocean fertilisation may be scalable without major cost escalation. Deployment of iron fertilisation could likely be delivered at a scale of not more than 3.7 $GtCO_2$ pa, though uncertainty about net downward carbon transport makes this number questionable and caveats remain regarding environmental risks[137]. No significant new engineering developments would be required for operation, but major conventional infrastructure such as ships, ports and chemical plants would need to be created. Fertilisation operations could in principle be commenced almost immediately, but there are major scientific and engineering challenges in developing methods for verification of the sequestration achieved.

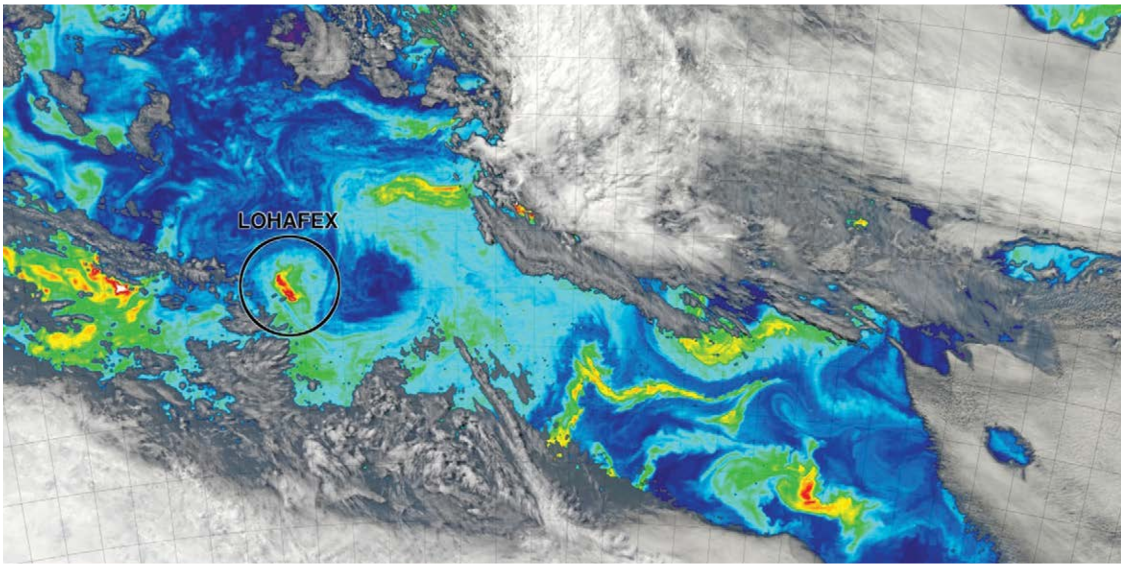


Image
Bloom resulting from the LOHAFEX iron fertilization experiment that took place in the South Atlantic in early 2009. Warm colours indicate high-biological productivity. NASA Goddard Space Flight Center, Ocean Ecology Laboratory, Ocean Biology Processing Group. Moderate-resolution Imaging Spectroradiometer (MODIS) Aqua Chlorophyll Data; 2018 Reprocessing. NASA OB.DAAC, Greenbelt, MD, USA. doi: 10.5067/AQUA/MODIS/L3B/CHL/2018.

A simplistic approach (assuming that all iron is fully used in increased plankton production, a high carbon-to-iron ratio in settling material, and that all carbon is sequestered without remineralisation) yields cost estimates for iron fertilisation that are very low, around $10 per tCO_2. However, estimates allowing for significant remineralisation through respiration predict the cost to be about 50 times higher, around $500 per tCO_2[138].

Risks to implementation

Implementing nutrient addition should be straightforward, but ensuring that it was effective and not damaging to ocean ecosystems would be much more difficult. It would require large-scale and long-term ship operations on the high seas that would be vulnerable to interference if faced by strong opposition. Algal blooms and associated oxygen depletion also pose a risk, as does further depletion of already-scarce phosphorous.

Monitoring and evaluation

For ocean fertilisation to be successful, a significant fraction of the extra organic carbon formed needs to sink and reach the deep ocean. Such assessment of the downward carbon flux, potentially from direct assessment of air-sea CO_2 fluxes, would be essential to any international carbon accounting agreement.

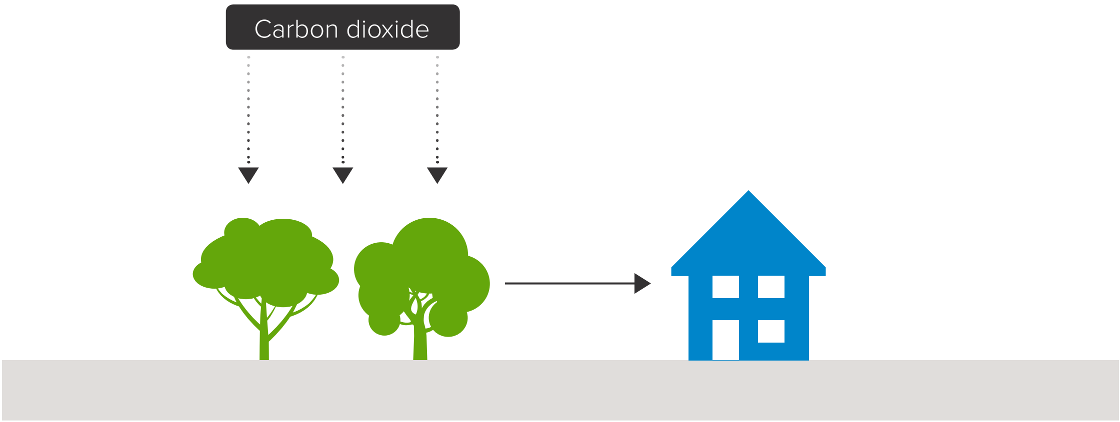
Social factors

Public perception of ocean fertilisation is very mixed, with some people and organisations being positive, sometimes influenced by the claimed (but extremely uncertain) potential to enhance fisheries' yields, and others being extremely negative, usually on ethical and ecological grounds[139,140,141].

Policy factors

Suitable locations for nutrient addition are mostly in international waters, where such an activity would currently be banned under the London Convention and Protocol[142]. Ocean fertilisation would therefore currently be illegal and would require treaties to be amended, unless it were to be agreed that it did not constitute "dumping".

2.7 Building with biomass



Basic principle of operation

Carbon is sequestered through photosynthesis in the natural world in plants and trees. Plant-based materials such as timber and straw can be used in construction, enabling carbon to be stored in infrastructure. Harvesting timber from mature forests allows space for new planting and the continued uptake of carbon into forests that would otherwise no longer provide net carbon uptake. Materials can perform various functions in the building process; for example, timber and bamboo can provide structural foundations while hemp and other forms of cellulose fibre can provide insulation. Each application will vary in lifespan[143] and, while not a permanent storage solution, biomass products can potentially sequester carbon for several decades.

There are also new types of engineered wood products, such as glulam, oriented stand lumber and cross-laminated timber, which are manufactured from wood and create more construction opportunities than are available using 'normal' wood.

Technology readiness

Wood has been used in construction for over 10,000 years. Hard wood is often used for its durability, but it is slow to grow, which limits its viability for this purpose. More recently, thermal and chemical treatments have been developed that can improve the properties of soft wood and take advantage of its faster growing cycle. The most developed of soft-wood treatment is acetylation, where acetic anhydride is used to cause a chemical reaction in the plant cell wall, which reduces the wood's reactivity. This process enhances the material's stability, durability and resistance to fungal decay and fire[144].

Increasingly ambitious wooden buildings and bridges are being constructed, such as an 18-storey building at the University of British Columbia. Biomass in other forms is also used in construction and there is potential for very fast-growing bamboo to be engineered into slabs with material properties better than conventional timber[145]. Construction blocks (Durisol) made from recycled timber avoid the sustainability issues related to wood from virgin resources and provides a cleaner route for disposal of treated wood. As brick and insulation substitutes, they may require smaller changes to design and construction practice than other biomass based building materials.

While these techniques are relatively well understood, further research is needed to establish whether large scale, treated timber structures behave fundamentally differently to non-combustible buildings in a fire, how to improve the coating of the timber to achieve superior strength and performance, how to ensure structural integrity under various climatic, geological, and vibration conditions, and how to recycle or dispose of the timber structures at the end of their useful lifetime[146].

Storage potential and longevity of storage

Building with biomass can both avoid new emissions and provide storage for CO_2 captured in forestry. The potential GGR potential from building with biomass through replacement of conventional construction materials is estimated to be in the range 0.5 to 1 $GtCO_2$ pa[147]. It has been claimed that this could save 14 – 31% of global CO_2 emissions and 12% to 19% of global fossil fuel consumption. However, to achieve this scale, 34% to 100% of the world's sustainable wood growth would be required[148].

Carbon remains sequestered for the duration over which the building or timbers are in use. Generally, the lifespan of wooden buildings and lifetime emissions associated with electricity and heating costs are comparable to that of concrete and steel structures[149]. Considering carbon sequestered only, Wood for Good estimated that 3.8 $MtCO_2$ could be captured in the UK every year if 200,000 three-bed, timber framed houses were built a year[150]. The method of decommissioning timber buildings will also affect their lifetime emissions. To maximise sequestration potential, the materials should be reused, or burnt with CCS, although this may be difficult to ensure at scale[151,152].

Life cycle assessment studies of the carbon emissions saved by timber building relative to steel and concrete have been inconclusive[153,154]. One study found that sustainably harvested wood used for building has slightly greater GGR potential than if used for bioenergy[155].

Natural resources required

The cost of transition to building with biomass has been considered negligible[156] but to facilitate an increase in scale, more trees would need to be planted, which will require additional land. The fast growing, high yield renewable softwoods trees, such as radiata pine grown largely in New Zealand, require as little as 25 years of growth to reach maturity for harvesting, whereas in the UK sitka spruce trees can provide a local alternative with around 40 years growth. There will be energy requirements for harvesting, treating, processing and transporting. Water requirements will be similar to those for afforestation and reforestation.

Environmental benefits and challenges

These materials provide an alternative to standard construction materials, including steel and concrete, which are typically carbon-intensive to produce. Timber is thought to have potential long-term benefits for tall buildings as it is less dense; resulting in reduced weight burden on both the structure and foundations, saving additional steel and concrete. Offsite manufacture may offer potential efficiency benefits, reducing disruption and waste[157] and any waste created could be used for bioenergy (with or without CCS). Creating a mass wood product market could also help to incentivise reforestation.

Good forest management is a critical element in the production of wood for the construction industry, however, there are risks of poor management. There are also potential biodiversity risks if all of the trees grown are of the same species. Additionally, at the end of their lives the wooden infrastructure materials would have to be repurposed for the carbon to remain captured, which may be a challenge if adopted at scale.

Scalability and engineering challenges

Construction with wood products is technically scalable, but potential demand for wooden structures is uncertain and increased afforestation will compete with agricultural land. With an increasing global population, it is estimated that 60% of the infrastructure required by 2030 is yet to be constructed[158]. If the right incentives are put in place, building with biomass could provide storage for a significant amount of carbon. In the UK there may be further constraints from the existing building regulations and limited timber engineering skills and expertise, so rapid wide-scale adoption could be difficult to facilitate[159]. The construction industry has been widely seen as risk-averse due to small profit margins, but some uptake of timber building has been seen over recent years. For example, 22% of new-build homes in the UK are now timber framed, with proportion in Scotland alone as high as 76%[160] and their construction is commonplace in Scandinavia and North America.

Risks to implementation

Shortages of sustainable wood supply, alongside uncertain demand and slow build-up of expertise in timber construction may limit implementation. Building requirements would need modification to permit unfamiliar construction methods and provide the necessary quality assurance and fire safety for the uptake of timber building to increase. There is an additional risk that processing and transportation reduce the extent of the benefits of this GGR method.

Monitoring and evaluation

The benefits of extending the longevity and security of carbon storage, originally created through forestation, in the built environment needs to be recognised by carbon accounting agreements. There are some mechanisms for recording the use of timber in construction but these vary from country to country. Within the UK, this is carried out by TRADA, the Timber Research and Development Association, although this is limited to the building stage and does not consider the end of the building's lifespan.

Social factors

Although some countries have a tradition of building with wood, in others, such as the UK, there is some public unease associated with the fire performance of timber framed houses[161]. There are, nevertheless, also significant aesthetic qualities associated with building using engineered wood products, which means there is a drive for their increased use from architects.

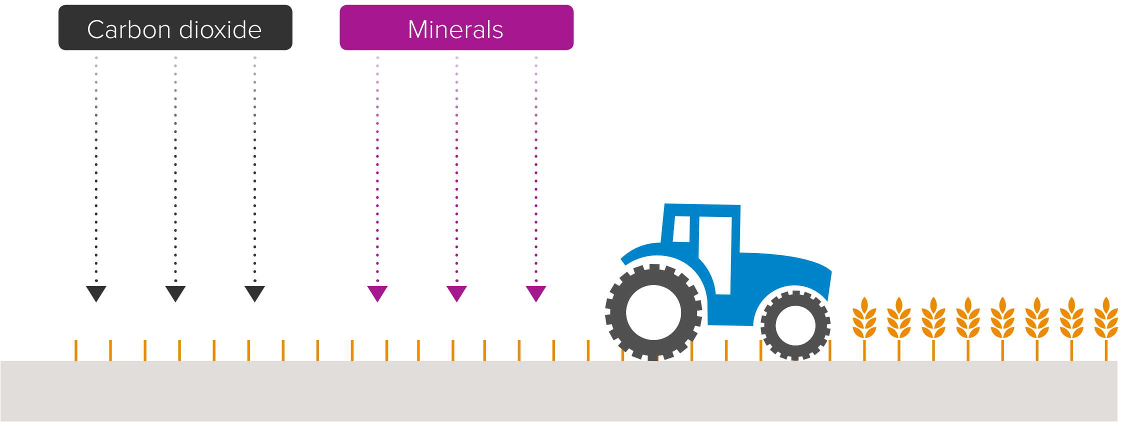
Policy factors

Incentives for tree planting and sustainable forest management would be needed to significantly expand the scale of building with wood. Policy and regulatory support would also be required to ensure commercial viability and encourage the change from conventional building materials, including implementation of more appropriate building standards.

There is greater need for cooperation in this area between business and government, as risk aversion in the construction industry may be a greater hindrance to deployment than competition from alternative materials.

As with BECCS, if biomass used for building is imported, there will need to be international agreement about the country that can claim the carbon credit and a mechanism to monitor the storage.

2.8 Enhanced terrestrial weathering



Basic principle of operation

On geological time scales, silicate rocks naturally break down, or ‘weather’. This chemical reaction removes CO_2 from the atmosphere and releases metal ions and carbonate or bicarbonate ions. These ions are either washed into the ocean to increase its alkalinity, or are precipitated as carbonate minerals, like limestone, on land.

Enhanced weathering could accelerate this process by milling silicate rocks containing calcium or magnesium (for example, basalt) to increase the reactive surface area and dramatically increase the rate of mineral dissolution. The most pragmatic approach for deployment is spreading the fine-grained rock dust over large areas of managed cropland because they are already actively managed and altered. Plant roots, and their associated microorganisms, speed up the weathering process and high levels of CO_2 in the soil, due to respiration of organic material, lead to acidity that further accelerates the process by a factor of 2 to 10[162].

Technology readiness

Enhanced weathering could technically be applied now. The agricultural sector routinely applies granular fertilisers and various forms of lime, making applications of fine-grained silicate rock feasible at scale with existing farm equipment. Technology for mining, crushing and grinding rocks is well established, and might take advantage of rock already partially ground that is available in mine tailings (see 2.9).

Storage potential and longevity of storage

Estimates place global removal potential between 0.5 and 4.0 $GtCO_2$ pa by 2100 if two thirds of the most productive cropland soils (900 Mha) were treated with basalt dust at 10 to 30 tonnes per ha pa, depending on climate, soil and crop type[163].

Theoretical considerations suggest a maximum, gross, carbon capture potential of 0.3 tCO_2 per tonne of basalt, assuming a sufficiently fine particle size for complete dissolution on decadal time scales[164]. On this basis, applying 10 to 50 t per ha pa of basalt to 70 Mha of the annual corn and soy crops in the corn-belt of North America could, in the long-run, sequester 0.2 to 1.1 $GtCO_2$ pa[165]. Improving these estimates is a research priority.

Significant precipitation of carbonate minerals in agricultural soil as a result of enhanced weathering could limit long-term application and reduce these estimates.

Based on the results of a simple model, there is a maximum CO_2 capture potential in the UK of 12 to 21 $MtCO_2$ pa for low-to-moderate application rates (10 to 20 tonnes per ha pa) and 19 to 27 $MtCO_2$ pa for a high application rate (30 tonnes per ha pa)[166].

A significant proportion of the CO_2 removed from the atmosphere during enhanced weathering is ultimately likely to be stored in the surface ocean as dissolved inorganic carbon. The ocean storage capacity is large and should be stable (see 2.10). A smaller but presently unknown fraction of the carbon would be stored as carbonate minerals in soils or potentially elsewhere on land. This is likely to be long-term storage, but little research has yet directly assessed this permanence.

Natural resources required

Enhanced weathering on cropland requires no additional land and can be co-deployed (for example) with the feedstocks for BECCS and biochar to increase sequestration potential per unit of land area. However, mining of silicate rocks may require land for surface (open pit) mining. The need for such mining is decreased if using silicate wastes that are already available such as mine waste, cements, ashes and slags.

If scaled up, enhanced weathering would require supplies of reactive silicate rocks and significant energy required for rock extraction, grinding and transportation, leading to additional CO_2 emissions from the energy consumed. Fast-weathering olivine-rich rocks for which commercial mines are already in operation are often considered, though major continental flood basalts, which are a result of historic volcanic activity, also have promise and are located near to productive agricultural regions where rock might be required.

The annual waste from silicate mining and industrial processes could provide 9 to 17 Gt mineral pa globally, which may be sufficient resource for 0.7 to 1.2 $GtCO_2$ pa of CO_2 sequestration[167]. Using 64 Mt pa of the UK's estimated 86 Mt pa of silicate waste would enable an application rate to all arable land of 10 t per ha pa[168]. However, further research and development (R&D) would be required to assess the suitability of this material for croplands. Higher application rates would require supplementing silicate waste with additional materials obtained by mining, grinding and spreading.

Environmental benefits and challenges

Enhanced weathering with basalt has long been practiced on a small scale and the first patent for using silicate-rich slag as fertiliser was obtained in the United States in 1881 and has been used widely since[169]. There are a number of established benefits that can lead to increased food production and soil improvement[170]. Increased levels of phosphate and other nutrients, reduced soil acidification and increased soil carbon stocks may increase plant and soil health as well as human nutrition (from harvested crops) and result in decreased requirement of pesticide and fertiliser, improving economics of the agricultural sector. Basalt addition has the potential to rejuvenate an estimated 100 to 1000 Mha of marginal agricultural land[171], which could significantly expand the current global cropland.

However, where mining and processing of new rocks is required, these are likely to have some negative environmental and ecological impacts, especially if linked to tropical deforestation. Very small silicate rock particles can cause silicosis if inhaled, so this must be avoided during mineral processing and application to land. Once spread, impacts on soil microbial biodiversity remain to be determined. Particles washed into rivers, and ultimately the oceans, may decrease water clarity, and result in sedimentation and pH changes, with unknown impacts for marine biodiversity and function[172].

Fast-weathering olivine-rich rocks contain relatively high concentrations of various metals, and in some cases asbestos, which may represent a significant environmental risk if they accumulate in soils, water and the food chain. Basalts have lower concentrations of some of these metals and significantly higher concentrations of phosphorus, which would be useful for application to croplands. The chemical composition of waste materials (such as mine tailings or slags) and risk of toxicity have not been widely assessed and would require assessment before use.

Other life cycle impacts associated with energy use, such as acidification, eutrophication, human and eco-toxicities, will also be generated. These have not yet been quantified and warrant further research.

Scalability and engineering challenges

A rigorous cost-benefit analysis including co-benefits has not yet been performed. Such a study would allow assessment of the attractiveness of enhanced weathering implementation among farmers and land managers worldwide and in the UK. Dedicated pilot projects and programmes could establish the evidence base within a decade or two and help resolve key uncertainties through data acquisition, development of practice and biogeochemical modelling.

Current cost estimates are uncertain and vary widely. The most detailed analysis for a basic silicate rock, such as basalt, gives estimated costs of \$52 to \$480 per tCO_2, dominated by mineral processing and transport costs[173]. Deployment costs may be partially offset by gains in crop productivity and reduced requirements for lime, fertiliser, pesticide and fungicide applications.

Monitoring and evaluation

Carbon capture by weathering over millions of years is a well-established climate control mechanism, underpinned by decades of geochemical theory. However, audited field-scale assessments of the efficacy of CO_2 capture resulting from adding crushed reactive silicate rocks to forested lands and croplands are still required, including evaluation of CO_2 capture in soils as carbonates and in streams and rivers as dissolved inorganic carbon. Such field trials must be accompanied by detailed environmental monitoring to develop rigorous audited testing.

Image
Pulverized basalt is dispersed in a corn field prior to tillage by a machine traditionally used for lime application at University of Illinois Energy Farm, University of Illinois at Urbana-Champaign.
© Ilsa Kantola.

Risks to implementation

Enhanced weathering is relatively immature and requires further research, development and demonstration across a range of crops, soil types, climates and spatial scales. Experimental and small-scale evaluation of its efficacy and permanency as a means of GGR remain priority research areas to understand its future relevance and contribution alongside environmental monitoring and reporting.

Social factors

Assessments of public opinion in the UK indicate support for research on enhanced weathering, provided it is conducted in small-scale trials with strict monitoring, risk minimisation and transparency of results[174]. Engagement of the Australian and New Zealander public highlights the need for improving the profile and basic understanding of the concept, but analyses suggest this currently poorly-defined concept is unlikely to raise major public concerns[175].

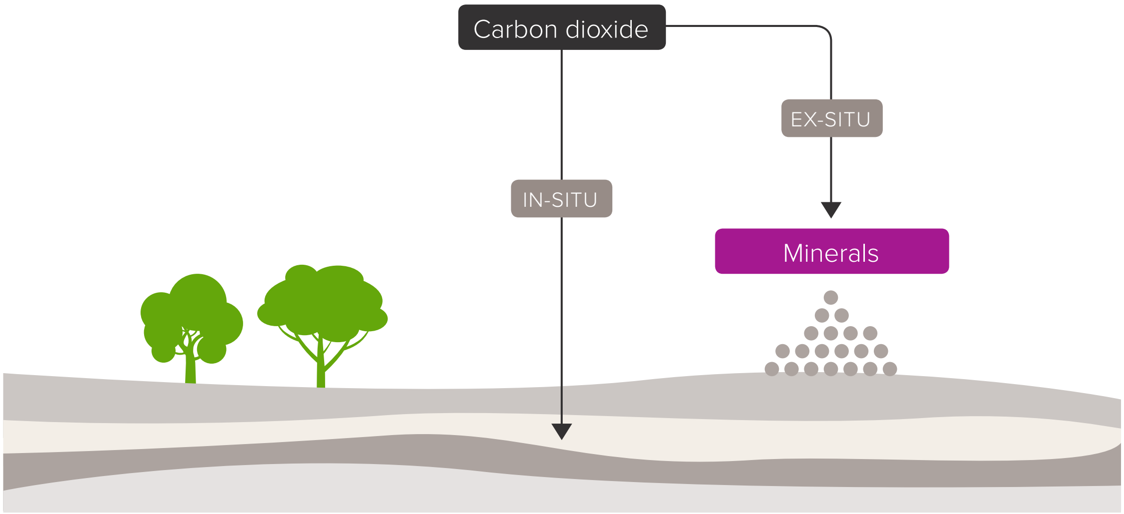
Large-scale deployment could raise public concerns regarding rock mining, especially if ecosystems are impacted. Enhanced weathering will also need to be managed carefully to avoid local opposition, for instance due to noise and disruption from rock transportation and spreading, and any actual or perceived health impacts from rock dust.

Policy factors

Enhanced weathering is not presently included in national or international carbon accounting agreements. To do so will require fuller appraisal of the ecological implications and establishment of monitoring and verification processes.

In the UK, spreading waste material on land requires an environmental permit. New regulations and standards may be required if that is to be undertaken for the practice of enhanced terrestrial weathering on cropland.

2.9 Mineral carbonation



Basic principle of operation

The conversion of silicate rocks to carbonates (as also used in enhanced terrestrial weathering) can be accelerated by industrial processes above ground (*ex situ*) or in silicate rocks below the surface (*in situ*). Most demonstrations of mineral carbonation have relied on a CO_2-rich gas and are, therefore, best considered as an alternative to conventional CCS for storage, rather than for direct CO_2 removal from the atmosphere.

Ex situ approaches accelerate reactions by grinding and pretreating the minerals before reacting with CO_2. *In situ* processes rely on the injection of CO_2 into permeable rock and acceleration by higher temperatures and pressures at depth. The resulting product of both these processes is a stable carbonate mineral, which may have commercial use as construction material or for steel production. It is also possible that the products, such as magnesium carbonates, might be used to increase ocean alkalinity for further GGR[176].

Technology readiness

Many groups, funded by governments and industry, have demonstrated *ex situ* approaches for mineral carbonation. Despite high demands for raw material and energy, some companies have commercialised carbonation processes at small scale (for example Calera in the USA). The UK hosts one of the few companies to commercialise *ex situ* mineral carbonation (Carbon8), presently used for treating hazardous industrial wastes. *In situ* carbonation from injection of CO_2 into basalts has been demonstrated in Iceland in the CarbFix project[177], but presently only at a scale of 0.01 $MtCO_2$.

Storage potential and longevity of storage

Suitable silicates for mineral carbonation include basalt and similar rocks that are present in very large quantities in many areas of the world. The theoretical storage potential of mineral carbonation is therefore effectively limitless. Limitations derive from cost and scalability of the approach.

The resulting carbonate minerals are stable and provide perhaps the most secure of any form of sequestered CO_2.

Natural resources required

For *ex situ* carbonation, the primary resources are silicate minerals and energy. Energy requirements vary significantly depending on the process pursued, but range from 1.5 to 8.8 GJ per tCO_2[178]. Taking into account the full life cycle and energy consumption of *ex situ* mineral carbonation, the additional greenhouse gas emissions range from 0.5 to 1.1 tCO_2 per tCO_2 removed[179]. Therefore, at best, only half the CO_2 is removed by mineral carbonation and, at worst, more CO_2 is generated then removed. The use of pre-ground material, such as industrial waste or mine tailings, reduces the energy demands on this process and the need for additional mining.

Land is required for *ex situ* carbonation if additional mining is pursued, or for storage of the carbonated product, but land is not the primary limitation. Water is required during *ex situ* carbonation to enhance reaction rates and for dust suppression in mines.

Environmental benefits and challenges

Increases in mining activity for *ex situ* carbonation, or drilling and injection activity for *in situ* carbonation, as well as energy conversion, would be accompanied by the usual environmental considerations of these activities. There are no data on net, life cycle, CO_2 removal for *in situ* carbonation.

Mineral carbonation of some environmentally hazardous waste materials can be performed in a manner which stabilises the wastes allowing use in products such as aggregate.

Scalability and engineering challenges

Scalability and cost are the major limitations on mineral carbonation. Two to three tonnes of silicate mineral are needed for a reaction to sequester 1 tCO_2, so to sequester 3.7 $GtCO_2$ pa would require efficient reaction with around 10 Gt pa of rock. For context, this is about three times the global production of crude iron ore.

Cost estimates for *ex situ* carbonation vary from \$50 to 300 per tCO_2. Early estimates for *in situ* carbonation are much lower at \$17 per tCO_2. The latter remains higher than conventional geological storage, but may not require the long-term monitoring needed for CCS, avoiding the additional cost). As mentioned earlier, carbonation cannot remove CO_2 directly from air and it would need to be coupled with DACCS or BECCS[180].

This resource demand and the high cost mean that pursuit of *ex situ* mineral carbonation has so far been seen as viable only for disposal of certain industrial wastes, such as slags or mining fines. Companies pursuing this approach rely on the need to make wastes safe, or on sale of the end-products. Pursuit at larger scale would require a financial incentive and would then be best located where there are suitable rocks and a supply of CO_2 from power-generation or another GGR approach, such as DACCS, to provide CO_2. In the UK, there is significant waste from the steel and cement industries that might be carbonated (as described in Low-carbon concrete). There are also some minerals that would be suitable as potential feedstock for *ex situ* carbonation, particularly in Scotland, Northern Ireland, and Cornwall.

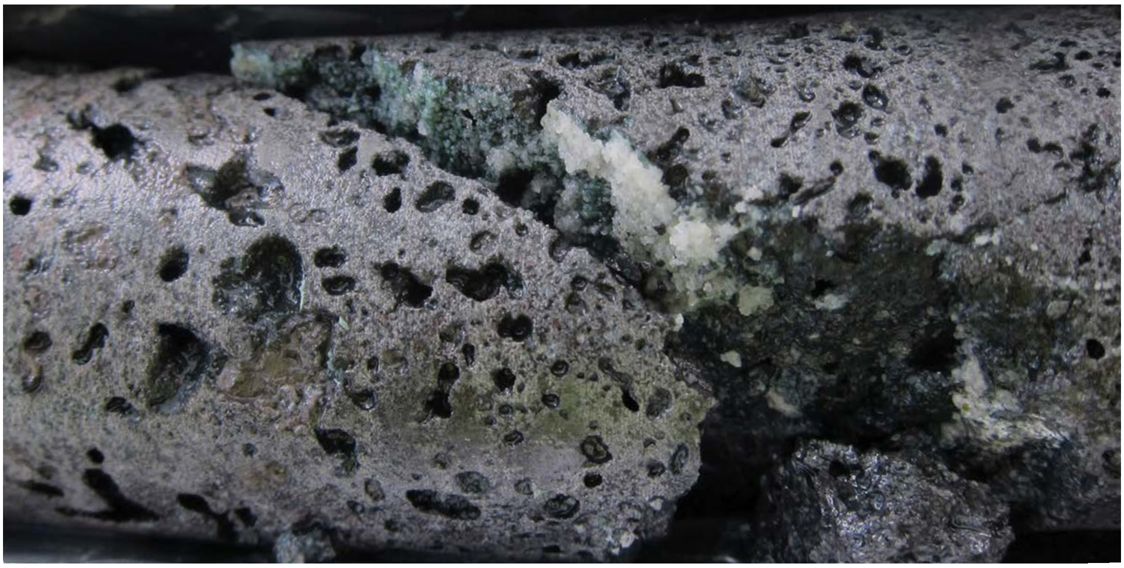


Image
Core from injection site showing CarbFix project CO_2 bearing carbonate minerals within basaltic host rock. Photo Sandra O Snaebjornsdottir © Carbfix.

Scalability of *in situ* carbonation depends on finding suitable reservoirs with close proximity to the CO_2 source and reservoir development (drilling and building a storage infrastructure). Scaling up *in situ* carbonation may also be limited by the process of carbonation itself, which changes the rock structure. Carbonation reduces the porosity of the rock to CO_2, but also causes expansion that can result in fractures. The former impedes carbonation, while the latter could enhance it, and the overall balance will vary depending on a variety of factors[181]. Globally, the storage capacity for *in situ* carbonation is huge, but in the UK it is likely relatively small. However no serious evaluation of potential onshore and offshore reservoirs has yet been performed.

Risks to implementation

The risks of implementation are small. *In situ* carbonation also circumvents the risk of CO_2 leakage inherent in conventional geological CO_2 storage.

Monitoring and evaluation

The products of *ex situ* carbonation can readily be measured, and ongoing monitoring is not likely to be needed given the stability of the resulting minerals. *In situ* carbonation is less well developed, but first results from the CarbFix project have demonstrated >95% CO_2 removal following injection into Icelandic basalts within less than two years[182]. This positive result would require replication at other sites to provide confidence about replicability, scalability, and protocols for monitoring CO_2 disposal.

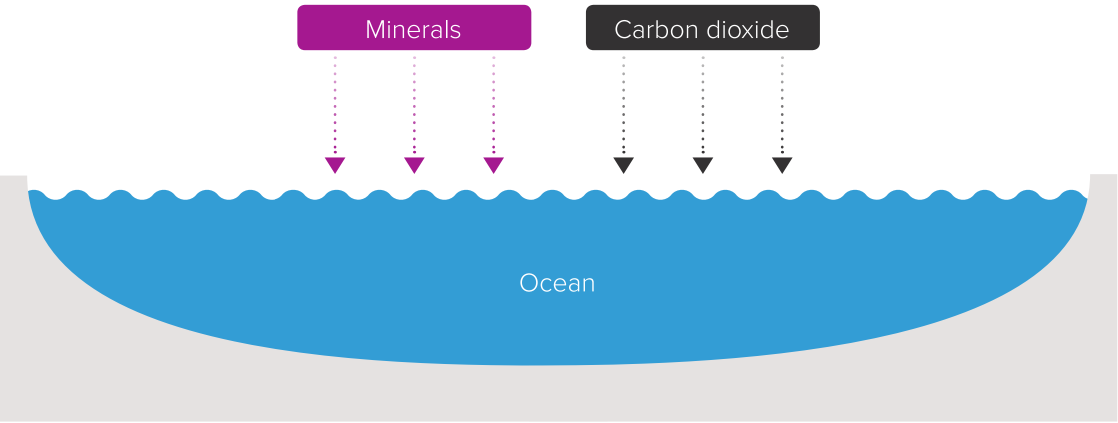
Social factors

The stable end-product of mineral carbonation makes it an approach that could generally be perceived more positively by the public than many other GGRs. However, opening new mines would likely meet with public opposition.

Policy factors

Neither *in situ* nor *ex situ* carbonation have yet been pursued at sufficient scale to factor into national carbon budgets. If proven workable and economic at scale, it will be important that *in situ* carbonate is given similar credit as conventional geological CO_2 storage if it is to be incentivised. De Beers announced their desire to develop a carbon-neutral mine using *ex situ* carbonation of mine waste which, if successful, would suggest incentivising GGR in the mining sector could be effective[183].

2.10 Ocean alkalinity



Basic principle of operation

The ocean alkalinity approach to GGR seeks to increase carbon uptake into the ocean by increasing the seawater concentration of stable, positively-charged ions, such as calcium (Ca^{2+}). The ocean contains about 65 times more carbon than the atmosphere, some as carbonate (CO_3^{2-}) but mostly as bicarbonate (HCO_3^-) ions. The concentration of these negatively charged forms of carbon is controlled by concentration of positively charged ions like Ca^{2+}, described as alkalinity[f].

Intentionally increasing the ocean's alkalinity leads to transfer of dissolved CO_2 to the ionic forms of carbon, and hence to additional uptake of CO_2 from the atmosphere[184]. This might be achieved directly by addition of lime (CaO or $Ca(OH)_2$) to seawater. It might also provide an alternative to traditional CCS by reacting a CO_2-rich gas with water and limestone and transferring the carbon-rich products to the oceans. Increased alkalinity would also result if the dissolved products of enhanced terrestrial weathering, including positively charged ions and carbon, are transported into the ocean.

Technology readiness

Increasing the carbon content of the ocean by increasing the alkalinity of seawater relies on well-understood chemistry and can readily be demonstrated in the laboratory. No field-scale trial of the approach has been undertaken, however. At its simplest, enhancing alkalinity would use existing technology; there is plentiful limestone, lime is already produced from it for the cement and other industries, and distribution from ships would not require technological advance. CCS would, however, be required where lime is produced to ensure that CO_2 emissions generated during the calcination process do not outweigh the emissions removed by ocean alkalinisation. Reaction of CO_2 in flue gases with limestone to produce high-alkalinity solutions has also been demonstrated in the lab, but not scaled up to industrial level. Application at scale also requires research into the environmental response to consider possible negative consequences on ecosystems, or reversal of the alkalinity addition.

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[f] Note Alkalinity is defined as the concentration of net positive charge in ions that do not change chemical form with pH (such as Ca^{2+}, Mg^{2+}, Na^+ etc.) and is balanced by net negative charge in ionic chemical species, particularly CO_3^{2-} and HCO_3^-. It is not just the opposite of acidity.

Storage potential and longevity of storage

Increased ocean alkalinity could theoretically remove many $GtCO_2$ pa. The uptake of additional carbon would only lead to a small fractional change to the large natural carbon content of the oceans. Modelling suggests that increased alkalinity could lead to additional ocean storage of as much as 3500 $GtCO_2$ by 2100[185] though this assessment does not consider how this large alkalinity addition would be realised.

Carbon stored in the ocean in this fashion is stable as long as alkalinity remains high. However, if the alkalinity increase were sufficient locally to cause mineral precipitation (either spontaneously or through increased shell production), this would reduce the carbon-carrying capacity of the water and reverse the CO_2 uptake. If alkalinity was initially added from weathering or reaction of limestone then this would completely reverse the benefit, while if it were from dissolution of silicates or from lime produced with CCS, only about half of the CO_2 uptake would be reversed[186]. The likely extent of carbonate mineral formation in response to increased alkalinity is essentially unknown and represents a limitation in present assessment of the effectiveness and longevity of this GGR technique.

Natural resources required

The primary resource requirement for ocean alkalinity is a source of calcium or magnesium minerals to provide that alkalinity. A natural source is limestone, mostly composed of calcium carbonate, which covers around 10% of the earth's surface, but it would need to be extracted and converted to lime for direct addition. Limestone extraction at levels similar to that of the global cement industry would be required to achieve uptake of 3.7 $GtCO_2$ pa[187]. Around 5 GJ of energy is required per tonne of CO_2 removed by calcium carbonate[188], with the main energy requirements for the mining and grinding of limestone and, for direct lime addition, production of lime by calcination. This calcination process also produces about 60% of the mass of CO_2 that is consumed on subsequent addition to the ocean, so efficient pursuit of alkalinity addition for GGR would require storage of the CO_2 from calcination, or result in significantly reduced overall benefit.

For approaches using reaction of CO_2 in flue gas with limestone to produce alkaline solutions, water is an additional resource requirement, and may require location on the coast and the use of seawater. Land use requirements would arise from the additional (new) mining required.

A full assessment of the UK's potential for ocean alkalinity addition has not yet been conducted. The UK has plentiful limestone deposits, an active cement industry, coastal power-generation, and a strong shipping industry, so could pursue this approach.

Environmental benefits and challenges

An increase of alkalinity would partially offset the effects of ocean acidification caused by high atmospheric CO_2 concentrations, so controlled addition of alkalinity could have beneficial consequences for ecosystems in some regions[189], though these have not been assessed in the field.

At locations of alkalinity addition, there is the potential for adverse effects on local ecosystems due to the resulting high pH. Lime(stone) also contains impurities, some of which may either be toxic or act as nutrients to perturb ocean ecosystems. The response of the ocean ecosystem to both high pH and to impurity addition has not yet been assessed.

Other environmental challenges are the environmental impacts commonly associated with mining (e.g. biodiversity loss, acidification of drainage, perturbation of nutrient cycles) and associated with the requirements for energy and CCS. Depending on the mechanism for distribution of the alkalinity, there would be additional impacts from shipping, for example due to the high-sulphur fuel currently used in shipping.

Scalability and engineering challenges

Addition of alkalinity to the ocean could rely on existing technology. Small scale application might use waste fines from existing limestone production[190], but removal of 4 $GtCO_2$ pa would require doubling the global production of lime, and around 100 ships for ocean distribution globally[191]. Extending this to reach the full potential capacity would require significantly more resources. New infrastructure would be required for lime production, ideally to produce pure CO_2 for CCS, or for reaction of power-station flue gas with limestone. Coastal operation would minimise land-transport costs, and would likely be essential for limestone neutralisation of flue gas, given water requirements.

The full cost of GGR by production and oceanic distribution of lime have been estimated as $72 to $159 per tonne of CO_2[192,193].

Risks to implementation

The major risks are environmental, and reflect insufficient knowledge of the response of the ocean ecosystem to enhanced alkalinity and associated addition of mineral impurities. There is also risk associated with possible partial reversal of CO_2 uptake if the precipitation of carbonate minerals were to occur.

Monitoring and evaluation

Direct measurement of CO_2 uptake by the ocean in response to alkalinity addition would be challenging, but monitoring the addition of lime or the products of flue gas neutralisation would be relatively straightforward. The possibility of partial reversal by mineral precipitation would require evaluation and may need to be monitored, particularly close to sites of addition.

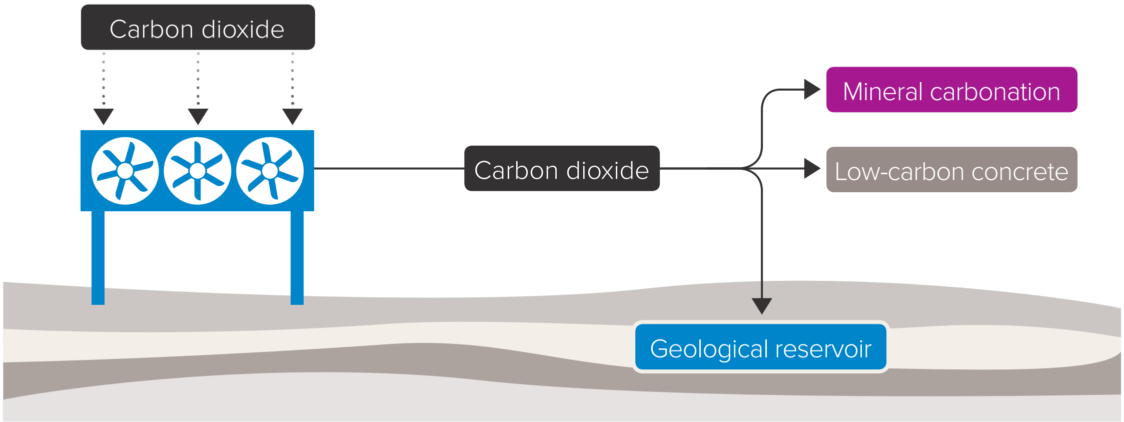
Social factors

The oceans hold a special place in the environmental awareness of many societies and there is often a dislike of processes that intentionally interfere with them. This may be an impediment to the large-scale application of alkalinity addition. Smaller scale deployment for mitigation of the impact of ocean acidification (for example on a coral reef) may not face the same opposition.

Policy factors

The London Convention and Protocol[194] controls addition of material to the ocean and prohibits “deliberate disposal at sea of wastes or other matter from vessels… or other structures at sea”. Interpretation within the Convention of the intentional addition of lime for GGR rather than as a waste is unclear, but consideration in this regulatory framework would be required before pursuit of ocean alkalinity addition from ships.

2.11 Direct air capture and carbon storage (DACCS)



Basic principle of operation

Direct air capture and carbon storage (DACCS) is the name given to a family of different technologies that use chemical bonding to remove CO_2 directly from the atmosphere and then store it. CO_2 is captured from the air into a 'separating agent' that is then later regenerated with heat, water or both, releasing the CO_2 as a high purity stream for subsequent geological storage, mineralisation or utilisation. Two key challenges in DACCS are the large flows of air required for a relatively small amount of CO_2 captured and the resources required for regeneration of the separating agent. There are a large number of different technologies that could feasibly be used for this purpose for example;

So-called 'artificial trees', using a large exposed surface area of carbon adsorbing material to passively remove carbon from the atmosphere. Once saturated, the adsorbent is humidified or soaked in water at low pressure. This releases the CO_2 and allows the adsorbent to be dried and reused[195]. This process is also being commercialised to provide CO_2 for greenhouses at small scale[196].

'Supported amine absorption', in which chemicals called amines (also routinely used for CCS) are held on a porous material with a large surface area. Air is then passed through this material and the amines react with the CO_2. Once saturated, this material is heated releasing the CO_2 and regenerating the absorbent for further capture. This process has recently been implemented in a small commercial plant by Climeworks[197]. A similar process based on amines supported on ceramic monolith supports has been demonstrated by Global Thermostat, which, similarly to Climeworks, can use low grade waste heat for regeneration of the amine[198].

The 'lime-soda process' used by Carbon Engineering[199], where sodium hydroxide (NaOH) absorbs CO_2 from the atmosphere creating sodium carbonate (Na_2CO_3) and water (H_2O). Lime (CaO) is then added to regenerate the sodium hydroxide, leaving a calcium carbonate ($CaCO_3$) precipitate which is heated to regenerate the lime and produce CO_2[200].

All these processes have high energy or heat requirements that may be prohibitive, but could be partially alleviated if integrated with other systems. By co-locating DAC technology with industrial processes that emit waste heat, such as gas power plants with CCS, the DAC process could reduce the energy requirements and cost.

Technology readiness

There are a wide range of DACCS processes at various stages of maturity[201]. Developments at laboratory and pilot plant scale are increasing, in part to explore alternative methods that can reduce energy requirements of the processes, one of the main barriers to adoption.

Meanwhile more mature technologies, like amine absorption, are closer to practical implementation, with at least four plants now operating at demonstration and semi-commercial scale. It is estimated that these technologies currently lie between pilot plant development and prototype demonstration in the field.

Storage potential and longevity of storage

The storage potential and longevity of DACCS depends on the storage potential associated with the selected sequestration method. If geological storage is used, then long-term (approaching indefinite) storage is possible. Globally, even if only depleted oil and gas fields are considered for use, storage capacity of the order of 900 $GtCO_2$ is estimated to exist[202]. The predicted capacity for UK based CCS storage is of the order of 20 $GtCO_2$[203].

If alternative uses are made of the captured CO_2, the storage longevity is dependent on the ultimate fate of the carbon atoms and can vary from over 100 years if used in structural polymers, to only months if used to produce fuels.

Natural resources required

The resource requirements differ according to the nature of the DACCS process used.

Passive DACCS processes, such as 'artificial trees', depend on natural circulation of air through the capturing agent so do not have a high operating power demand, but do require significant land area. Active contacting processes, in contrast, can be more compact, but require power for continuous flow of air through a device. In both cases, the regeneration of the capture agent requires one or more resources; typically some combination of water, heat and low pressure/vacuum. These resources must be supplied from low-carbon sources to ensure sustainable CO_2 removal over the whole life cycle. Depending on the capture mechanism DACCS may be able to deal with intermittent energy supply from renewables.

A thermodynamic analysis estimates that the theoretical minimum energy requirement for DAC is 30 kJ per mol CO_2[204] (0.68 GJ per tCO_2). In practice, technologies are likely to require 10 times this amount, but even at that energy requirement combined cycle gas power, which produces c. 10 GJ per tCO_2 emitted, could potentially be used for net removals. Nevertheless, most designs anticipate the use of renewable energy or waste heat as far as possible. Furthermore, additional resources, such as water and land, would be required dependent on the chosen sequestration method, but this would be relatively low compared to the other land-based GGR pathways.

Environmental benefits and challenges

In terms of environmental challenges, passive processes may necessitate significant land use and lead to changes of the local landscape. Other processes may require combustion of fuel for thermal regeneration of the CO_2 capture agent and therefore mitigation of local and global pollution is critical. Amine-based carbon capture processes should be designed to avoid release of degradation products (such as nitramines and nitroasamines). Life cycle environmental impact assessments for the different DACCS technologies are limited, with only one study published so far[205].

Scalability and engineering challenges

The implementation of DACCS faces two major technical issues: access to adequate low-carbon energy and water to drive capture and regeneration and dealing with the resultant high purity CO_2 stream. However, one of its advantages is that it can be located wherever access to the necessary resources is convenient. The technology and storage requirements of DACCS are similar to those of power generation and CCS and so the timescale of ramp-up will also be comparable. Large scale deployment by 2050, with early deployment in 2030, should be possible from a technical point of view. Cost estimates for the capture process (not including storage) for early stage projects typically range from \$200 to \$600 per tCO_2[206,207], with companies like Carbon Engineering, aiming towards \$100 per tCO_2[208].

Risks to implementation

The main risks of DACCS are associated with the requirement for storage, and the transport of CO_2 at high pressure and with integrity of CO_2 storage.

Monitoring and evaluation

There are three elements in the DACCS system that would require effective monitoring: life cycle impacts of the material and energy inputs (emissions and environmental); the amount and efficiency of capture; and the integrity of CO_2 storage. Where the CO_2 is not stored geologically, the life cycle of the material used to store CO_2 must be understood and used to quantify the actual storage over different lifetimes.

Image
Carbon Engineering's DAC system. Shown are the air contactor (right) and calciner (left).
© Carbon Engineering Ltd.

Social factors

Concerns around DACCS are expected to be similar to those for any medium-size industrial facility, related to amenity, landscape and noise, and around land use where relevant. For the former, co-location with existing industrial processes will facilitate planning and may provide access to waste heat that can be used for the regeneration step. Methods requiring large areas of land may co-exist satisfactorily with other uses, such as agriculture.

Policy factors

DACCS is now being referred to in the mainstream media[209], but there is no specific current policy support beyond basic R&D via research councils and other funding bodies. In the UK, there is no near-commercial activity.

2.12 Low-carbon concrete

Basic principle of operation

Concrete is made by curing cement with aggregate. At present cement production is responsible for around 5% of global CO_2 emissions though a number of technologies have been suggested to dramatically decrease these emissions and to store CO_2 in the built environment[210]. Some approaches may provide limited GGR however, at large scale, these technologies generally provide useful reductions in emissions and do not achieve net removal of CO_2 from the atmosphere.

Altering the constituents, manufacture, or recycling method of concrete could enable increased storage of CO_2 in the built environment could be enabled. Manufacture of aggregate and cement can be performed in a way that reduces CO_2 requirements and curing can be carried out in such a way that extra CO_2 is consumed.

- **Replacement of aggregate with mineral carbonation products**
  Globally, around 40 billion tonnes of aggregate and sand is consumed by the construction industry[211]. Silicate minerals could be transformed into carbonate (see 2.9) and these used to replace conventional sources of aggregates. This process can provide future GGR only if the CO_2 source in mineral carbonation is derived from the atmosphere.

- **Carbonation curing**
  Curing and ageing of cement reabsorbs a fraction of the CO_2 emitted during its production. Concentrated streams of CO_2 (ca. 99%) can be used to speed up the curing process of concrete and achieve a higher strength material than normal moist curing[212]. This approach can be used for cast concrete products, which make up a relatively small fraction of concrete, but not for more widely used concrete produced on-site. This curing typically consumes less CO_2 than is produced during the manufacture of Portland cement and so provides a reduction in net emissions, rather than net GGR. Novel approaches to cement production which capture the CO_2 released could make this process net negative, as long as the CO_2 was subsequently stored.

- **Alternative cement production**
  Portland cement is traditionally made by heating limestone to produce lime, a process that releases CO_2. Alternative cement chemistries use magnesium oxide produced from silicate minerals and magnesium carbonates to reduce emission of CO_2. Approaches for cement production from limestone that capture CO_2 could also reduce emissions. While useful for limiting CO_2 release, these approaches do not provide net GGR.

Technology readiness

There are a number of start-ups at various stages of technology readiness, including some that are now at commercial level, albeit at small scale.

Mineral carbonation: the UK-based Carbon8 processes hazardous waste produced from cleaning off-gases at municipal solid waste incinerators into aggregates. Excess unreacted lime in the solids used to clean the gases is carbonated to calcium carbonate, consuming CO_2. The overall process is not net negative, because CO_2 was emitted during the original lime manufacture, but serves to decrease emissions.

Carbonation curing: the US-based Solidia Technologies uses alternative raw materials and carbonation curing to produce high strength materials with higher efficiency. Another company, Carbon Cure, retrofits their technology to conventional concrete plants to inject CO_2 into the concrete mix. Until the lime used to make the cement in such processes is produced without CO_2 emissions, these approaches are again not net negative.

Magnesium-based cements: Novacem was a company set up in the UK to pursue this approach, but failed due to the level of investment required and the commercial risks involved. There is little activity in this area at present.

Novel lime production: the start-up, Origen Power is pursuing an approach to lime production from limestone that produces a pure stream of CO_2, making it easier to use or store. Future expansion of this approach to cement manufacture might enable CO_2 curing of cement to become net negative.

Storage potential and longevity of storage

Carbonating steel slags and their use in cured concrete blocks could achieve GGR. Replacing all masonry blocks used in the US and Canada could sequester 12 $MtCO_2$ pa[213], with further gains if gas power were to be replaced by renewable energy. In the UK, laboratory-based work suggests scope to sequester over 0.2 $MtCO_2$ pa in aggregate produced from waste materials[214], though these could only be considered as providing net GGR if using existing wastes. Additional GGR would require carbonation of virgin silicate minerals.

There is substantial capacity for changes in cement production to reduce CO_2 emissions from this sector. These reductions would be valuable to meeting climate goals, but present technologies would only generate net GGR if remaining CO_2 emissions are captured and stored.

Resources required

Substantial energy costs are incurred during grinding of virgin or industrial minerals for production of aggregates by carbonation. Transport costs can also be significant if raw materials are not located close to CO_2 sources, as is the case for virgin feedstocks in the UK.

Environmental benefits and challenges

The mining, processing, grinding, and transport of aggregates for mineral carbonation generates various environmental impacts, largely related to energy consumption. Life cycle assessment comparing CCS and mineral carbonation for European power generation suggests that, despite the net CO_2 reduction potential, mineral carbonation may produce other environmental impacts and a higher cost of electricity that make it a potentially less attractive option than CCS alone[215].

There are environmental benefits if waste materials are consumed. For instance, air pollution control residues from municipal solid waste incineration are classified as a hazardous waste so their carbonation not only immobilises CO_2 but also heavy metals, rendering them non-hazardous.

Scalability and engineering challenges

Supply of raw materials is a key challenge for scalability. Some of the highest-quality virgin feedstocks are geographically concentrated, resulting in high transport costs and potential socio-political complexities. Volumes of industrial feedstocks, notably coal ash and steel slag, are uncertain. Another challenge is the quality of aggregates made from carbonation in comparison to incumbent cement materials, and as such may only replace other aggregates in low-specification products.

Costs for mineral carbonation aggregate systems are estimated at \$50 to \$300 per tCO_2, depending on material and process specifications and the value of the end product[216,217].

Risks to implementation

Acceptability of low-carbon cements by customers as well as by incumbent producers in a notoriously conservative, low margin, high volume and highly standardised industry will be key[218]. Meeting regulatory standards on performance and compressive strength metrics will be challenging: historically, changes to regulatory frameworks can take decades to implement.

Monitoring and evaluation

Reporting mechanisms exist for the environmental performance of building materials to monitor compliance with European sustainability standards. In the UK, the Construction Products Association represents manufacturers and suppliers of construction products and provides monitoring and evaluation data for the sector. This includes data on aggregates formed by carbonation, construction products cured using carbonation, use of magnesium-based cements and other technologies that alter CO_2 emissions. For novel processes, such as new routes to lime production, monitoring of the effectiveness of long-term CO_2 storage will be required to assess net GGR.

Social factors

Public views of these methods may be affected by the quality and long-term durability of cement products and industry and government support.

Policy factors

As mentioned earlier, 60% of the infrastructure required by 2030 is still to be built[219]. Thus, there is an opportunity for low-carbon concrete to be used more widely in building this infrastructure. However, policy support, including an emphasis on proscriptive regulatory standards to performance-based standards to increase penetration of products, will likely be essential.

2.13 Other GGR approaches

A number of other GGR approaches have been proposed and a selection are discussed below. These techniques are not presently considered viable at large scale. Many are variants of methods discussed in preceding sections (see McLaren 2012[220] for a more complete overview).

Cloud alkalinity

Amirova & Tulaikova (2015)[221] propose adding an alkaline material to clouds, so that the water droplets absorb and neutralise extra CO_2. This is closely related to ocean alkalinity, but would also incur the very high costs of airlifting the vast quantity of material needed.

Biomass burial

Several authors (for example, Strand & Benford 2009[222]) have proposed near-permanent burial of biomass in terrestrial or deep ocean locations. This would compete with BECCS and biochar for plant material, but without offering the energy-production or nutrient-retention benefit of these approaches, and is therefore unlikely to see near-term application at scale. Some theoretical estimates have estimated such burial could operate at a scale of up to 4 $GtCO_2$ pa (in addition to burial through soil carbon sequestration described above). The security of storage is uncertain, but could be millennial in suitable reservoirs. However, ocean disposal would at present contravene the London Convention and Protocol.

Enhanced ocean up-welling

Enhancement of ocean up-welling to promote phytoplankton growth (by wave-driven pumps[223]) is a variant of ocean fertilisation that uses naturally-occurring rather than human-supplied nutrients. While such methods might indeed enhance plant production[224], they would not increase carbon sequestration[225] because high nutrient ocean water also contains extra dissolved inorganic carbon (just enough to utilise the extra nutrients).

Enhanced down-welling

The rate at which atmospheric carbon is transferred to the deep sea could plausibly also be enhanced by increasing down-welling. Pumping ocean water onto the surface of ice sheets would increase brine formation and encourage CO_2 is transported downward by the overturning ocean circulation[226]. However, increasing down-welling by 1 million m^3 per second, which would be a very substantial engineering challenge, would increase ocean uptake of carbon by only about 0.04 $GtCO_2$ pa.

DACCS by freezing

Agee *et al* (2013)[227] have suggested cooling Antarctic air to condense, deposit and store solid CO_2 'snow', using electricity generated from strong local winds. The cost of cooling the very large volume of air involved to -140°C has not been estimated, but would likely be prohibitive even with very efficient heat exchangers.

Marine BECCS

N'Yeurt *et al* (2012)[228] have proposed a variant of BECCS using fast-growing marine macro-algae (kelp seaweeds). While this would avoid competition for land resources, it would either require large tethered floating structures in deep water, or place additional stress on coastal waters, which are already a limited and heavily utilised resource. Anaerobic digestion of algae for methane production is slow and would require capital investment for large processing plants, while aerobic combustion would require either low-carbon heat for drying, or large areas of land for air-drying.

Electrochemical liming

Rau (2008)[229] proposed a variant of enhanced weathering, using electrochemical splitting of seawater to dissolve limestone. This has been demonstrated in the laboratory, and some estimates of costs made[230], with particular constraints associated with the capital cost of the plant and large supplies of low-carbon electricity required.

2.14 Removal of gases other than CO_2

Consideration of GGR has focused overwhelmingly on CO_2. Other gases with a significant role in global warming are methane, N_2O, and several chlorofluorocarbons (CFCs). Both methane and N_2O are present naturally in the atmosphere, but human activity is increasing their concentration. These are, by molecule, more powerful greenhouse gases than CO_2, but are presently at much lower concentrations than CO_2, making it more difficult to remove them. Their greater impact in absorbing energy, however, means that their removal could be as effective as that of CO_2 per volume of air if an approach similar to DACCS could be developed. The length of time that a gas persists in the atmosphere is also of importance, for example N_2O has a lifetime of about 100 years, whilst methane only persists 10 years. Action on either could be valuable, but would need to be sustained to achieve permanently lower atmospheric concentrations to be effective in achieving long-term climate influence.

Some bacteria break down methane as their source of energy and carbon. Intentional use of such bacteria has been proposed to reduce methane emissions from landfill and sewage plants[231]. A similar approach might allow removal from the atmosphere, but has not been demonstrated at the low atmospheric concentration of methane.

In the presence of a relevant catalyst (for example, TiO_2), both methane and N_2O can be broken down by sunlight. However, contact with very large quantities of air (without using excessive energy) would be required to achieve a significant impact. Greenhouses with high chimneys that use solar energy to produce high volumes of hot air to pass over catalysts have been proposed as a way to encourage such breakdown[232]. However, while this approach is feasible in principle, it is entirely untested, and is likely to be challenging to engineer it to be effective at the low gas concentrations of the atmosphere. Such greenhouse plants would need to be located in sunny locations like deserts, but could also potentially produce electricity. At a smaller scale, clothing coated with TiO_2 has been proposed as an approach to catalyse removal of methane from urban air[233].

TABLE 2

A summary of removal potentials and costs from the literature alongside technology readiness levels (TRLs) (either from the literature or expert assessment).

GGR method	Global CO_2 removal potential ($GtCO_2$ pa)	Cost per tCO_2 (US$)	Technology readiness level (TRL)
Increased biological uptake			
Afforestation, reforestation and forest management[234,235,236]	Afforestation/ reforestation 3 – 20 forest management 1 – 2	3 – 30	8 – 9
Wetland, peatland and coastal habitat restoration[237]	0.4 – 20	10 – 100	5 – 6
Soil carbon sequestration[238,239]	1 – 10	10 profit – 3 cost	8 – 9
Biochar[240,241,242]	2 – 5	0 – 200	3 – 6
Bioenergy with carbon capture and storage[243,244]	10	100 – 300	Bioenergy: 7 – 9 CCS: 4 – 7
Ocean fertilisation[245,246]	1 – 3	10 – 500	1 – 5
Building with biomass[247]	0.5 – 1	0	8 – 9
Natural inorganic reactions			
Enhanced terrestrial weathering[248,249]	0.5 – 4	50 – 500	1 – 5
Mineral carbonation[250]	–	50 – 300 (*ex situ*) 20 (*in situ*)	3 – 8
Ocean alkalinity[251,252]	40	70 - 200	2 – 4
Engineered removal			
Direct air capture[253,254,255]	0.5 – 5	200 – 600 (early stage) 100 (longer term)	4 – 7
Low-carbon concrete[256,257,258]	>0.1	50 – 300 (mineral carbonation)	6 – 7

There are 9 TRLs which describe the maturity of technology; TRL1 basic principles, TRL2 invention and research, TRL3 proof of concept, TRL4 bench scale research, TRL5 pilot scale, TRL6 large scale, TRL7 inactive commissioning, TRL8 active commissioning and TRL9 operations.

Note: These figures are typically developed with a range of different assumptions and predictions and so are not necessarily directly comparable. They represent technical potentials and may not take social aspects of deployment into consideration. Removal potentials demonstrate year on year removals, but for the GGR methods that saturate this does not continue indefinitely. Costs variably represent actual, predicted or targeted values. All are presented rounded to 1 significant figure to provide some guidance to order of magnitude expectations.

Chapter three

Cross-cutting issues

Left
Sky at dusk. © baona.

3.1 Introduction

The first part of this report considered individual GGR methods, but to meet the ambitious climate change targets set in the Paris Agreement, one method will not be sufficient and a suite of GGR methods will be required.

The following section, based largely on expert views of working group members and others consulted in writing this report, discusses a range of cross-cutting issues, which must be considered in implementing a suite of methods to maximise GGR potential while minimising adverse consequences.

These issues are grouped into seven categories: resources, storage, environment, science and technology, economics, legislation and social.

Image
Saltmarsh in Scotland.
© Kloeg008.

3.2 Resources

GGR is, in essence, the 'unmixing' of a greenhouse gas from the atmosphere. This process requires work, which is manifested in the use of resources such as energy, land, water, nutrients and geological storage. Even where GGR occurs 'naturally', as in photosynthesis in plants, significant resources are required to achieve appreciable additional sequestration levels, and to prevent carbon release once stored.

As a result, different GGR methods may be applicable in different geographies depending upon local circumstances and resource availability. Each resource that could be used for GGR may not then be used for other activities, for example farming, and so these issues should also be considered within a broader sustainable development context.

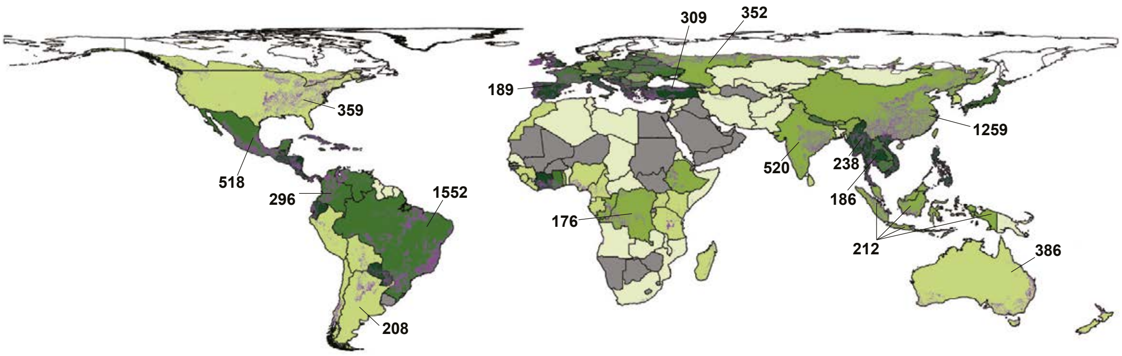
Multiple GGR methods often compete for the same resources. As such, the maximum removals of each technology cannot merely be added to give the maximum of the system. For example, BECCS and forestation may compete for land, nutrients and water, while BECCS and biochar may compete for biomass feedstock. Which method is deployed in each case will then depend on a number of the cross-cutting issues considered here.

Land

Many GGR methods have a significant requirement for land. In some cases, they can be co-deployed with each other or other activities (for example, enhanced weathering, soil carbon sequestration and food production), but in others they clash (for example, forestation and BECCS, which can compete with each other and with food production). At the upper end of estimates for land requirements for forestation, an equivalent to twice the world's currently cultivated land would be required. Reaching a cumulative removal of 810 $GtCO_2$ by forestation would require 2600 Mha of land globally (c. 100 times the land area of the UK), leading to predicted increase in food prices of about 80% by 2050 and a more than fourfold increase by 2100[259]. Land use is an important consideration in comparing BECCS and DACCS for example. BECCS requires significant land area, while DACCS has a negligible land footprint. However, to maximise the GGR potential of DACCS, the large energy requirements would need to be met by renewables, such as land-based wind or solar, where the land requirements could again become significant.

FIGURE 4

Distribution of potential GGR by reforestation by country.



KEY

🟪 Reforestation extent kgCO$_2$e ha^{-1} yr^{-1} ■ 0 🟩 1 – 211 🟩 212 – 758 🟩 759 –1,749

🟩 1,750 – 3,000 🟩 3,001 – 7,700 ☐ No mitigation (Boreal zone)

Source: From Griscom *et al.* 2017.

Raw materials

A major constraint on the implementation of many GGR methods is the availability of raw materials: BECCS and biochar require biomass feedstock; ocean alkalinity, mineral carbonation and enhanced terrestrial weathering require a supply of appropriate minerals.

In some cases these needs can be met through waste materials, however much present-day waste already has some economic use[260]. The benefits of waste utilisation will change as manufacturing processes evolve.

In cases where there are high levels of demand for raw materials, and in almost all scenarios for BECCS, virgin material is required. Mining of new minerals or growth of energy crops can put pressure on other systems. Generally, the natural distribution of material inputs, or land for crop growth may place geographical constraints on technology location. If there is a reliance on the import of materials, emissions from transport would be significant; so it is important to consider the whole life cycle of technologies.

Methods such as forestation, some soil carbon sequestration techniques, BECCS and ocean fertilisation have significant requirements for nitrogen or phosphate fertilisers[261,262]. If the net effect is an increase in global fertiliser demand, this will have knock on effects due not only to production emissions, but also on the cost of fertilisers and their use in other key industries, such as food production. Enhanced weathering, on the other hand, may have soil fertility benefits that could reduce the amount of fertiliser required for agricultural land[263].

Energy

Many GGR methods require energy in different parts of the life cycle. Where minerals are utilised, they first must be mined, crushed and refined (where relevant); distribution of materials across land or ocean requires fuel; and DACCS may require energy to drive fans or to provide the heat for regeneration of the capture medium. The emissions associated with energy generation must be factored into the life cycle consideration of each of the methods.

Methods with high energy requirements, such as DACCS, may become more viable as the energy system is decarbonised as their net GGR would be greater, though at large scale this could place significant additional burden on national energy demand. Similarly, while technologies such as biochar or BECCS can generate energy, they too will impact energy markets and may have unintended consequences.

Water

GGR methods that require the growth of biomass (forestry, BECCS, biochar), enhanced weathering and DACCS all place some requirement on water supplies. The most significant demand per tonne CO_2 removed is that of BECCS, which would require c. 5 km^3 water to remove 1 $GtCO_2$. When compared to total global renewable freshwater supply on land (110,000 km^3 pa) or current human usage (25,000 km^3 pa), it is clear that water availability should not provide a global constraint, but may do when considered within an individual location.

Trade-offs

The availability of resources may prove important in balancing other trade-offs of deployment of one method over another. For example, different forms of DACCS use different regeneration steps and technology could be selected depending upon the availability of water and low- or high-grade heat.

Trade-offs will also occur between resources, cost, social impact and other factors.
For example growing biomass in highly productive regions further from points of demand will reduce land requirements, but increase transport energy and costs. These considerations are best explored using system-wide life cycle models that account for resource requirements and constraints.

3.3 Storage

Once removed from the atmosphere, CO_2 must also be stored. Different GGR methods can be distinguished between those with built-in storage, for example forestation and soil carbon sequestration, and those that require a separate activity to store the CO_2, for example BECCS and DACCS (see Table 1).

For the former, the amount and longevity of CO_2 stored are determined by the nature of the method. Typically, these are time dependent and often require continued maintenance. For the methods with no inherent storage, the scale and longevity are dependent explicitly on a separate storage solution, such as CCS, building materials and mineral carbonation. These two groups are discussed below with respect to their storage potential and constraints.

GGR methods with built-in storage

Storage of carbon in the natural environment has the lowest permanence, can saturate beyond a certain point and is vulnerable to reversal. Forestation, soil carbon sequestration and habitat restoration, for example, use biological methods to increase the storage of carbon in the natural environment. All three reach a point of saturation on the order of 10 to 100 years, beyond which continued action is needed to ensure carbon remains stored. All three are vulnerable to reversal through human action (for example, deforestation), fire or disease. In the case of forestation, continued sequestration could be enabled by managed use of biomass (for buildings or in BECCS) and replanting.

Biochar and enhanced terrestrial weathering store carbon in soils in a (potentially) more stable form than soil organic matter and may take longer to reach saturation. Little is known about the longevity of carbon storage in soil biochar, although some work suggests it can persist on a centennial scale. Enhanced terrestrial weathering can store carbon for centuries to millennia. Significant precipitation of carbonate minerals in soil could reduce the storage potential, but this would be avoided if the products of enhanced weathering were transferred into the ocean.

Ocean alkalinity and fertilisation have the potential for large and almost indefinite storage of carbon in the ocean (the latter only if the carbon is transported to the deep ocean sediments), but neither has been tested in the field and significant uncertainty remains.

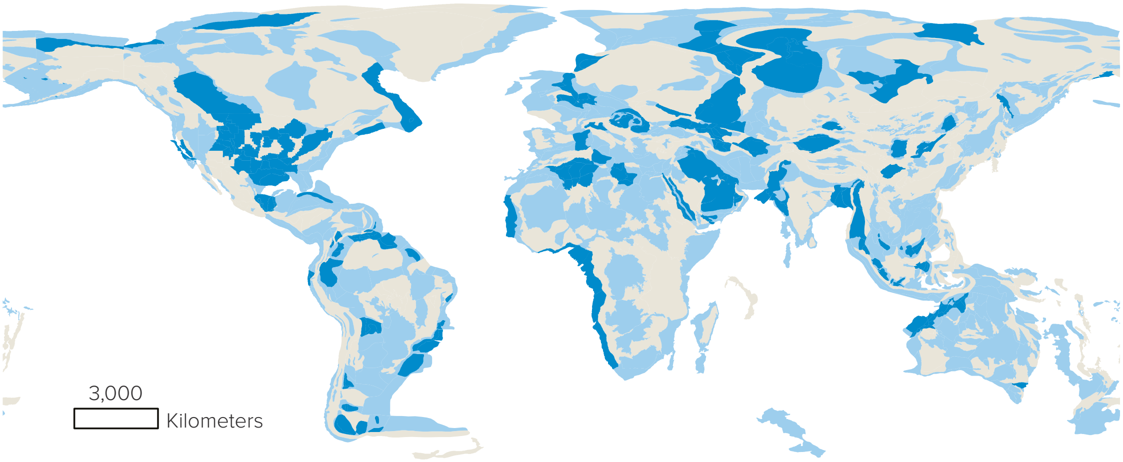
GGR methods without built-in storage

A number of GGR methods involve removal and storage as separate activities. The storage mechanism used plays a significant role in determining the cost, scale and permanence of the approach as a whole.

GGR methods which produce a pure, or nearly pure stream of CO_2 (BECCS, DACCS) require additional storage: in sub-surface sediments (as in conventional CCS), through mineral carbonation, as bicarbonate ion in the ocean, or potentially as CO_2 liquid in the deep ocean[264]. In a future world with CCS power generation could produce greater volumes of CO_2 than captured in GGR, and so may drive storage requirements.

FIGURE 5

Estimate of the geological storage potential of CO_2 for sedimentary basins of the world.



KEY

🟦 Highly prospective 🟦 Prospective ⬜ Non prospective

Source: Adapted from Bradshaw and Dance 2005 doi:10.1016/B978-008044704-9/50059-8

Sub-surface storage in sedimentary rocks is the most widely discussed option owing to previous experience by the oil and gas industry. For the UK, the total offshore storage potential related to depleted oil and gas fields is verified at 1 $GtCO_2$[265]. However, it is believed that the actual storage potential could be much greater, possibly around 20 $GtCO_2$[266]. The CO_2 could be stored in geological deposits for a very long time (millennia or longer). However, leakage remains a concern and can range from 0.00001% to 1%, depending on the permeability of the geological structure and its faults or defects[267]. The main constraints for deployment of this conventional storage route include storage efficiency, transport infrastructure, energy penalties and high costs.

Mineral carbonation of surface (*ex situ*) and subsurface (*in situ*) silicate rocks, such as basalt, is yet to be tested on a large scale, but the latter has been successfully demonstrated at small scale in Iceland. *Ex situ* carbonation is constrained by land requirement due to the need storage of the carbonated product, where such product is not put to secondary use. Carbonate minerals are stable and represent perhaps the most secure CO_2 storage option.

Reaction of CO_2 gas with limestone and disposal of the resulting products in the oceans may also be a viable and stable long-term store of captured CO_2 (see 2.10), though research into the stability and the environmental consequences is required, and there are substantial water requirements.

Right
Timber framed housing.
© fstop123.

Deep ocean storage of CO_2 as a liquid is a subject of ongoing research and is theoretically possible[268]. However, at present the UN Convention on the Law of the Sea (UNCLOS) prohibits direct disposal in the water column of the high seas (rather than in the sea bed or subsurface sediments). This storage route also has significant issues relating to environmental and societal concern.

Secondary storage

In some cases, the longevity of storage of CO_2 from GGR can be increased with the addition of an extra step. Most notably, with forestation, trees could be used as biomass for BECCS, or as building materials. In the latter case, carbon storage lifetime is increased by the lifetime of the buildings and wood products and could provide added benefit by avoiding emissions from production of steel or concrete. Reusing and recycling materials at end of a building's life would again increase the longevity of storage but this will be constrained by contamination from fire-proofing. Another option would be recovery of energy from these materials combined with CCS (like BECCS), although this would be difficult to achieve at scale. Full life cycle assessments will be required to determine the impacts of these activities.

3.4 Environment

Impacts on biodiversity

Many GGR methods have the potential to have significant impacts on biodiversity, especially when applied at scales necessary for meaningful removal. These will depend upon how and where deployment occurs but could be positive or neutral or detrimental to biodiversity. Soil carbon sequestration is likely to be beneficial or have neutral impact, BECCS is likely to have a negative impact and the impact of forestation will vary strongly with location. For BECCS in particular, the areas of highest potential bioenergy yield overlap significantly with current, and likely future, protected areas, signifying potential conflicts between biomass growth and biodiversity. Widespread implementation of BECCS would be expected to have a significant impact on biosphere integrity (see Figure 6).

Other greenhouse gases

As well as removing CO_2 from the atmosphere, a number of GGR technologies have either positive or negative effect on emissions of other greenhouse gases. Many of the technologies that involve the natural environment affect systems that are either sources or sinks for N_2O and methane. Where and how these changes take place will determine the broader impacts. For example, adding biochar to rice paddy soils sequesters CO_2 while significantly increasing methane emissions and decreasing N_2O emissions. Application to pasture systems shows the opposite effect (increased N_2O; decreased methane). Some other applications have no effect on release of these gases.

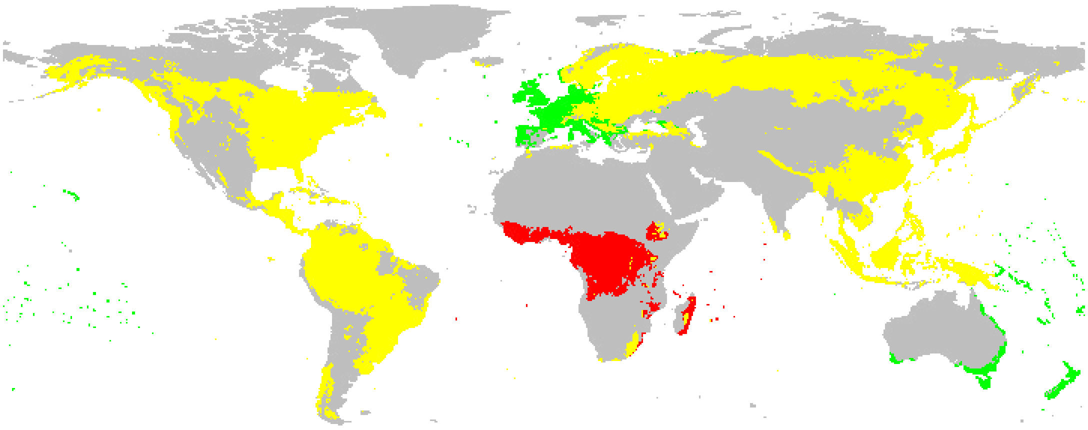
Accurate quantification of greenhouse gas fluxes over large areas is challenging and requires sophisticated soil and gas sampling. Full life cycle assessment of the impact of other greenhouse gases as a result of GGR has yet to completed.

Other pollutants

Many GGR methods release pollutants either directly through their application, or due to the raw materials, infrastructure and transport associated with their application. Enhanced weathering and ocean alkalinity both rely on adding minerals to the environment and, because these minerals are not pure, addition of impurities may release elements that are toxic into soil, surface waters, or the ocean. Production of raw materials also has potential for release of pollutants through, for example, mining of silicates for enhanced weathering, or chemical manufacture for DACCS. Transport is one of today’s largest pollution sources and is involved in nearly all GGR methods for movement of raw material and for distribution of materials or products. The environmental consequences of this increase in transport will need to be assessed, in addition to the additional emissions, to determine the overall effectiveness of each method.

FIGURE 6

Impact of biodiversity conservation for biomass production.



KEY

🟩 Below boundary (safe) 🟨 In zone of uncertainty (increasing risk) 🟥 Beyond zone of uncertainty (high risk)

Source: From Heck *et al* 2018.

Nutrient cycles

GGR approaches that alter biological systems on land or in the ocean will inevitably alter the cycles of nutrients, such as nitrate and phosphate (and, in the oceans, iron), often intentionally by addition of fertiliser, but also unintentionally. The environmental consequence of the changes in nutrient cycles that would result from large scale pursuit of GGR are not yet well understood, but could be widespread and profound, and need further study.

Other climate-related impacts

The implementation of some GGRs can have the effect of brightening or darkening the surface of the Earth, and therefore affecting how well sunlight is reflected or absorbed (albedo). The overall impact of each GGR method depends upon the initial state. If plants are grown on dark ground, for example, during restoration of wetlands or forestation in tropical areas, the effect of the relevant GGR may be increased reflectivity and reduced warming. Where the ground is darkened, as by the application of biochar to soils or agroforestry on snow-covered boreal land, reflectivity is reduced and would cause additional warming.

Application of GGR methods can also impact rainfall, surface roughness, and the efficiency of water flow onto the ground. As well as impacts on the wider environment, these effects can have a net warming or cooling effect.

3.5 Science and technology

Most proposed GGR methods require additional scientific and technological research and development (R&D) before they could be implemented at a significant scale. In some cases this requirement may be the issue limiting their application. The main areas of concern, and the methods affected, are discussed below.

Scientific and technological feasibility and effectiveness

For some methods, there remains significant uncertainty as to whether they would actually work in practice as intended, or be sufficiently effective at net removal of greenhouse gases. Addressing this issue may require anything from fundamental scientific investigations, through bench, pilot and demonstration scale development and testing. This is a particular concern for those methods in which the rates of the basic processes involved are not yet well-established under field conditions, notably, enhanced terrestrial weathering, ocean alkalinity addition, mineral carbonation and enhanced ocean productivity. For most other methods, further work is required to bring the technology to full operational readiness or optimise operating conditions.

Cost

For the technologies where costs remain high or uncertain, there needs to be dedicated work on cost estimation from demonstration-scale activities and further technological development to reduce costs. Uncertainty in costs often relates to uncertainty in the effectiveness of a method. Costs for most terrestrial biomass-based methods, and those involving the built environment, are likely to be lower, making cost-uncertainty less challenging for these methods.

Scalability

Methods, such as forestation and habitat restoration, are inherently constrained by the availability of suitable land and potential saturation of the storage capacity. R&D may be required to maximise scalability in these cases. In other cases, the potential scale is as yet uncertain and needs to be ascertained. There is a need for larger scale demonstrators to understand the actual potential for DACCS and the most effective mechanism for CO_2 capture. Present calculations for scalability of enhanced terrestrial weathering rely on the availability of waste materials rather than a robust understanding of the process *in situ*. Similarly, scalability evaluations of ocean alkalinity are based on poorly constrained assumptions about the response of ocean ecosystems.

Security and permanence of storage

GGR pathways that store carbon as impermanent organic materials with sub-centennial and uncertain lifetimes may prove ineffective without appropriate management. The lifetimes under practically achievable management regimes therefore need to be determined, and will be a major constraint on their utility, since long-term climate amelioration relies on removal of CO_2 for at least several centuries. This is of much less concern where the lifetime of the carbon storage is inherently long, as it is for ocean alkalinity and mineral carbonation. For most other methods, the lifetimes are expected to be adequate, but need to be more firmly established.

Verification and monitoring

Widespread deployment of GGR techniques will require monitoring, verification (and in some cases certification) of carbon removed. For some methods such as mineral carbonation and building with biomass, the carbon stored is a tangible product that is easily measured and does not require periodic monitoring. In others, where the product is an enhanced carbon content of an environmental reservoir (for example in soil or wetlands), establishing the amount of carbon removed and stored with the necessary precision, and verifying that it remains secure, will represent a major technological challenge. In some cases, this may even be a limiting constraint.

Environmental impacts

The environmental impacts, including those of scaling, will need to be determined for all GGR methods, though the level of uncertainty required varies. For ocean fertilisation in particular, where a major modification of an ecosystem is required to effect a small removal of CO_2, much improved ecosystem modelling capabilities would be required before deployment.

Right
Real time monitoring of ecosystem gas exchange over a land-use transition from grassland to Miscanthus bioenergy in mid-Wales. Ultrasound and near infra-red sensors being used in the eddy covariance technique to image wind structures moving across the canopy. These rotating eddy currents are the primary mechanism for the exchange of carbon and water between the land and atmosphere.
© Jon McCalmont.

3.6 Economics

Economic considerations relating to GGR methods range from the beneficial establishment and reinforcement of new technologies and markets, through to exacerbation of existing market failures and misallocation of resources. This section considers six economic factors that could have a material impact on the pace and scale of the deployment of GGR methods.

Carbon prices

Carbon prices are important for GGR because, if designed appropriately, they can provide an economic reward for both mitigation of emissions and for GGR. Carbon pricing has been spreading around the world, with most recent estimates suggesting that 15% of global emissions is now covered by some kind of explicit carbon price, established through taxation, cap and trade, or some combination of the two[269].

With some notable exceptions like Sweden and Finland, these carbon prices are much too low to incentivise the scale of emissions reduction implied by the Paris Agreement. The Stern-Stiglitz High-Level Commission on Carbon Prices suggested an appropriate range would be \$40 to \$80 per tCO_2 for 2020 and \$50 to \$100 per tCO_2 for 2030[270], and other work suggests that the social cost of carbon is already well over \$100 per tCO_2[271]. However, the vast majority of carbon prices today are well below that range. The UK carbon price floor stands at £18 per tCO_2 (c. \$25), for instance. The key carbon price in Europe – the European Allowance price under the EU Emissions Trading Scheme – has been around \$10 per tCO_2 for many years. Some prices in other countries are closer to \$1 per tCO_2. Prices vary between countries as a result of differences in public and political attitudes and policy approaches towards climate change.

Many GGR technologies could be economically profitable with carbon prices in the 2030 recommended range of \$50 to \$100 per tCO_2. At \$1 to \$10 per tCO_2, most are not profitable without other (non-price) interventions from government. While carbon prices remain heterogeneous and patchy, there is some evidence that they are spreading in coverage and that there is willingness from policymakers to gradually increase such prices over time[272].

While incentives are likely to be required for GGR, these could be provided either by public subsidy or the private sector. For instance, if a mandatory sequestration obligation were imposed upon all extractors of carbon, the costs of removal would be passed through the supply chain and borne ultimately by the users of fossil fuels and the shareholders of fossil fuel firms. If public subsidy is provided, it could either be provided from earmarked carbon tax revenues, or general revenue. While the former is often intuitively and politically appealing, finance ministries and treasuries tend to be opposed as the revenue generated from any particular tax does not necessarily logically map onto the appropriate level of spending in the same area. For example, as carbon emissions are reduced, the income from an emissions tax could drop, while GGR levels would need to be maintained or even raised.

Regulatory instruments

It should be noted, however, that carbon pricing is not the only possible government initiative to incentivise removals. Other mechanisms are a necessary part of the policy portfolio. These may be motivated by associated market failures or designed to complement carbon prices that are incomplete in coverage or at levels below the social optimum[273]. For instance, in the building sector, building regulation standards could permit or even encourage building with biomass or low-carbon concrete. In the energy sector, an obligation could be imposed upon companies extracting fossil fuels to sequester some proportion of the carbon extracted[274]. This could serve to ensure more level incentives at the margin for GGR and to pump-prime the CCS market, overcoming 'first of a kind' costs and investment hold-up problems.

Support for technological progress

Many of the GGR technologies under consideration still need to decrease in price, through additional research, economies of scale and learning by doing. Such processes take time and cost money. How society chooses to allocate its resources to supporting research, development and demonstration, can have a material impact on the pace and effectiveness of technology cost reductions. The 'Mission Innovation' agreement in Paris to double public spending on clean energy technologies could have a significant impact on cost reductions, but such resources should be spent wisely[275]. The UK and other countries remain committed to doubling spending, some of which will be directed to GGR-related technologies.

'Leakage' from GGR technologies

Efforts to deploy GGR technologies can be economically and environmentally counterproductive if spatial and temporal 'leakage' effects are not considered.

Spatial leakage describes situations where efforts to deliver a desirable economic outcome in one location result in an unintended and undesirable economic outcome in another location. For instance, indirect land-use change can involve spatial leakage – efforts to increase or protect forests in one location, without measures to meet demand for crops or ranching for meat, may push up crop and meat prices, increasing deforestation in another location. Spatial leakage effects of bioenergy on fuel prices are potentially large[276].

Temporal leakage occurs when efforts to remove greenhouse gases from the atmosphere only delay, rather than permanently solve, the problem at hand. This delay may nevertheless be valuable. For instance, building with biomass delays the return of CO_2 sequestered in the biomass to the atmosphere by the difference between the lifespan of the standing stock of forest and the lifespan of the harvested stock, plus the life of the biomass building product – which in some cases can be decades. This is a different effect to the displacement effect of building with biomass rather than with traditional cement, which reduces emissions now.

Social opportunity costs

The economic resources (traditionally known as the 'factors of production') required to create the goods and services required for a particular GGR method – physical resources, labour, capital and entrepreneurship – each have potential alternative uses. Some of these uses may be in different GGR pathways, other alternative uses are in the broader economy. Understanding the full social opportunity cost of developing GGR methods is important to delivering sensible outcomes. If the market-based prices of such resources are equal to the social costs, then this is not an issue of concern from an economic perspective.

Labour requirements and jobs – the labour and capital intensity of GGR methods can differ both between methods and over the lifetime of a GGR project. Methods, such as forestation and BECCS, have significant ongoing costs in the form of monitoring and verification requirements. The capacity of local labour markets and the ability and appetite of relevant financing systems to cover capital and operating requirements are relevant considerations. In areas where unemployment and job creation is a priority, approaches that have a higher labour-to-capital ratio may be politically preferable.

Supply-chain management – finally, the co-deployment of GGR methods may have significant effects on the distribution of economic profit over time within the whole system, as various elements of the supply chain are likely to become scarce at different points in time. For instance, at one point during the scale-up of offshore wind, there was such a scarcity of marine vessels able to take the structures to their intended location that supernormal profits accrued, increasing costs along the entire offshore wind supply chain. One could imagine similar effects with the scale-up of forestation, bioenergy plantations, and the use of biomass in buildings together. Periods of very high wood prices may occur, as shortages arise on the supply side, followed by potential of surplus wood leading to wood product prices falling, reducing income for smallholder producers. Achieving a relatively smooth coordination of scaling up activities across a long supply chain requires careful planning and investment.

Financing GGR

The financing need for GGR is likely to be very large, potentially cumulatively in the USD trillions by 2100. If capital markets are functioning correctly, GGR activities will be financed if they come with an attractive risk-adjusted return. This could be encouraged through the implementation of policies designed to reduce risk of investment for the private sector and provide appropriate returns through economic incentives. Given the short timeframe on which deployment is required, governments may choose to directly intervene in markets. This might alleviate the high costs associated with 'first of a kind' activities, while building experience in the sector and enabling any associated economic spillovers.

3.7 Legislation

Reporting within international frameworks

A constraint on delivery of GGR is the difficulty of monitoring its effectiveness in a transparent and consistent way.

Guidelines from the United Nations Framework Convention on Climate Change (UNFCCC) request that nations report greenhouse gas from human activity in national greenhouse gas inventories. National reporting is subject to an international review process to ensure credible measurement, reporting and verification of greenhouse gas flux, with guidelines developed by the IPCC. Guidelines for reporting of emissions were first applied to monitor greenhouse gas inventories following the Kyoto protocol in 1997, and have been refined continually since.

Reporting guidelines for removals of greenhouse gas are significantly less well developed than those for emissions. Most land-based GGR (forestation, wetland restoration, and soil carbon sequestration) is included in existing reporting, but other GGR methods are not. Reporting of GGR in the land sector is difficult and subject to high uncertainty because the land is simultaneously a source and sink of greenhouse gases due to both natural and anthropogenic processes that are hard to disentangle. Other issues include assuring additionality (proving the activity is additional to what was happening anyway), permanence (risk of future loss of stores due to natural disturbance or harvest), and indirect land use change (whereby an activity such as forestation on pasture land may displace the pasture activity elsewhere). Similar difficulties will be encountered in establishing appropriate reporting guidelines for other GGR methods. To be rigorous, these reporting guidelines will need to be based on the best available science, be specific to each GGR methodology, and include a level of detail comparable to those for other processes, such as agricultural emissions.

Reporting guidelines will also need to deal with long-term risks, including the permanence of storage. GGR methods have multiple risks that may differ in the short and long term (for example leakages and process reversals), so management of these risks on an extended timescale will be required.

Separation of emissions and removals in greenhouse gas reporting is important because the risks associated with emitting and then removing and storing CO_2 are not the same as if no emissions occurred at all and will vary depending upon the technologies employed. Additional difference will exist if different greenhouse gases are emitted and stored and, more generally, the uncertainties associated with reporting of both emissions and removals would need to be considered.

Although the Paris Agreement is not legally binding, a large and increasing number of countries have set in place national legislations that ensure their own commitments have legal structures. In the UK, the 2008 Climate Change Act provides a legal basis for the UK's emissions reductions and its contribution to international frameworks. In China, international commitments are integrated in their national five-year plans, which form the basis of much of China's socio-economic decisions. Increasingly formal legislative frameworks mean that there are procedures in place in case of litigation, at least at the national level, which enhances the chances of success for any climate actions, including GGR.

Sustainability, regulation and equity

The Paris Agreement includes specific recognition of the central role of sustainability and equity. The governance of GGRs is an issue of increasing focus, in particular where there is demand for large areas of land and resources and ensuring regulation of sustainability beyond the direct CO_2 removal is an important issue. For example, the sustainability of biomass production is critical for the successful application of BECCS. If biomass is produced in unsustainable ways, for example by cutting existing forests to produce wood pellets, then emissions created in production of that biomass may reduce or completely cancel CO_2 removal during subsequent production of energy and CCS. As the demand for biomass and timber for GGR grows, regulation of sustainability becomes an international challenge, with environmental standards and social safeguards, as well as emissions reporting standards, varying between the country that produces the biomass and the country that will import and benefit from it.

Equity in burden sharing for emission reductions is a highly debated and sensitive issue in the negotiations, along with financing. At present, the UK operates under the broad principle that its emissions should be no more than the global average per-capita emissions by 2050. However, the fair responsibility for GGR of the most developed nations could be considered to be higher, to compensate for historic emissions and for developing countries' limited capacity both economically and technologically. Such issues of equity are at the heart of the Talanoa Dialogue of the Paris Agreement, which will guide the 'Paris rule book' that will regulate the agreement in the future.

Verification and confrontation with Earth observations and expected pathways

Countries currently apply their own accounting rules in their nationally determined contributions (NDCs), which raises issues for transparency, comparability and credibility. National emissions and removals are not routinely independently verified, but this could be undertaken through earth system observations of atmospheric CO_2 concentrations[277] and tracking of progress with respect to expected pathways[278]. Effective reporting of GGRs may require implementation of this more rigorous regime. Independent verification by Earth observation is currently challenging, both for technical and governance reasons. Emissions reporting guidelines for land-based emissions and removals include both the deliberate emissions (e.g. deforestation) and natural carbon sinks from managed land, but do not include the physical location and limits of that managed land. Therefore, insufficient information is provided to compare reported emissions and removals with independent estimates from scientific understanding and data.

Tracking GGR with respect to expected pathways also requires that the protocols and practices for reporting GGR be revised in integrated assessment models. For example, for BECCS, at present models would account for the biomass energy emissions under 'agriculture, forestry and other land use', but the bioenergy is reported under process emissions, providing a fragmented picture of the real effect of BECCS, reflecting what happens in the UNFCCC reporting[279].

Improving NDCs

The Paris agreement includes a five-yearly assessment; the Global Stocktake. A key element of this Global Stocktake is to support more detailed and more ambitious NDCs, which are also to be revised every five years through a ratchet mechanism that will strengthen pledges through time. To support effective submissions of NDCs, and identification of appropriate additional activities, there needs to be information that is detailed and consistent enough on different mitigation activities, including GGR. This includes the effects of policies and measures on the outcomes, the management of co-benefits and risks, and the combined effectiveness of the GGR as global measures.

3.8 Social aspects

Social impacts on GGRs

Society, through organisations, interests and communities, relates to new technologies in complex ways. For example, it provides the expertise, finance and regulations that would make GGR possible, but it may also impose constraints on GGR development and deployment. Societal opposition, or insufficient social support could limit the deployment of technologies, but in cases where GGR development might conflict with other priorities and concerns, including the risk of deterring mitigation efforts, there is also a risk of too little social constraint[280]. This section focuses on public acceptance issues, and so touches on issues of ethics and governance but does not discuss these in great detail.

Society does not just plainly approve or disapprove each GGR method, but more subtly shapes the form of those methods. It influences where each GGR method can be deployed, how they can be designed, and what counts as good performance[281].

Furthermore, society responds not just to the technology as a material configuration, but the way prospective future technologies are thought and talked about has an impact in the present[282]. The existence of potential GGR methods for use in response to climate change can impact on policy, and there is ongoing debate about whether it will deter mitigation efforts. It is in this context that societal responses to GGRs and any resultant constraints should be considered.

Public perceptions and the role of policy

The perceptions of the general public matter for what is politically desirable and acceptable, although policies are substantially influenced by many other things, such as economic interests. Societal support for GGR is dependent on what deployment implies in terms of sustaining our fossil fuel dependence, incurring additional expenses and costs, and opening up new avenues for profitable investments[283]. In the case of CCS for fossil-fuel energy, the expectation of future technology deployment helped sustain climate policies that were dependent on that technology, but CCS has not yet reached (and may not reach) a sufficient level to justify these policies[284]. There is a risk that GGR is facing a similar future, entailing more talk than action, especially given the debate about whether it has been over-promised in climate modelling[285,286].

What influences public reaction to GGR?

Local communities may support or resist individual deployment projects on the basis of many different factors including their attachment to local landscapes, experience of the project-owning organisations, the decision-making process including any consultations, the distribution of benefits, costs and any compensation[287,288]. Location choice and design details matter, but so do ownership and governance models. In public deliberation exercises, topics of fairness and equity tend to arise repeatedly, with people reacting negatively to proposals that are perceived to entail unfair distribution of risks and benefits. Reactions are also dependent on levels of trust in the actors and processes involved. The controversy over genetically modified food may provide important lessons for GGRs, for example if people feel that solutions are being 'imposed' on them from above, or that solutions are being primarily driven by a profit motive. Public reactions will also be driven by the perceived compatibility of GGR with people's visions of how the world 'should' look in the future, which in turn will likely be correlated with people's underlying values[289,290].

Locating GGR projects

Some parts of the environmental system tend to be more sensitive than others to adverse public reactions, but no simple solutions emerge. National publics have shown reluctance towards geo-engineering technologies that intervene in complex natural systems[291], especially open systems (oceans, the atmosphere) as opposed to relatively closed systems, such as physically contained interventions in land surfaces and the subsurface. However, even within land-based systems, the risk of local communities raising concerns increases when interventions move closer to or beneath inhabited areas.

For wind energy, going offshore has unlocked deployment potential in the UK and it is tempting to see parallel opportunities for GGRs. DACCS is sometimes presented as flexible regarding location and possible to locate in areas with little existing land use[292]. However, caution is required in terms of thinking that places – both on and off shore, and both over and under the land surface – are empty. There are always (potential or actual) conflicting human uses and interests, as well as natural features deserving protection[293,294]. The selection of 'viable' locations is never a matter only of objective facts, but crucially depends on power relations among social actors. Similarly, whose land use is seen as most important, or who manages to represent natural features effectively, is a matter of who has influence. Poor populations in the developing countries may have other ideas about the use of 'marginal' land than agro-industrialists. Brownfield investments in deindustrialised areas may be popular for offering jobs, but may nevertheless constitute exploitation of marginalised parts of the population[295].

Secondary implications of GGRs

To understand the full implications of GGR requires consideration of the whole production chain, or socio-technical system. Society will react to the growing of biomass for BECCS, mining or quarrying of materials for enhanced weathering, and the demands for additional low- or zero-carbon energy for DACCS, or for mineral grinding, to storage of carbon in soils, oceans or geologic reservoirs. Experience with objections to gas pipelines[296], underground carbon storage[297], and both wind and nuclear power[298] illustrate these challenges well.

Aside from the specific production chains, society may also resist the implications of the general idea of GGR. The key lesson from recent public deliberations on energy systems was that the public would accept a coherent strategy for a low-carbon energy transition, but resisted technologies (like CCS) that appeared to prolong the underlying unsustainable approach[299]. Again, GGR would seem highly vulnerable to this, especially in the light of so called 'moral hazard' where the potential existence of GGR methods could deter mitigation.

Chapter four
Scenarios

Left
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4.1 GGR pathway building

Two example scenarios have been developed to examine how individual GGR methods and cross-cutting issues might apply in the practice of meeting real-world targets. There are too many variables and uncertainties for these to provide absolute solutions, However they present plausible, though not necessarily optimal or desirable, future worlds in which ambitious efforts are made to limit climate change using GGR.

The UK scenario for 2050 is intended to provide one example of actions that could be taken by a single nation. The global scenario for the whole century is then presented to demonstrate how GGR might be used internationally to meet the overall goals of the Paris Agreement.

Left
Rendering of Carbon Engineering's air contactor design. This unit would be one of several that would collectively capture 1 $MtCO_2$ pa. © Carbon Engineering Ltd.

4.2 UK scenario – annual GGR of 130 $MtCO_2$ in 2050

About the scenario

The Climate Change Act commits the UK to an 80% reduction in emissions by the year 2050 relative to 1990 levels. This requires reduction of net emissions to 160 $MtCO_2$ per year in 2050.

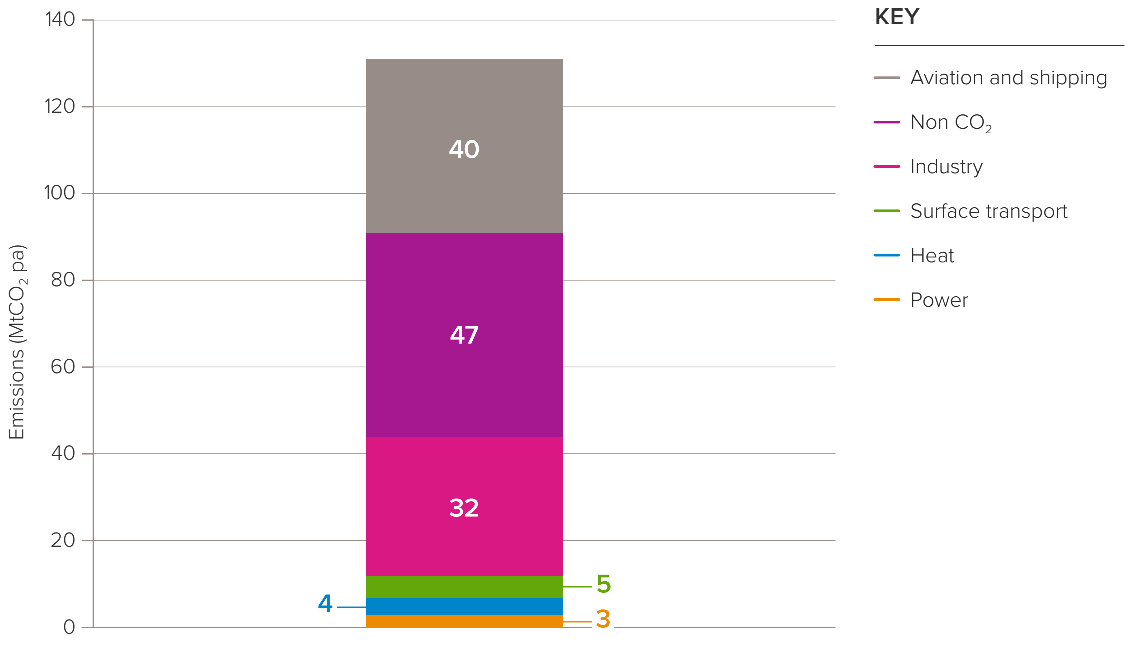
The Committee on Climate Change, the independent UK body that advises the government on emissions, considers that maximising the feasible opportunities to decarbonise across energy, heating, transport, industry, and agriculture sectors with currently known or anticipated technologies could reduce annual UK emissions slightly further than 80% by 2050, but not to lower than 130 $MtCO_2$ pa (Figure 7).

The Clean Growth Strategy, published by the UK government in October 2017, recognises the need to legislate for a net-zero UK target in the second half of the century to meet the obligation of the Paris Agreement.

Sitting alongside the Climate Change Act and the UK's ambition to play a leading role in this field, this report builds a scenario around the ambition of achieving net-zero greenhouse gas emissions by 2050. This is not the only possible target, but it is one method by which the UK could go beyond the 2°C goal and contribute to meeting the 1.5°C aspiration.

FIGURE 7

Residual GGR emissions in 2050 with maximum reductions to emissions in all sectors.



Source: Committee on Climate Change 2016 UK climate action following the Paris Agreement report.

A scenario is presented below that deploys a range of GGR methods together to counterbalance the 130 $MtCO_2$ pa emissions remaining after ambitious UK decarbonation[300]. This is not the only scenario that could meet the target, but is considered a plausible, albeit highly challenging, route to net-zero emissions. This scenario is based on the combined expert view of the working group and the wide range of advisors to this report, informed by the literature summarised earlier, a stakeholder workshop held to inform this work and our knowledge of current research.

The scenario meets the target of 130 $MtCO_2$ by 2050 by action in the UK only. It allows for import of resources, but does not consider international purchase of carbon credits or direct payment for action in other countries. It might in future become possible and sensible for the UK to pay for GGR to be done where it is most cost effective, or where there are the required resources. This international market does not yet exist, but could provide an additional approach to help meet the UK GGR target, although related issues of ethics, equity, sustainability and monitoring would arise.

Summary of findings from the UK scenario:

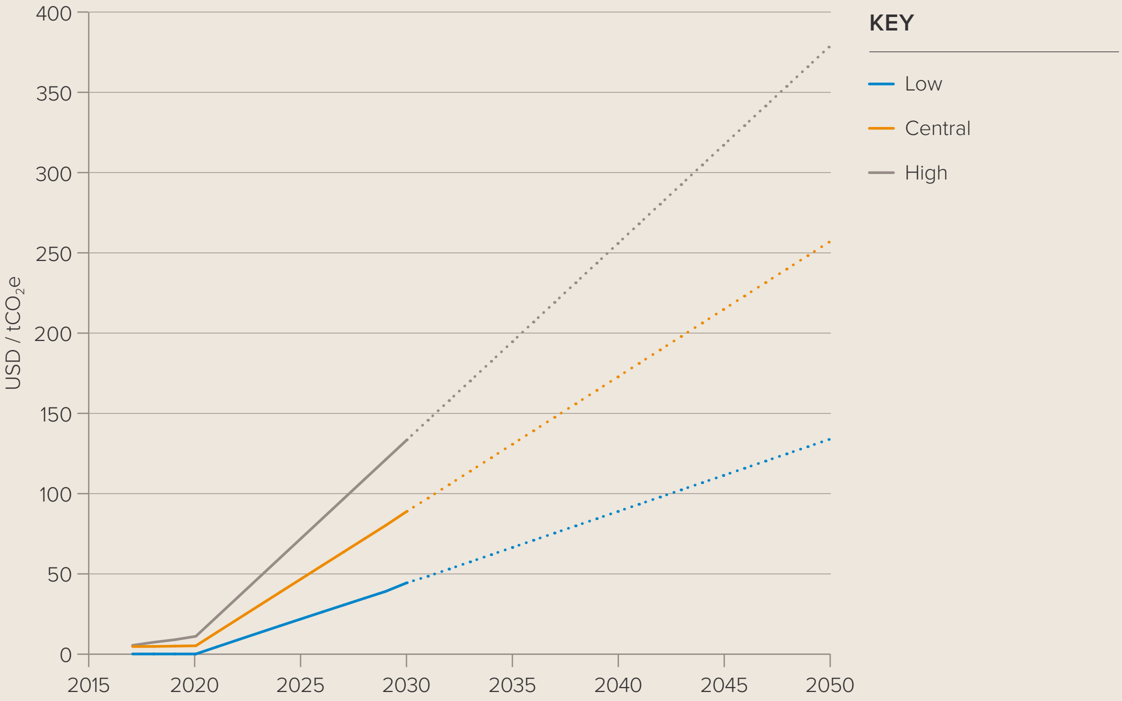
- GGR at a scale of 130 $MtCO_2$ pa is very challenging and costly. It is likely to be achievable in the UK, but only with substantial use of CCS with bioenergy and DACCS and with many methods deployed at the limit of their maximum deployment.
- GGR is not an alternative to very substantial emissions reductions across the economy. The GGR target already assumes an ambitious reduction in UK emissions and without these measures the target of net-zero is unlikely to be achievable by 2050.
- A suite of GGR methods would be required.
    - Some are well-established and others require further research, but show considerable promise.
    - Several land-based GGR pathways can be put into action now. However, many of these methods will need continued maintenance and need to be replaced by alternative methods in the longer term.
    - BECCS and DACCS will be required in addition to application of these land-based approaches (and especially beyond 2050 when the sinks resulting from the biological methods have saturated).
    - Ocean pathways are unlikely to be feasible in this timeframe.
    - The scenario considers stretching targets for each of the GGR methods, but where these can be sustainably exceeded they should be. This will provide robustness if some methods prove infeasible or socially undesirable, and the flexibility to favour methods that prove more effective or less expensive.

- BECCS and DACCS have different advantages and disadvantages:
    - BECCS provides energy co-benefits and has the potential to be cheaper but requires both the import of biomass and land-use change.
    - DACCS limits change in land use and has (potentially) low environmental impact but to be effective it requires decarbonised energy and the development of more expensive technology.
    - Both require large scale storage and other complementary CO_2 transport infrastructure.
    - Development of bioenergy could be ramped up without CCS to enable removals with BECCS as CCS becomes available in the longer term.
- Additional research, development and deployment demonstration is required for most GGR techniques.
- Pilot projects and larger scale demonstration projects are of particular importance to demonstrate the application and impact of GGR at moderate scale.
- Improvements in monitoring and verification of CO_2 uptake and storage, and of sustainability over the life cycle arealso critical.
- Research is required on how public understanding will limit, shape and drive GGR methods.
- As the UK is a relatively small and densely populated area, it could benefit from the opportunity to act in an international market to pursue GGR approaches where they can be pursued more readily and cost-effectively.
- An anticipated carbon price of $100 per tCO_2 by 2050 could make many GGR pathways economically viable.
- To achieve the levels of GGR required in this scenario requires significant action, starting now.

CARBON PRICING IN THE UK

One economic enabler to bring these GGR methods to market would be a credit for removal and storage of carbon from the atmosphere. The future of carbon prices in the UK is unclear, but analysis suggests that by 2050 they may reach above $100 per tCO_2. This would enable many of these methods if the prices were also applied to CO_2 removal, which is not currently the case. At present, the UK carbon price is set through a combination of a carbon price floor (£18 c. $25 per tonne) and the European Union Emissions Trading System (EU ETS); continuation of the price floor and the UK participation in the EU ETS are not presently clear beyond 2020. Government guidance for policy assessment indicates that carbon values will rise to between £40 and £120 [2017 GBP] by 2030 ($55 and $170)[301] setting a trend which would lead to prices between £120 and £340 ($170 and $470) in 2050.

UK Department for Business, Energy, and Industrial Strategy short-term assessment of future carbon values for policy appraisal (up to 2030) and extended trends. Values converted from real 2017 GBP (1 GBP=1.4 USD).



Source: Updated short-term traded carbon values, January 2018, Department for Business Energy and Industrial Strategy.

GGR pathways to reach the UK target

The GGR methods described in Part 1 are grouped into four categories to meet the UK target of removing 130 $MtCO_2$ pa by 2050:

1. Methods ready for deployment.
2. Methods yet to be demonstrated at scale.
3. Methods requiring CCS.
4. Methods not expected to be feasible in the UK by 2050.

*The numbers stated are based on expert judgement for this single plausible scenario.

1. Methods ready for deployment

(GGR methods already pursued to some extent)

Total removal by 2050: 35 $MtCO_2$ pa

Forestation, habitat restoration, soil carbon sequestration, and building materials represent currently available GGR methods that together could provide almost one quarter of the target GGR for the UK to reach net-zero emissions. They would provide an extremely valuable contribution, and one that can be achieved comparatively easily, for a relatively low cost and with some co-benefits. Given that these four methods exploit already established activity, they could be ramped up rapidly from now. Regulation could incentivise changing land use and management practices with GGR benefits in mind, for example in a reformed (or in the UK replaced) Common Agricultural Policy. Many of these methods have some uncertainty involved so it would be important to plan for more to ensure that the desired target can be met, and to measure and monitor efficacy of each approach.

Forestation, habitat restoration and soil carbon sequestration are already included to some extent in existing international emissions reporting. Current UK government policy does not set expected levels to 2050, but the scale of GGR suggested for these three methods would represent a marked increase compared to activity expected in present plans.

i. Forestation: 15 $MtCO_2$ pa

To reach this ambitious target, a high degree of forestation is utilised on 1.2 Mha of land – adding to the total current UK woodland area of 3.2 Mha. This is equivalent to 5% of all UK land, or 80% of 'available land' (see box, Land use in the UK). The UK Northern Forest, planned to cover 0.1 Mha, is expected to sequester only one hundredth of this amount of CO_2 annually, although its present planning is not optimising carbon removal and involves relatively small uptake per hectare. Nevertheless, this comparison gives a sense of the challenge of realising 15 $MtCO_2$ pa, both in the land area required and the need for explicit focus on CO_2 uptake over other benefits.

This large-scale deployment is driven by the low cost of this route to GGR and by a number of co-benefits that come from the resulting woodland, including economic benefits from commercial forestry. These benefits include production of wood for building and as a biofuel, each with alternate GGR potential. Forests take approximately 10 years to ramp-up their maximum sequestration rate and reach maturity (when they no longer take up additional carbon) after 20 to 100 years. This carbon would then need to be protected, or could be harvested for long-lived wood product storage or energy/BECCS, enabling regrowth and continuous use of forests for mitigation.

ii. Habitat restoration: less than 5 $MtCO_2$ pa

Restoration of UK wetlands and peatlands holds promise for some GGR and is expected to boost biodiversity and other ecosystem functions. The UK contains around 0.8 Mha of freshwater wetland, c. 0.05 Mha of saltmarsh and 2.7 Mha of peatland. A substantial proportion of these is degraded, with 80% of UK peatland in poor condition and two thirds not yet covered by restoration schemes.

Taking moderate estimates of restoration potentials for all UK saltwater and freshwater wetlands would bring GGR of around 2 $MtCO_2$ pa and restoring 1 Mha peatland would bring a further 1 $MtCO_2$ of GGR pa, as well as reducing future emissions of CO_2. The estimates of GGR from freshwater wetland restoration in particular vary substantially (0.4 – 18 tCO_2 per ha pa) and so realised removals may be somewhat lower or substantially higher. Furthermore, in undertaking this restoration activity the impact of future sea level rise would need to be considered in coastal management plans, and the impact of methane flux from restored peatland factored into overall climate benefit.

iii. Soil carbon sequestration: 10 $MtCO_2$ pa

Many of the techniques that would lead to soil carbon sequestration are already deployed on some UK farmland or close to current practice. Various established techniques can be implemented on both arable and pasture land, the exact combination of which will determine the impact on land efficiency and crop yield. On pasture this could involve changes to vegetation and livestock management, and on arable land changes to crop, nutrient and water management. In the UK specifically, spreading of organic material (manure) is unlikely to play a significant additional role as 95% of available material is currently utilised, though addition of other organic amendments (compost, sludge) could play a small role.

This estimate suggests that additional soil carbon sequestration practices are deployed to 4.5 Mha, three-quarters of current arable land, and the proportion of pasture land not set aside as 'available'. In the UK specifically, payment and reporting could be enabled through changes to agricultural or land management subsidies. After as little as a decade or two, soils would approach a new, higher, equilibrium carbon concentration and reach saturation. By, or not long after, 2050 it is possible that many areas undergoing soil carbon sequestration will have reached this stage and would require maintenance to prevent reversal. Retaining this amount of GGR beyond that point would then need additional capacity from another method, for example DACCS.

iv. Building materials: 5 $MtCO_2$ pa

Building with biomass/wood could provide GGR in the region of 4 $MtCO_2$ pa, with the addition of c. 1 $MtCO_2$ from modified concrete. Both materials offer the additional benefits of reducing the use of carbon intensive materials and providing a longer-term storage option for carbon capture processes for a relatively low cost.

Reaching 4 $MtCO_2$ pa would be the equivalent to building 200,000 three-bed, timber framed houses each year (compared to 220,000 new houses built across the UK annually at present), although in practice other building types could account for a portion of the 4 $MtCO_2$ pa. The sustainable harvesting of this wood would allow additional trees to be grown without increasing forest land footprint, increases permanence of storage, and allows additional removal through new growth.

Despite progress in use of faster growing soft woods, it will take decades for forests to be grown specifically for this purpose and will require planting of additional UK forest or importing of biomass at scale. Under the UNFCCC/IPCC approach to estimating greenhouse gas flux, land sinks, including harvested wood products, are reported in the country of origin. While building with imported biomass would reduce requirements for other building materials (and their associated emissions), it would not necessarily provide negative emissions for the UK.

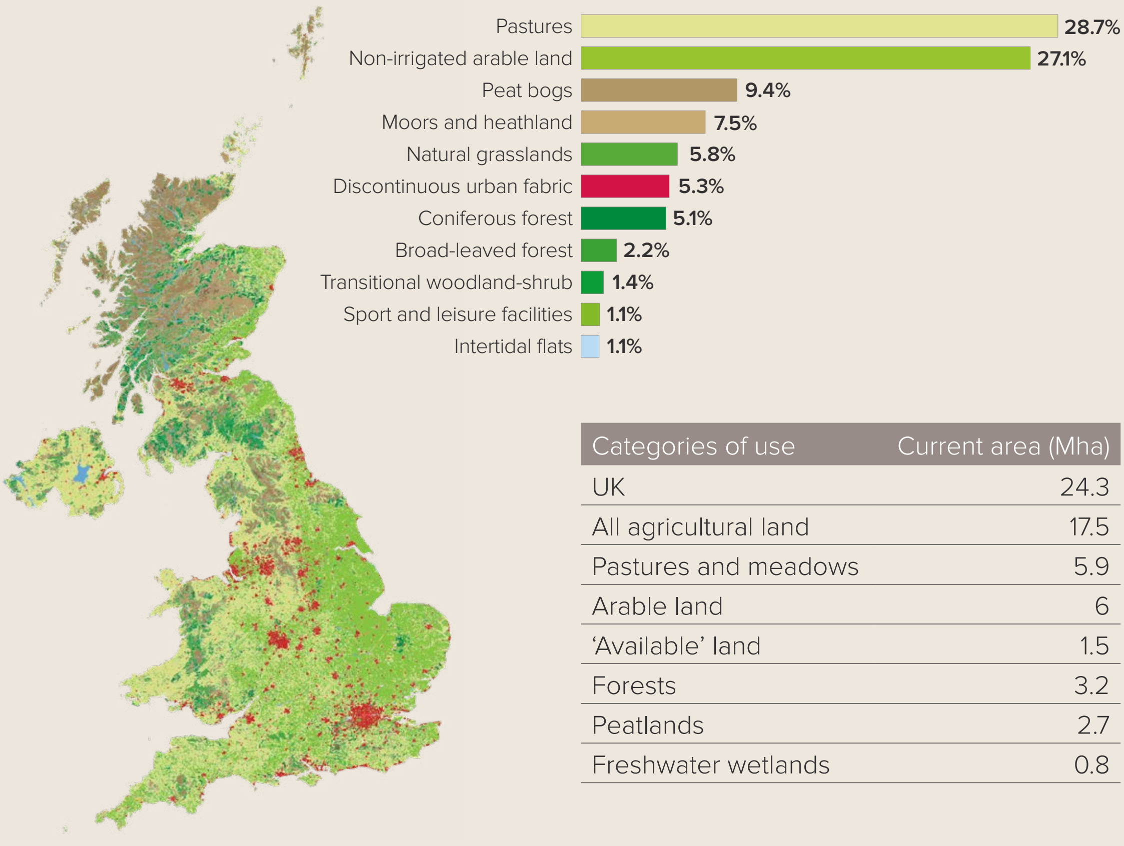
Modification of concrete manufacture used for building may also have potential for GGR. The use of existing stocks of waste minerals to make aggregates has potential to be net negative, with relatively small CO_2 uptake potential (<1 MtCO_2 pa). If developed, new technology that captures CO_2 emitted from the decomposition of limestone would reduce primary emissions of CO_2 and may also allow small amounts of additional GGR through CO_2-curing of pre-built concrete products or end-of-life mineral carbonation of concrete.

Land use in the UK

Many of the methods to be deployed in the UK involve the use of land, which is a limited resource. To define the available land, large areas of the UK must be excluded, based on current use and natural characteristics. National parks, National Scenic Areas and Areas of Outstanding National Beauty are typically restricted. Furthermore, much of UK land is currently used for pastures and subsidised in some form through the EU's Common Agricultural Policy (CAP), although this may change after Brexit. The remaining area is largely made up of agricultural land (Graded 1 to 3), required for food production. Lovett *et al*. estimate there is 1.5 Mha of available, poorer quality or non-agricultural land that could be used for GGR[302].

FIGURE 8

UK land cover as determined by satellite imaging.



Categories of use	Current area (Mha)
UK	24.3
All agricultural land	17.5
Pastures and meadows	5.9
Arable land	6
'Available' land	1.5
Forests	3.2
Peatlands	2.7
Freshwater wetlands	0.8

In assessing land availability for energy crops in the Great Britain, Lovett *et al*. overlay seven constraints: natural and semi natural habitats, slope > 15%, high organic carbon soils, urban areas, roads, rivers and lakes, designated areas, existing woodland and cultural heritage sites.

Copyright rests with the European Commission; Acknowledgement: Produced by the University of Leicester, The Centre for Landscape and Climate Research and Specto Natura and supported by Defra and the European Environment Agency under Grant Agreement 3541/B2012/R0-GIO/EEA.55055 with funding by the European Union.

The scenarios developed in this section account for key known interactions. In some cases, GGR methods can be co-deployed (Table 3) and are additive (for example enhanced weathering with BECCS crop growth), while in others they may not be additive (for example the application of biochar and soil carbon sequestration); however, many of these interactions are not fully understood.

Furthermore, land availability will be affected by a number of future trends not explicitly considered here. Predicted UK population growth of almost 20% by 2050 will increase competition for land with rising demand for food and homes. Decarbonisation of the energy system may require more land for solar fields and wind farms. In contrast, major lifestyle changes, such as an increasingly urban population, or reduction of meat consumption could make more land available. Additionally, technology development to improve crop yields could allow more biomass or food to be produced on less land.

TABLE 3

The division of land primarily for the growth of biomass and the complementary GGR methods that can be deployed on different proportions of the same land.

	Land (Mha)	Primary Uses (Mha)		Complementary methods (Mha)	
‘Available’ land	1.5	Forest	1.2	Enhanced weathering	1.2
		Biomass for BECCS	0.3	Soil carbon sequestration	0.3
				Enhanced weathering	0.3
Arable land	6	Biomass for BECCS	0.7	Soil carbon sequestration	4.5
		Biomass for biochar	0.1	Biochar	1.5
				Enhanced weathering	6
				Total	
				Soil carbon sequestration	**4.8**
				Biochar	**1.5**
				Enhanced weathering	**7.5**

2. Methods yet to be demonstrated at scale

(GGR methods with potential contributions to the target not yet deployed)

Total GGR by 2050: 20 $MtCO_2$ pa

The two methods of biochar and enhanced terrestrial weathering, offer potential for large scale GGR but are yet to be demonstrated at that scale. They could become contributors to UK GGR targets before 2050 and continue to contribute in the second half of the century. They involve spreading of materials across land, often with broader consequences than CO_2 removal, including potential addition of undesirable substances, such as metals from minerals or tar from pyrolysis of biochar. Understanding these impacts, and what regulation needs to be developed around them, will be an important step in the delivery of these pathways.

i. Biochar – 5 $MtCO_2$ pa

Biochar provides the option for storing carbon in soils in a more stable form than achieved through soil carbon sequestration methods. This pathway requires biomass for production of biochar and land to spread it on. Both biochar and soil carbon sequestration are compatible with arable land but cannot be deployed on the same land so this scenario splits arable land use between the two. To remove 5 $MtCO_2$ pa would require the deployment of biochar to a quarter of the 6 Mha of UK arable land. If biochar was ready for deployment now this could also be applied with forestation to maximise the land availability.

The production of biochar to remove 5 $MtCO_2$ pa would require 0.1 Mha of land for perennial energy crops, assuming an even split between the use of residues and specifically grown crops. In a scenario with operational BECCS, biochar and BECCS will be in competition for biomass, and biochar may only be applicable where co-benefits are significant. There remains uncertainty around the consequences and co-benefits of biochar application on UK soils, which would need to be clarified before widespread application. However, if proven, biochar has the benefit of being deployable on a more local scale and not requiring CO_2 transport and storage infrastructure.

ii. Enhanced terrestrial weathering – 15 $MtCO_2$ pa

Enhanced weathering of silicates in agricultural soil is at a relatively low-level of technology readiness, but existing research suggests it has the potential to be a contributor to UK GGR by 2050, and to have further potential into the second half on the century. Estimates of potential for enhanced weathering rely mostly on the availability of mineral resource and existing knowledge of weathering rates. Models suggest that spreading of silicates at 20 t per ha pa over 5.4 Mha of arable land could achieve the 15 $MtCO_2$ pa, although it may prove more efficient to increase the mass per ha and apply to less land-area. Approximately two thirds of this annual mass of silicate might be provided by waste material from industries (cement, steel, etc) assuming it is not contaminated, but the remaining third would have to be mined specifically.

The environmental and agricultural implications of enhanced weathering at scale are not well known and will require research, particularly during pilot demonstrations in the field (including monitoring of changes in soil chemistry, biological productivity, and assessment of the fate of removed CO_2). Combining enhanced weathering with soil carbon sequestration or biochar is likely to be possible on the same land, though positive and negative interactions may alter efficiency and will need assessment. Enhanced weathering is unlikely to be cost-effective as a GGR approach on land that is not farmed. As with these other forms of GGR on farmland, there may be co-benefits, such as increased productivity and soil improvement, to incentivise uptake by farmers, but it is likely that financial incentives will also be required to see enhanced weathering effective at large scale.

3. Methods requiring CCS:
Total GGR by 2050: 75 $MtCO_2$ pa

GGR methods described in the previous two sections have built in storage of carbon, but together can provide less than half of the target 130 $MtCO_2$ pa required for the UK to reach net-zero emissions. An additional 75 $MtCO_2$ pa would need to be delivered by two approaches requiring dedicated long-term storage of CO_2: BECCS and DACCS. Crucially, meeting the UK target, therefore, depends on rapid development of the carbon transportation and storage infrastructure required for CCS. The UK has access to substantial sub-surface reservoirs such as depleted oil and gas fields and saline aquifers in the North Sea providing sufficient capacity for the required carbon storage if the infrastructure is developed. Neither BECCS nor DACCS have yet been demonstrated to operate at a large scale.

i. BECCS – 50 $MtCO_2$

The UK is likely to be a net importer of biomass for energy, alongside using domestic biomass resources. If UK demand for bioenergy grows, it is likely that this net balance of imports will continue. More than half the biomass used in the existing DRAX power station is imported, on which basis this scenario assumes 50% of BECCS biomass is imported (sufficient for 25 $MtCO_2$ GGR pa). This assumption requires that the carbon-credit for BECCS resides in the country sequestering the carbon, not the country where biomass is grown (which is the current basis of international reporting). BECCS of 10 $MtCO_2$ pa could be supported from UK bio-waste, two thirds from waste straw and one third from forest trimmings from mature forests, though use of these residues would preclude their use for increasing soil carbon stocks. Growth of perennial energy crops on c. 1 Mha of land would provide BECCS of another 15 Mt CO_2 pa, using conservative estimates of productivity. Some of this required land area could come from 'available land' (defined in land use section above), but biofuel cannot be grown on the same land as new forests.

The large area assigned to forestation in this scenario therefore requires that more than half of the energy crop is produced on existing farmland. It is likely that this could be achieved without decreasing food supply, given present areas of farmland set-aside[g].

This level of BECCS could produce 0.2 EJ (50 TWh) pa of electricity, 14% of the UK's current electricity generation. This is approximately the equivalent to three coal fired power stations converted to run at full biomass capacity (and with the CCS capacity to capture and store the resulting CO_2).

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[g] All BECCS here has been considered to be land-based but deployment with an ocean-based feedstock could provide an alternative if shown to be viable under UK conditions.

ii. DACCS – 25 $MtCO_2$ pa

If all the methods above are pursued to their maximum potential, an additional 25 $MtCO_2$ pa GGR is still required to meet the target. This would have to be met by substantial application of DACCS, which is a technological challenge. DACCS has been demonstrated at small scale (50 tCO_2 pa) but is yet to be proven at large scale. Development of the required infrastructure would, however, have long-term benefit in providing GGR into the second half of the century, as the biological methods reach saturation.

Current estimates suggest a high carbon price will be required to make DACCS feasible, but this is likely to reduce as demonstrators are developed and the process is optimised. The energy requirements of DACCS necessitate a low-carbon source of energy for maximum carbon efficiency. If removal and storage are undertaken at 10 times the theoretical minimum energy requirement, and unless 'waste' or stranded energy can be utilised, this level of removal would suggest an additional requirement for 0.2 to 0.4 EJ (50 to 100 TWh) pa, the equivalent to the energy generated from BECCS capturing 50 $MtCO_2$. At present, despite substantial expertise in chemical engineering and industrial fluid handling, the UK does not have significant research presence in the field of DACCS and so, without rapid R&D investment, would likely rely on this technology being developed elsewhere.

4. Methods not expected to be feasible in the UK by 2050

The following GGR methods, outlined earlier, have barriers which make them unlikely to be used for substantial GGR in the UK by 2050:

Mineral carbonation

This remains an immature technology. While *in situ* carbonation has been successfully demonstrated in basalts below Iceland, this approach relies on suitable silicate rock in unprotected areas. No such location has been identified or scoped in the UK. *Ex situ* carbonation in the lab or field has yet to be demonstrated at low cost or large scale. Both forms of carbonation have potential for longer-term application as technologies develop and may become part of the applied GGR portfolio in the second half of the century.

Ocean alkalinity

Intentional increase of alkalinity of the oceans at large scale has not yet been demonstrated in the field. Uncertainties remain about the possible reversibility of some of the GGR due to carbonate precipitation, and about the environmental implications at the point of addition. There is also a public mistrust of technologies that manipulate the oceans. Although this approach may prove viable and become useful in the second half of the century, it is unlikely to be employed at scale before 2050. Indirect ocean alkalinity may result on this timeframe as a result of run-off from land of the products (alkalinity and associated carbon) of enhanced-terrestrial weathering. Small scale direct increase of alkalinity may also be pursued to mitigate against ocean acidity in vulnerable ecosystems, such as coral reefs.

Ocean fertilisation

Current research suggests that ocean fertilisation is unlikely to be effective for GGR purposes. While the process could in theory operate to sequester CO_2, questions remain about the efficiency of net downward carbon flux that can be achieved, and there are substantial environmental risks. As with ocean alkalinity, public perception is also likely to be unfavourable to this ocean-based technology. It is not anticipated that ocean fertilisation will prove useful in meeting the UK target.

Both ocean-based methods also face legislative barriers, since international legislation (the London Convention and Protocol) forbids ‘dumping’ of materials into the ocean and this explicitly includes ocean fertilisation, excepting that for research purposes.

Key actions for UK net-zero

- Pursue rapid ramp-up of forestation, habitat restoration, and soil carbon sequestration, across large UK land-areas.
- Establish an incentive or subsidy system to encourage changes of land practice, particularly for soil carbon sequestration. This could form part of the framework put in place to replace the EU Common Agricultural Policy.
- Encourage changes in building practice to use wood and concrete manufactured with carbonated waste (while recognising overall limited potential for GGR of these approaches).
- Develop monitoring and verification procedures and programmes to track the effectiveness of GGR delivered by each method.
- Grow and import sustainable biomass at large scale to meet the need for both energy and GGR demands.
- Pursue research into the GGR potential of enhanced weathering and biochar in UK agricultural soils, and into BECCS and DACCS for longer term deployment. This should include assessment of the co-benefits, social and environmental risks, monitoring and evaluation, and include field-based pilot demonstrations.
- Capitalise on UK access to suitable reservoirs for CCS and relevant engineering and industry expertise to establish substantial infrastructure for transport and storage of CO_2.

4.3 Global scenario – 810 $GtCO_2$ by 2100

About the scenario

It is not yet clear whether it will be possible to keep global mean surface temperature rise to the Paris Agreement's ambition of no more than 1.5°C above pre-industrial levels. Following the Agreement, a significant body of work has been dedicated to understanding how this target can be met. One method of doing so involves the use of integrated assessment models to assess viable socio-economic scenarios for future energy and carbon use. All integrated assessment models scenarios that keep warming below 1.5°C require large-scale deployment of GGR methods. By 2100, the median of projected cumulative removals is 810 $GtCO_2$[h,303] and this value is taken here as the global target.

The use of a cumulative target for the end of the century contrasts with the earlier UK annual 2050 target. This allows explicit consideration of the saturation of natural carbon sinks, which is likely on this extended timescale, and of the development of further technologies.

Summary of findings from the global scenario

- With concerted international action, the target of 810 $GtCO_2$ cumulative emissions by 2100 could be achieved.
- At a global scale, there is significant scope for land-based biological GGR.
  - This comes with the vulnerability to reversal associated with natural storage, with continued maintenance required to prevent such reversal.
  - Most biology-based approaches would reach saturation before 2100. Sustainable usage of biomass (forests for building, BECCS) would, however, enable renewal through new growth.
- Location of technology and co-location with other activities will be important considerations for feasibility.
- Trading schemes would enable action to be taken in the most effective locations.
- Biological storage used near maximum capability might enable this target to be reached without CCS. However, the large land requirements and saturation of biological stores make it very likely that BECCS and DACCS be needed by 2100.
- Monitoring for effectiveness and sustainability will be required at scale.
- On this timescale, new technologies may be developed, but they are not relied upon in this scenario.

For this global scenario, which considers cumulative GGR over the whole century, GGR methods are grouped into two: those that become saturated during this timeframe and those that do not. As in the UK scenario, approximate values for CO_2 uptake are assigned to each GGR based on overview of the literature and the combined expert view of the working group, the stakeholder workshop, and wide range of advisors to this report.

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[h] Footnote: range 440 – 1020 $GtCO_2$

1. Saturating storage

250 to 670 $GtCO_2$ by 2100

The GGR methods deployed here involve storage of carbon in the natural environment, and so are limited by the availability of land. This will mean interaction with a large number of other land-using activities, most notably food production. In many cases this storage could saturate before the 2100s, providing a carbon store that will require continual management and be vulnerable to natural disasters or human action.

i. Forestation 100 to 300 $GtCO_2$

Forestation and forest management has the potential to achieve a large proportion of the GGR needed to meet the global target, but with a correspondingly large requirement of land. Employing improved management of existing forestry to half of the world's 1900 Mha of native forests which are under non-intensive management for wood production could yield 30 $GtCO_2$ of GGR over a period of 50 years. An additional 300 to 800 Mha of new forest (equivalent to 2 to 6% of world land surface, or 1 to 3 times the area of India) would store an additional 80 to 300 $GtCO_2$ over a period of 25 years. To reach the cumulative total this land requirement could be reduced by good forest management, harvesting trees once they have reached maturity and allowing additional CO_2 to be sequestered with new trees on the same land. Utilisation would also provide a market to subsidise the sequestration activity, though managing this sustainably or with limitations to biodiversity damage would be critical.

In siting forests, location is relevant. Focusing reforestation on tropical areas could reduce the land area required due to higher sequestration rates there, while covering snow-covered areas with forests could be counterproductive for limiting temperature change, resulting in local net-warming through reduced surface reflectivity.

ii. Coastal and wetland habitat restoration 10 to 20 $GtCO_2$

Habitat restoration values depend heavily on the type of land restored, but scope exists particularly for mangrove, saltmarsh and seagrass restoration. Achieving this level of restoration would come with a number of co-benefits – for example, restored mangroves resulting in increased protection to coastal flooding and improved biodiversity. However, without a price for the sequestration, the incentive for action may be limited. This target would require restoration of up to all of the above habitats available to be restored (in addition to reforested land), many of which exist in nations that do not currently have payment mechanisms to enable such restoration. Saturation would be reached for a significant proportion of these habitats before 2100 and they will require continual maintenance to avoid reversal. Alongside restoration of degraded habitats, destruction of current natural habitats will also need to cease for full impact of this action. For reference, a sink of 2.6 $GtCO_2$ was lost between 2010 and 2016 because of the clearance of African vegetation (including forest and other habitats)[304].

TIMELINES

The long atmospheric residence time of CO_2 means that global temperatures are closely related to cumulative emissions of CO_2 rather than to emissions in any particular year or period[305]. This might suggest that GGR could be applied at any time to mitigate climate change. There are, however, critical issues related to timescale:

1. Ramp-up and saturation of biological stores

It can take significant time to plant large areas of forest and, once planted, it takes about a decade for forests to reach their maximum rate of carbon uptake. Forests and other biomass stores (soil, wetlands) also reach saturation between 20 and 100 years, beyond which they cannot take up additional carbon without an expansion of the land-area used.

2. Ramp-up of new industries

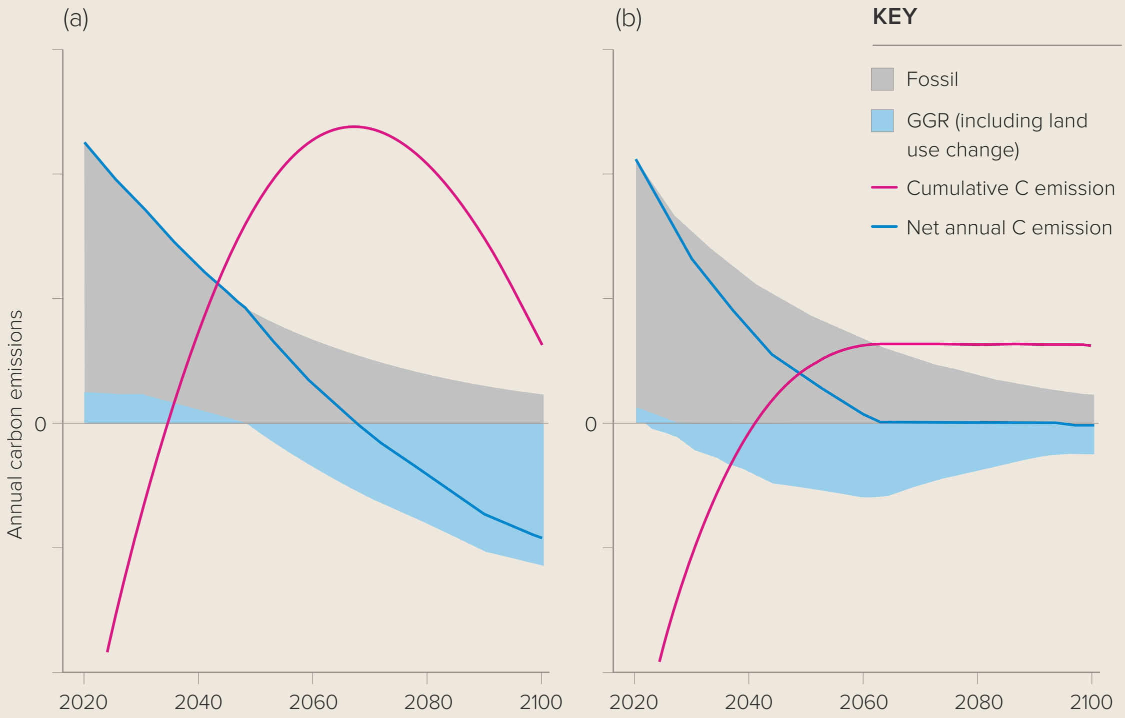
There will be a significant ramp-up period while new technology is demonstrated, appraised, and the infrastructure for large-scale deployment built. For GGR approaches at a high level of technology readiness, this process can commence as soon as there is the political and economic will. For other GGR approaches, additional research and demonstration is required that will further lengthen the time before large-scale application can be pursued.

At present rates of emissions, atmospheric levels of CO_2 to cause warming in excess of 1.5°C will be reached in 10 to 30 years[306]. Even with the rapid decreases in emissions projected in the more ambitious integrated assessment models, significant levels of GGR are required by 2050. To meet these levels will require ramp-up in preceding decades and therefore rapid action now.

3. The danger of overshoot

It is possible that emissions could cause the atmospheric greenhouse gas concentration to exceed the threshold defined to reach 2°C, peaking then decreasing, known as overshoot. Such pathways are represented in many integrated assessment models scenarios and are a feature of the difficulty of rapidly cutting net emissions to limit warming when the climate is already close to this temperature. There are, however, several reasons why overshoot might be undesirable. Natural systems will experience additional perturbations during overshoot (for example, ocean acidification) and in some cases may undergo irreversible change (for example melting of land-ice and consequent sea-level rise). Overshoot also implies temporary use of larger amounts of GGR while atmospheric CO_2 concentration is reduced, and a subsequent decrease in GGR could lead to stranded assets associated with GGR infrastructure in the very long term[307]. Overshoot is also likely to involve substantial development of BECCS and other GGR late in the century, which will place extreme future pressure on land with implications for land-use in a more densely populated world as well as for environmental sustainability. The assumption underlying overshoot scenarios, that significant GGR can be left until late this century, also carries societal and policy risk in reducing the motivation for action now, increasing the risk that action is delayed indefinitely.

Example emission pathways with identical cumulative emissions by 2100. Blue lines depict annual net emissions, red lines are cumulative, showing (a) Late century GGR, with substantial 'overshoot', (b) No Overshoot: GGR ramped up early then phased out to avoid an overshoot.



Source: Figure adapted from Obersteiner *et al*. 2018.

iii. Soil carbon sequestration 20 to 100 $GtCO_2$

Achieving soil carbon sequestration at this scale would involve improving soil management in arable and grazing land. Even the upper end of this removal range averages at 1.2 $GtCO_2$ per year, which is towards the lower end of technical potentials highlighted in the literature. However, non-technical barriers to implementation may delay deployment and result in the need for higher levels of sequestration over a shorter timescale.

Implementation of soil carbon sequestration globally is even more complex than considering implementation within an individual nation like the UK. For example, encouraging or incentivising a vast number of actors to undertake these practices, let alone monitoring their implementation and impact, would provide a significant challenge. Similarly, encouraging continued maintenance action past the point of saturation will be essential. Co-benefits associated with that maintenance would assist, but difficulties will remain if maintenance is not associated with a financial incentive.

iv. Building with biomass 20 to 50 $GtCO_2$

Although building with wood is common practice in many places, this level of removal would be additional to current wood building markets, possibly achieved by building 5 to 20 million multi-story buildings over the next 80 years. This level of removal would additionally avoid emissions associated with non-biomass based building materials. Removal of wood for building enables forests to continue to take up carbon even once they have reached maturity and provides a financial incentive for forestry. The lifetime of the built products and end-of-life disposal method will be important considerations.

v. Biochar 100 to 200 $GtCO_2$

Biochar becomes a more realistic prospect at scale by 2100 than in 2050. There is direct competition for use of biomass between biochar and BECCS and land competition with soil carbon sequestration. In this scenario the potential soil fertility and quality co-benefits of biochar and ability to deploy in places without CCS infrastructure drive a significant amount of utilisation worldwide.

Utilisation of biochar at this scale would require 400 tonnes of biochar at 50 tonnes per ha pa, spread on between 7 and 14 Mha land (4 to 8% of global arable land), and producing 500 to 2800 EJ (140,000 to 780,000 TWh) of energy in pyrolysis over this period. It is likely that this biomass would come in part from crop waste and in part from dedicated biomass crops – presuming a 50/50 split would require land for biomass growth of c. 20 to 130 Mha at the lower end of sequestration and 40 to 260 Mha at the higher end.

2. Permanent storage

Up to 800 $GtCO_2$.

The following methods can be deployed at large scale and the captured CO_2 is expected to be permanently removed from the atmosphere. They provide significant potential for CO_2 removal, but are at a range of technology readiness, with significant remaining uncertainties.

Both BECCS and DACCS have large requirements for geological storage capacity – by traditional CCS in sedimentary geological formations or by mineral carbonation. Global sedimentary CCS storage capacity is estimated at 3360 $GtCO_2$ (20% of theoretical capacity[308]), so is unlikely to become a limiting factor. This technology is not risk free, however, and some degree of CO_2 leakage is expected.

i. BECCS c. 300 $GtCO_2$

Assessment of the extent of possible biomass production based on land-area constraints suggest a range of 300 to 700 $GtCO_2$ GGR may be achievable with BECCS. If dedicated high-productivity energy crops are used, and grown evenly in time between now and 2100, this range requires between 100 and 500 Mha of land, equivalent to between 7% and 35% of all global arable land. Non-arable land could be used for this purpose, but in either case this would require a great deal of land-use change and could put significant pressure on food production.

Land use could be reduced through the use of crop residues, though the often cited 50% contribution from residues would be hard to achieve at this scale. With significant changes to land area, it is technically possible to grow biomass at this scale, but there is increasing evidence suggesting that dedicated biomass growth will be a challenge for freshwater availability and for nutrient cycles. These challenges and the need to balance biofuel with food production suggest that sustainable deployment of BECCS is likely to be at the lower-end of the range based on the land-area constraints alone.

The energy potential of BECCS is highly uncertain, but very loose estimates would put this scale of deployment on the order of 10 to 100 EJ (2,800 to 28,000 TWh) a year (cf world electricity generation of 90 EJ (25,000 TWh) in 2016). Considering a more realistic time frame in which BECCS implementation increases over the 21st century would lead to much increased land requirements and energy potential. World electricity demand is expected to increase significantly over the coming century, but if BECCS energy supply outpaces demand, financial incentives for the associated removals will be reduced and without a significant price for sequestration, action may be limited.

ii. DACCS 200 to 500 $GtCO_2$

In the second half of the century, substantial use of DACCS becomes a possibility, but remains reliant upon a realistic carbon price due to the lack of co-benefits. Technological development is likely to increase efficiency and lower cost. The potential for large scale removal with limited requirements for land and limited negative consequences is likely to drive deployment. At the scale suggested here, DACCS would be a very significant global industry. At a carbon price of $100 per tCO_2 the DACCS industry would have a turnover of tens of trillions of USD, potentially larger than the present oil and gas industry. At this scale, requirements for chemical manufacture (such as amines) and the need for power and water would become significant. If removal and storage is achieved at 10 times the theoretical minimum energy requirement and removals operate at 12 $GtCO_2$ a year this would require 80 EJ (22,000 TWh) annually, roughly equivalent to all of the current world electricity generation, though further efficiency gains might reduce this. At a future point that DACCS is no longer required, there is the risk of stranded assets.

iii. Enhanced weathering: c. 100 $GtCO_2$

The lack of field-scale demonstration of enhanced weathering means that there is significant uncertainty about the carbon sequestration potential and the environmental and agricultural impacts of its long-term use. Nevertheless, present understanding suggests this is a promising approach with potential agricultural co-benefits and makes significant deployment likely before 2100. Where the material released in this terrestrial process ends up in the oceans, long-term stability of the removed CO_2 makes enhanced weathering a route to permanent storage of CO_2 without the need for CCS. Achieving GGR of 100 $GtCO_2$, or an average removal of 1.2 $GtCO_2$ a year, requires around 12 Gt of mineral resource per year, spread over 600 Mha (two thirds of the most productive cropland). It is again noted that deployment would likely be weighted to the latter half of the century – at which point additional land used for biomass growth could also be treated.

A significant fraction of the silicate required could be met from waste materials and there is sufficient waste from silicate mining to remove 0.7 to 1.2 $GtCO_2$ a year. Use of this material reduces the energy and cost requirements of additional mining and grinding of silicates. However, it would be limited in the cases where waste contains toxic heavy metals. In the long-term, the energy for mineral processing and transport is anticipated to come largely from decarbonised sources.

The long-term implications of large-scale enhanced weathering for agriculture, terrestrial and freshwater ecosystems, and for the ocean from the implicit increase in alkalinity, are poorly known and require further research, particularly during early demonstration. The fate of metals released by enhanced weathering and their impact on the environment, and the interaction of enhanced weathering with soil carbon sequestration, are among important unresolved questions.

iv. Ocean alkalinity: uncertain

The intentional deployment of ocean alkalinity for GGR is not likely in the coming decades, but may be pursued as a form of permanent carbon storage without CCS later in the century. Pursuit of land-based enhanced weathering would lead to increase in ocean alkalinity, providing a test of the long-term consequences of this approach for ocean ecosystems and for the long-term stability of carbon in the oceans (but without mimicking the short-term impact of direct alkalinity addition and direct uptake of CO_2 into seawater). It is also possible that intentional addition of alkalinity will be pursued at a local scale to mitigate the impact of ocean acidification on vulnerable ecosystems (such as reefs). Such applications would provide direct demonstration of the costs, benefits, and risks of larger scale intentional pursuit for GGR.

Public attitudes and legislative barriers provide a limitation, but if the full consequences of action were understood, these might be overcome.

Any such large-scale application would require a substantial source of alkalinity, most likely of lime at a scale greater than present lime production, or the direct industrial neutralisation of CO_2 with limestone.

v. Concrete: uncertain

Present low-carbon approaches to concrete manufacture generally reduce CO_2 emissions, but do not provide net removal of CO_2 from the atmosphere (and are not pursued at a scale to be significant). Development of new technology that would capture the CO_2 emitted during cement production would allow net carbon negative concrete to be produced, for example, from CO_2 curing of pre-built concrete products such as concrete blocks. This could become a larger route to GGR later this century, but its level of application cannot yet be assessed.

3. GGR pathways unlikely to prove useful at scale

i. Ocean fertilisation:

While theoretically possible to sequester up to 300 $GtCO_2$ by iron fertilisation by the end of the century, inefficient net-removal of carbon to the deep ocean makes it likely that the total possible GGR is significantly smaller. If pursued over large regions, as would be required, fertilisation also carries substantial risk of negative consequences to ocean ecosystems and nutrient cycles. Fertilisation is also currently forbidden under international conventions and unacceptable to much of the public. These negatives provide a strong argument against substantial deployment of ocean fertilisation for GGR.

Chapter five

Lessons learned from scenarios

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Tokyo cityscape. © ooyoo.

5.1 Lessons learned from scenarios

Meeting the aims of the Paris Agreement and limiting warming to 1.5˚C with the deployment of GGR would require the following international actions.

Meeting the temperature goals of the Paris Agreement is challenging and cannot be achieved without rapid and substantial emissions reduction
GGR targets in the scenarios described are pursued at the same time as steep reductions in emissions to meet the goals of the Paris Agreement. Meeting these GGR targets will be challenging and expensive, and the goals of Paris can only be achieved if GGR is pursued alongside rapid and substantial emissions reductions. Even with these emissions reductions, deployment of GGR requires availability of a large amount of additional energy (from a decarbonised energy system), the development of massive industries in the form of DACCS and BECCS, and the growth of biomass on a very significant land area.

RECOMMENDATION 1

Continue and increase global efforts to reduce emissions of greenhouse gases. Large-scale GGR is challenging and expensive and not a replacement for reducing emissions.

Multiple GGR pathways will be required
No single approach to GGR can achieve all the carbon removal required, either at national or global scale, to help meet the goals of the Paris Agreement and stabilise climate. Uncertainty over the future scalability of GGR methods (due to requirements for land and CCS, environmental impacts, reversibility of storage, and costs) also indicates the need to develop multiple GGR methods. Land-based biological stores can be developed rapidly but will saturate within a few decades and maintaining the same level of annual removals will require additional capacity from non-saturating methods.

RECOMMENDATION 2

Implement a global suite of GGR methods now to meet the goals of the Paris Agreement. This suite should include existing land-based approaches, but these are unlikely to provide sufficient GGR capacity so other technologies must be actively explored.

Storage and permanence – the need for CCS

Although some GGR methods come with built-in storage, these do not allow sufficient removal to reach net-zero emissions in the UK in 2050, and are unlikely to enable the 1.5°C Paris target to be met. Meeting that goal will require substantial dedicated storage of CO_2 removed from the atmosphere (in addition to storage of CO_2 undertaken as part of reducing emissions from fossil-fuel power-stations). At present, this can only realistically be achieved using below-surface sedimentary rocks (as occurs in conventional CCS). Sufficient capacity in such rocks for storage of the carbon resulting from required GGR is available, but this would require a rapid ramp-up of an industry that, although demonstrated successfully, has not been pursued at large-scale.

Other approaches to long-term storage of CO_2 are at a lower level of technology readiness and are unlikely to be available in the near future. Carbonation of below-surface silicate rocks and/or reaction of CO_2 with limestone and storage in the ocean may be additional routes to permanent storage of CO_2 at scale. These may augment but not replace conventional sedimentary CCS. 'Carbon utilisation' technologies, such as chemicals or liquid biofuels produced from CO_2, are gaining increasing interest, but, beyond those pathways discussed above, presently hold limited promise for use or storage at the scale required.

RECOMMENDATION 3

Build CCS infrastructure. Scenario building indicates that substantial permanent storage, presently only demonstrated in geological reservoirs, will be essential to meet the scale required for climate goals.

The timeline for deployment of GGR: research, development, and ramp-up

The deployment of GGR methods will require time. For options that come at low cost with co-benefits, soil carbon sequestration, forestation, and habitat restoration, large-scale deployment should begin now. The co-benefits provide pay-back irrespective of carbon sequestration and deploying now leaves options open in the future. Forests planted now, for example, could provide future biomass for use in BECCS and building in the future.

For those GGR methods that are not ready to be deployed, more R&D is needed through to demonstrator scale, in partnership with industry where relevant. This will lead to both improvements in technology and reductions in costs. Given the commitment to the Paris Agreement it seems very likely that substantial GGR industries will exist internationally.

Support for R&D is required across the full range of GGR methods and will drive technology development, but financial pull will also be required to drive deployment to market. Existing carbon prices provide a disincentive to emitting CO_2 to the atmosphere, but do not provide a corresponding incentive to remove and store CO_2 that has already been emitted. Carbon prices – or credits – could be extended to remunerate such removals (as in the United States' 45Q tax credit) and to encourage business investment in development and deployment of all GGR technologies that can be verified and operate without negative consequences.

More work is needed, across all GGR pathways, on monitoring carbon sequestration and environmental impacts, and on establishing approaches to evaluation and verification. This work will need to continue from research, through pilot field demonstration, and into the deployment phase.

Rigorous life cycle assessments have not yet been undertaken for many GGR pathways and are required to understand the consequences of each method. Deployment will have impacts on energy, food, water, land and other issues of prime consideration in the SDGs; impacts that would become apparent from life cycle assessments. The interactions of a suite of different GGR methods at large-scale may have cumulative impacts alongside mitigation activities, which are not immediately apparent from considering individual technologies in isolation. These impacts need to be understood, monitored and managed.

RECOMMENDATION 4

Incentivise demonstrators and early stage deployment to enable development of GGR methods. This allows the assessment of the real GGR potential and of the wider social and environmental impacts of each method. It would also enable the process of cost discovery and reduction.

RECOMMENDATION 5

Incentivise removal of atmospheric greenhouse gases through carbon pricing or other mechanisms. GGR has financial cost at scale and so will require incentives to drive technological development and deployment of a suite of methods.

RECOMMENDATION 6

Establish a framework to govern sustainability of GGR deployment. Undertake rigorous life cycle assessments and environmental monitoring of individual methods and of their use together.

Social acceptability

Ensuring the public acceptability of GGR methods will be vital, starting at demonstration scale. Although not generally facing the same public opposition as solar radiation management routes to climate control, the degree of social acceptability will vary across the different GGR methods. Social science literature shows that early engagement to involve the public and encourage supportive action amongst key groups (such as farmers) will be important. Whether activity occurs on public or private land, public attitudes may make GGR utilisation impossible in some locations and such considerations will need to be included in deployment plans.

Importance of location

Deployment of GGRs is likely to be heavily influenced by location, on both national and global scales. Methods requiring CCS may be more easily deployed around the relevant infrastructure. Methods requiring mineral, energy, biomass, or water might be most sensibly deployed where there is supply of those resources that could be utilised at low or no cost. A number of methods require significant land-use change from other activities. This will be particularly hard in highly populated areas or those with protected environmental status, but there are also ethical considerations when ‘available’ land is used by more sparsely populated or itinerant peoples.

International trade and carbon accounting
While it is possible to imagine some nations meeting their own needs for GGR, it is not likely to be the case for every country, nor to be the most globally efficient approach to meet GGR targets and the goals of the Paris Agreement. International trade in raw materials and carbon credits will be necessary in many cases and could help lower overall costs. Countries with natural resources used for GGR will export them and those with a need will import them. The largest such resource is likely to remain biomass, which is already traded internationally. Mineral resources for enhanced weathering or mineral carbonation may also be traded. International agreement about allocation of credits for GGR will be required for such trade. One question that needs resolving is whether the credit is gained by the country producing the resource or the country using it and storing the removed carbon, or whether the credits are shared.

Trading of carbon credits from GGR methods could also be used to increase efficiency, lower costs and enhance development of GGR. A country with large scope for GGR due to economic, technological or geographical reasons might choose to 'over-remove' CO_2 to cover other nation's requirements in exchange for payment. Countries with large capacity for CCS (such as the UK) or mineral carbonation (such as Iceland) might be paid to store CO_2; those with land and water to increase forest mass; and those with substantial non-carbon energy potential to pursue DACCS. While this report focuses primarily on the scientific and technical aspects of GGR pathways, it also recognises that successful deployment of GGR will depend on establishing international agreements on trade and carbon credits in the context of GGR.

In all cases measurement, reporting and verification will be critical to ensure CO_2 fluxes are accurately accounted for and standards set to prevent double-counting. Additionally, the ethical implications and social acceptability of these transactions will need to be taken into account.

RECOMMENDATION 7

Build GGR into regulatory frameworks and carbon trading systems. In the UK, as an example, active support for GGR implementation (soil carbon sequestration, forestation, habitat restoration) should be built into new UK agricultural or land management subsidies.

RECOMMENDATION 8

Establish international science-based standards for monitoring, reporting and verification for GGR approaches, both of carbon sequestration and of environmental impacts. Standards currently exist for biomass and CCS, but not for GGR methods at large.

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Basalt. © Probuxtor.

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CCS demonstration facility in Tomakomai, Hokkaido, Japan. Photo by Florian Kraxner with permission of Japan CCS Co. Ltd.

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