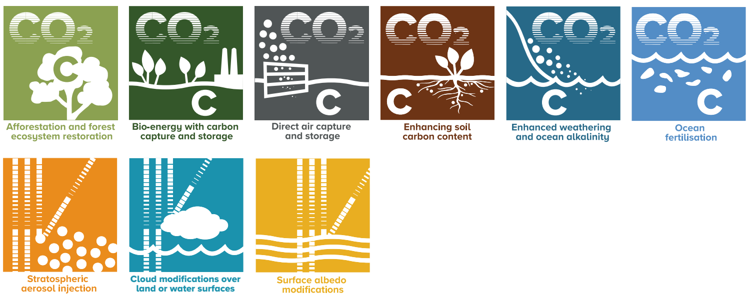
Carbon Removal and Solar Geoengineering: Potential implications for delivery of the Sustainable Development Goals

C2G2 Report | May 2018



C2G2 Carnegie Climate Geoengineering Governance Initiative

an initiative of CARNEGIE COUNCIL for Ethics in International Affairs

Carbon Removal and Solar Geoengineering: Potential implications for delivery of the Sustainable Development Goals

C2G2 Report | May 2018

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Terms used in this report

For a complete glossary of terms used in this report, please refer to the Geoengineering Glossary for Policymakers: A living guide to geoengineering terms and acronyms that can be found on the webpage of the Carnegie Climate Geoengineering Governance Initiative: **www.c2g2.net/glossary**

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Content

Foreword

Faced with the daily rigours of designing international climate policy, we can sometimes find ourselves missing the big picture: that our ultimate objective is to promote the greater wellbeing of humankind, as well as the other species with whom we share our fragile planet.

We can too easily find ourselves caught in silos, focused on achieving specific temperature targets and carbon dioxide concentrations, whilst forgetting the ultimate reason we do this. We need to find better ways to step back, to look at the wider implications of our work.

The Sustainable Development Goals, agreed by world governments in 2015, offer us a powerful tool. They represent the international community's best expression of our collective hopes and aspirations, and provide a compelling framework against which to assess the broader impact of our work — in our case, on the governance of two emerging families of technologies: solar geoengineering and large-scale carbon removal.

So far, discussion of these has tended to focus on one specific goal, agreed in Paris also in 2015: to limit average global temperature rise this century to well below 2°C and pursue efforts to limit temperature increase even further to 1.5°C. In so far as that is a shortcut for the health of the planet, it is a useful yardstick.

But as the debate around the potential use of Carbon Removal and Solar Geoengineering goes mainstream, policymakers are looking for a more textured analysis. How do these technologies benefit humanity across the board? How do we ensure the cure is not worse than the disease? What is the utility in keeping temperatures down if, in the process, we do harm to the communities we serve? How do we weigh up the risks and potential benefits, in order to take responsible, prudent decisions?

We at the Carnegie Climate Geoengineering Governance Initiative (C2G2) do not have the answers to all these questions, but we do think it is time to address them, and to that end, we see the Sustainable Development Goals are a great place to start.

This report is, at heart, an appeal to those grappling with the profoundly difficult questions surrounding any deliberate, large-scale intervention in the earth system. Our hope is that their decisions should be guided not just by the Paris Agreement, and strict climate science, but the whole spectrum of impacts on people, social and physical.

The potential deployment of large-scale carbon removal or solar geoengineering technologies is too big a question, too wide in scope, to keep to one expert community. We need to bring climate scientists together with development experts, government together with NGOs and private entrepreneurs, if we are to stand a chance of getting this right.

By publishing this, we hope to bring these communities closer together. If in so doing we set in train a wider debate, we will have succeeded.

Janos Pasztor
Executive Director, C2G2

Summary

This report explores the potential implications which two groups of experimental technologies aimed at managing global climate risk, known as *Carbon Removal* and *Solar Geoengineering*, could have for delivery of the Sustainable Development Goals (SDGs).

The report is based on a review of recent literature, combined with expert analysis and insights provided by a group of international academics and practitioners covering all 17 SDGs. While analysis is focused on implications these technologies may have for delivery of the SDGs in the lead up to 2030, it is also valid and highly relevant for the post-2030 period.

There are substantial knowledge gaps around these technologies, and what direct or indirect impacts could be expected if they were ever deployed globally. It is therefore not the purpose of this report to draw firm conclusions regarding their relative pros and cons as part of a portfolio approach to managing climate change risks. Rather, this report seeks to present an initial examination of academic research and expert knowledge to initiate a timely, evidence-based discussion of potential implications (positive or negative) that deployment of these technologies could have for delivery of the SDGs.

This report acknowledges that:

- **Current climate change is already having detrimental effects on delivery of the Sustainable Development Goals (SDGs)**. Climate change is expected to render delivery of all SDGs more difficult even if warming stays well below 2°C. Extreme weather events are already significantly increasing in severity at the current warming level of just 1°C.
- **Recent analysis indicates that current commitments by international governments to reduce emissions are likely to result in 3°C of global warming by 2100.** The corresponding impacts would be expected to have serious implications for the delivery of all SDGs.
- **Researchers are increasingly discussing the potential for intentional large-scale intervention in the climate system, using technologies and practices referred to as Carbon Removal or Solar Geoengineering**. Carbon Removal technologies seek to remove the main greenhouse gas, carbon dioxide, from the atmosphere; Solar Geoengineering technologies aim to directly alter the energy balance of the earth's atmosphere to cool the planet, in order to moderate some of the impacts of climate change.
- **Most scientific scenarios consistent with the global goal of limiting warming to 1.5°C or well below 2°C already rely on Carbon Removal technologies to remove accumulated atmospheric CO_2.** Even with a rapid scale-up, around 10 billion tonnes of CO_2 would still have to be removed annually in the second half of the century (around one-third of current global CO_2 emissions). While some natural processes could be leveraged such as large-scale afforestation, new technologies are also proposed such as directly capturing and removing CO_2 from ambient air. Some are land-based, like enhancing soil carbon content with biochar, and others ocean-based, such as ocean fertilisation.

Key observations in the report include:

- **The broader implications of Carbon Removal technologies for delivering sustainable development are insufficiently understood at this time.** The literature review presented in this report finds that many technologies are untested at scale and substantially more expensive than ongoing efforts to reduce CO_2 emissions, and their deployment could have significant adverse effects on delivery of the SDGs. However, positive effects for non-climate related SDG delivery beyond climate action are also possible, under specific conditions (e.g. remediating ecosystems, providing energy and decent work and enhancing food production). Achieving beneficial outcomes and avoiding social and environmental harm requires more research and policy-specific impact assessments that take local conditions into account.
- **Uncertainties surrounding Solar Geoengineering are large and deployment without adequate global governance would likely be highly disruptive with significant implications for SDG delivery**. The scientific literature suggests that modifications of the planetary energy balance might result in limiting temperature rise (and other associated impacts) rapidly and at low cost, but with potentially uneven results across regions and with regard to other climate parameters such as precipitation. Such interventions could introduce substantial and large-scale novel risks and side effects (e.g. rapid warming upon sudden termination, impacts of airborne particles on health, ecosystems and the ozone layer) as well as serious governance challenges to national and international institutions.
- **Delivery of at least three quarters of all SDGs (at least 13 out of 17 SDGs) is expected to be affected in some way if Solar Geoengineering or large-scale Carbon Removal were deployed.** These implications could be positive or negative in how they help attenuate climate change impacts or result in unwanted physical, socio-economic or political outcomes. Implications for the remaining four SDGs — including indirect implications — are identified as research gaps requiring further assessment.
- **Some forms of Solar Geoengineering or large-scale Carbon Removal could negatively affect delivery of more than half of all SDGs (at least 9 out of 17 SDGs**). The literature identifies potential risks in particular regarding delivery of SDG-6 (Clean Water and Sanitation), SDG-3 (Good Health and Well-being), SDG-1 (No poverty); and SDG-16 (Peace, Justice and Strong Institutions). Further risks are also identified for other SDGs including SDG-2 (Zero hunger), SDG-14 (Life below water), SDG-7 (Affordable and clean energy), SDG-8 (Decent work and economic growth) and SDG-15 (Life on land).
- **Potential risks to successful delivery of SDGs from the deployment of Solar Geoengineering are highlighted more frequently than those from large-scale Carbon Removal. Accurate assessment of relative risk between different technologies is not yet possible but should also be weighed against the risks that alternative options, including following current trajectories, would pose to successful SDG delivery.** The relative level of potential effects identified may also be a function of the current quantity or level of maturity of the literature available and reviewed for this report.

- **Deployment of Solar Geoengineering as well as large-scale Carbon Removal would be expected to have physical side-effects and socio-economic or political implications affecting the delivery of SDGs**. Physical side-effects in particular relate to: land-use and food security; water quality and availability; health; energy; economic productivity; and biodiversity. Socio-economic or political implications include: economic and cultural impacts; opportunity costs; political tensions and governance demands.
- **Extensive research gaps exist around the potential implications of deploying Solar Geoengineering or large-scale Carbon Removal** and a broad range of topics for further research are suggested, in particular concerning: socio-economic impacts; regional differences; economic impacts; impacts on agriculture and food security; health impacts; environmental impacts; policy instrument design; and governance.

Key recommendations include:

- **More transdisciplinary and geographically diverse research is required on the interconnections between Carbon Removal or Solar Geoengineering and delivery of Sustainable Development, which may include development of common assessment principles or metrics.**
- **Comprehensive quantitative analysis of potential risks and benefits of Carbon Removal and Solar Geoengineering is needed to avoid under- or over-estimating climate and Sustainable Development impacts.**
- **More social science and humanities research is needed, including critical reflection on the role of science and technology in the context of the SDGs.**
- **Integrated policy impact assessments are needed to understand potential policy designs to mobilise Carbon Removal and Solar Geoengineering, and what implications they would have for delivery of the SDGs.**
- **Governance of research and any potential future deployment of Carbon Removal or Solar Geoengineering will need to be carefully designed to ensure its support for Sustainable Development and to reduce the risk of negative impacts.**

Introduction

Anthropogenic climate change presents an increasing challenge to delivery of the United Nations 2030 Agenda for Sustainable Development and Sustainable Development Goals (SDGs) and is consistently cited among the greatest global threats to human development[1 2 3 4]. Despite momentum for addressing climate change under the Paris Agreement, recent assessments indicate that current commitments are still likely to result in average global warming of around 3°C by the end of the century[5]. Given the high levels of interdependency between limiting climate change and delivery of the other SDGs[6], it becomes increasingly important to ensure that any measures considered to address climate change do so in ways that help, rather than hinder delivery of the other goals.

Carbon Removal and *Solar Geoengineering* — often collectively referred to as Geoengineering or Climate Engineering[i] — are increasingly discussed as potential measures to address climate change in addition to greenhouse gas emissions reduction and adaptation efforts. Although often referred to collectively, they represent two distinct types of technology with very different aims. *Carbon Removal* is an umbrella term we use to describe Carbon Dioxide Removal, Greenhouse Gas Removal or Negative Emissions technologies which aim to address the human-induced cause of climate change (increased atmospheric concentrations of greenhouse gases) by drawing out carbon dioxide and other greenhouse gases from the atmosphere, whereas *Solar Geoengineering* technologies aim to address a symptom of climate change (global warming), by allowing more heat to escape the earth's atmosphere or reflecting more solar radiation into space, and thereby cooling the Planet.

Carbon Removal is already included in most scenarios presented by the Intergovernmental Panel on Climate Change (IPCC) for staying below 1.5°C or 2°C — in some cases starting as early as the 2020's[7] and increasing in scale over the remainder of the 21st century[8]. However, the efficacy and feasibility of many existing Carbon Removal technologies remains highly uncertain and concerns have been raised that large-scale deployment could result in significant physical, socio-economic or political consequences[9 10]. Similarly, large uncertainties exist around the feasibility and risks of Solar Geoengineering technologies[11 12 13] and serious concerns have been raised about the potential consequences of their deployment[14 15].

While both Carbon Removal and Solar Geoengineering may offer the potential to limit or avoid some of the negative impacts of climate change, they could also create new and novel risks and have substantial negative consequences for development outcomes nationally, regionally or internationally. Research into Carbon Removal and Solar Geoengineering to date has largely been disconnected from discussions concerning delivery of development outcomes such as those agreed under the United Nations 2030 Agenda in the form of SDGs. This report aims to address this gap, by making a first attempt to identify potential implications that Carbon Removal and Solar Geoengineering could have for delivery of the SDGs. It is intended for a broad audience of readers with either an interest in or mandate to

i Terminology is still evolving in the academic discourse. See **www.c2g2.net** for further discussion on this topic.

inform, design, implement or govern environment or development policy at local, national or international level. While analyses are focussed on what implications these technologies may have for delivering the SDGs in the run up to 2030, it is assumed that the international community will aim to maintain and improve sustainable development achievements beyond 2030, so the analysis presented here also remains qualitatively valid and relevant for the post-2030 period.

In Chapter 1 we introduce nine key types of Carbon Removal and Solar Geoengineering technologies examined in this report and go on to consider in Chapter 2 the different scenarios in which they might be deployed. In Chapters 3 and 4 we take a closer look at the key characteristics of these technologies and discuss possible implications each may have for delivery of the SDGs. In Chapter 5 we summarise what implications deployment of these technologies could have for delivering each of the 17 SDGs, with further detail of potential physical side-effects, climate related, socio-economic and political implications and areas for further research included in Appendix 1.

Methodological approach

This report is based on a review of recent literature combined with expert review and insights provided by a group of international academics and practitioners covering all 17 SDGs.

The literature review provides an initial, exploratory look at the current academic and grey literature on Carbon Removal and Solar Geoengineering at a time where systematic assessments in relation to Sustainable Development are only just emerging[16]. As a starting point, it takes the literature presented in three seminal interdisciplinary assessments[17] [18] [19] [20] and is consolidated with more recent peer-reviewed publications identified via (i) keyword searches related to 'Sustainable Development' and the individual SDGs and (ii) literature featured in online discussion platforms and newsletters on Carbon Removal and Solar Geoengineering.[ii]

Thirteen experts with expertise on specific dimensions of the SDGs then reviewed the preliminary findings, identified gaps in the analysis and suggested missing literature sources. A further seven experts were then interviewed and asked to identify what they considered to be the key potential negative and positive impacts of Carbon Removal and Solar Geoengineering in the context of specific SDGs.

While this report endeavours to present a balanced, impartial and evidence-based view of potential implications, significant gaps in knowledge mean that a comprehensive discussion of pros and cons for each technology or SDG remains impossible at this stage.

Research into Carbon Removal and Solar Geoengineering is a relatively new and fast evolving field of enquiry with many potentially important dimensions currently unaddressed in the scientific literature. Consequently, assessment of any relationship between deployment

ii The authors made use of the Forum for Climate Engineering Assessment's (FCEA) literature collection accessible at: **ceassessment.org/CDRnets-bibliography/** and the Google Group on Geoengineering accessible at **groups.google.com/forum/?hl=en#!forum/geoengineering** and the climate-engineering.eu newsletter accessible under **www.climate-engineering.eu/**

of these (in some cases theoretical) technologies and delivery of the SDGs has in many cases required a degree of extrapolation and expert judgement on the part of the authors in preparation of this report. Furthermore, once consideration is also given to the influence of the broader development context[21] the complex interdependencies between the various SDGs[22] and other factors such as variation in policy design[23] [24] the authors acknowledge that the ability to draw firm conclusions is severely limited and this work is therefore very much intended as a conversation starter, rather than a final word.

1. The key technologies

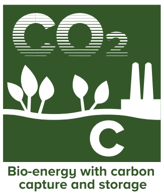
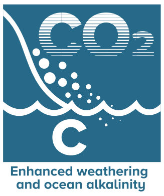
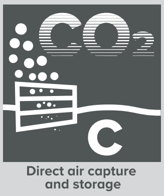
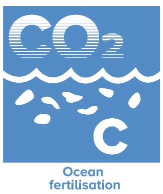
Deliberate large-scale intervention in the earth's climate system to counteract climate change is known collectively as Geoengineering[25] or Climate Engineering[26 27]. A variety of technologies are considered for such intervention and while the terminology and classification of these technologies is contested, they are often separated into two broad categories: those intended to remove CO_2 from the atmosphere, here referred to as as *Carbon Removal* and those intended to directly alter the energy balance of the earth's atmosphere, i.e. cooling the planet, here referred to as *Solar Geoengineering*.

1. 1. Carbon Removal[28]

Carbon Removal is the umbrella term we use here to describe technologies removing CO_2 or other greenhouse gases (such as methane, nitrous oxide or industrial gases) from the atmosphere, thus covering the commonly used terms Carbon Dioxide Removal, Greenhouse Gas Removal or Negative Emissions Technologies[iii]. Carbon Removal is distinct from emissions reductions which are the urgent focus of global efforts to reduce carbon dioxide emissions from current and future human activities. Carbon Removal is focussed on reducing existing levels of carbon dioxide in the atmosphere which have accumulated as a result of past emissions. In principle, Carbon Removal could, if implemented on a global scale, complement global greenhouse gas emission reductions and thereby contribute to slowing the rate and extent of global climate change, as well as a number of related impacts and risks (such as ocean acidification, sea level rise, ecosystem degradation and extreme weather events). However, the rate at which removal of CO_2 from the atmosphere might affect global temperatures is only just beginning to be understood[29]. The six types of Carbon Removal technologies and techniques examined in this report are briefly described in **Table 1** (page 12). In due course other ideas might eventually emerge, but these are for now the best understood.

iii However, removal technologies for non-CO_2 gases are hardly addressed in the literature.

Table 1: Overview of key Carbon Removal technologies examined in this report

	Technology	Description
	**Afforestation and forest ecosystem restoration**	Planting of forests and restoration of ecosystems that result in long-term storage of carbon in above- and below-ground biomass.
	**Bioenergy with carbon capture and storage (BECCS)**	Burning biomass for energy generation and capturing and permanently storing the resulting CO_2
	**Enhancing soil carbon content with biochar**	Biomass burning under low-oxygen conditions (pyrolysis) yields charcoal “biochar” which is then added to the soil to enhance soil carbon levels.
	**Enhanced weathering or ocean alkalinisation**	Enhancing natural weathering of rocks by extracting, grinding and dispersing carbon-binding minerals on land or by adding alkaline minerals to the ocean to enhance oceanic carbon uptake.
	**Direct air capture and storage**	Capturing CO_2 directly from ambient air by a chemical process, followed by permanent storage or use.
	**Ocean fertilisation**	Fertilising ocean ecosystems with nutrients to accelerate phytoplankton growth, which partly sinks to the seabed thus moving carbon from the atmosphere to the seabed.

Note: There are several ways in which these technologies can be grouped (see for example UNEP, 2017[30]), but for simplicity this report focusses on their core processes and associated potential implications.

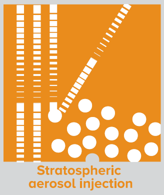
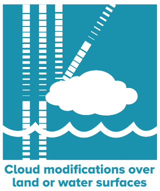
There is broad consensus within the scientific community that Carbon Removal would have to occur in addition to — and not as a replacement for — dramatic reductions in emissions[31] in order to achieve a "balance between anthropogenic emissions by sources and removals by sinks" (Article 4 of the Paris Agreement). Achieving such a balance is a physical necessity for stabilizing the climate system at any temperature level.

Most scenarios describing pathways to limiting warming to well below 2°C already anticipate and heavily rely on the application of some form of Carbon Removal[32] [33], and to date only one scenario in peer-reviewed literature keeps warming below 1.5°C by 2100 without it[34].

1.2. Solar Geoengineering[35]

Solar Geoengineering refers to a set of technologies and techniques that are still largely theoretical and aim to alter the planet's energy balance in order to reduce temperatures. In principle this can be done by increasing the reflection of solar radiation before it reaches the earth's surface or by enhancing the transmission of terrestrial radiation into space. One prominent proposal is a process called Stratospheric Aerosol Injection (SAI) which would theoretically disperse reflective aerosol particles in the upper atmosphere to reflect solar radiation — an approach for which large volcanic eruptions provide a natural analogue. Further ideas under consideration include modifying clouds by spraying seawater into the air directly above the ocean or seeding cirrus clouds to facilitate more thermal radiation to escape into space. Concepts for surface-based Solar Geoengineering include large-scale modification of the reflectivity of land surfaces such as painting human settlements white, conserving reflective ice-masses, covering desert areas with reflective material or selecting more reflective vegetation types as crops. Other approaches have been suggested in the past, such as mirrors in space, and new ideas may emerge if and when more research is dedicated to Solar Geoengineering. The basic mechanisms of three key types of technologies examined in this report are briefly described in **Table 2** (page 14).

Table 2: Overview of key Solar Geoengineering technologies examined in this report

	Technology	Description
	**Stratospheric Aerosol Injection (SAI)**	Injecting reflective aerosol particles or gaseous particle precursors into the lower stratosphere to increase the planetary albedo (reflectivity) and thereby reduce temperatures.
	**Cloud modifications over land or water surfaces**	This includes the potential seeding of clouds above ocean surfaces (e.g. with self-steering, autonomous ships), the whitening of clouds above land-surfaces to reflect solar radiation away from earth and the thinning of cirrus clouds to allow more heat to escape.
	**Surface albedo modifications**	Making various surfaces such as urban areas, roads, agricultural land, grasslands, deserts, polar ice-caps or oceans brighter to prevent solar radiation from heating up the areas covered.

It is currently unclear whether Solar Geoengineering technologies will ever be technically, politically, economically or socially feasible or indeed desirable and adequately governable. Current research is clear on the substantial cooling effect that Solar Geoengineering could have on global average temperature in case of relatively even application[36] and if some types of Solar Geoengineering worked as intended, they could in theory, be set apart from greenhouse gas emission reductions and Carbon Removal by their theoretical potential for rapid effect on global temperatures[37] and to a lesser degree also changes in precipitation[38,39,iv]. However, while potentially limiting secondary emissions (e.g. methane emissions from thawing permafrost[40]), Solar Geoengineering does not directly reduce anthropogenic GHG emissions and there is substantial, widespread agreement that it would not constitute a substitute for drastic cuts in greenhouse gas emissions or adaptation[41,42,43,44].

In theory, different types of Solar Geoengineering are expected to perform differently with regard to regional outcomes[45]. Recent research suggests it might be possible to deploy Solar Geoengineering in a way that would limit regional differences[46,47,48]. Nevertheless, some forms of Solar Geoengineering deployment could also result in significant regional differences. There are high levels of uncertainty about the full range of impacts of Solar Geoengineering, given that both academic research and public debate are still at an early stage. For example,

iv Note, however, that while for instance sea-level rise could be significantly slowed by Solar Geoengineering, it would not be perfectly counteracted due to divergent rates of change for surface air temperature and ocean thermal expansion (**Irvine et al., 2012**).

injecting aerosol particles into the stratosphere could — depending on the aerosol — influence ozone concentrations with mixed effects on ultraviolet radiation and thus cause potentially both positive and negative impacts on human and ecosystem health[49].

Finally, the climatic effects of Solar Geoengineering would only last as long as deployment was maintained. In the event of its discontinuation, global surface temperatures would be expected to rise rapidly towards the levels that would have been expected in its absence[50 51]. If Solar Geoengineering were being used to mask a large amount of warming, its sudden cessation could be very damaging as human and natural systems would have less time to adapt[52 53]. Given the severity of such a scenario, governance frameworks considering potential Solar Geoengineering in the future would need to be designed to limit the extent or entirely avoid such disruption[54].

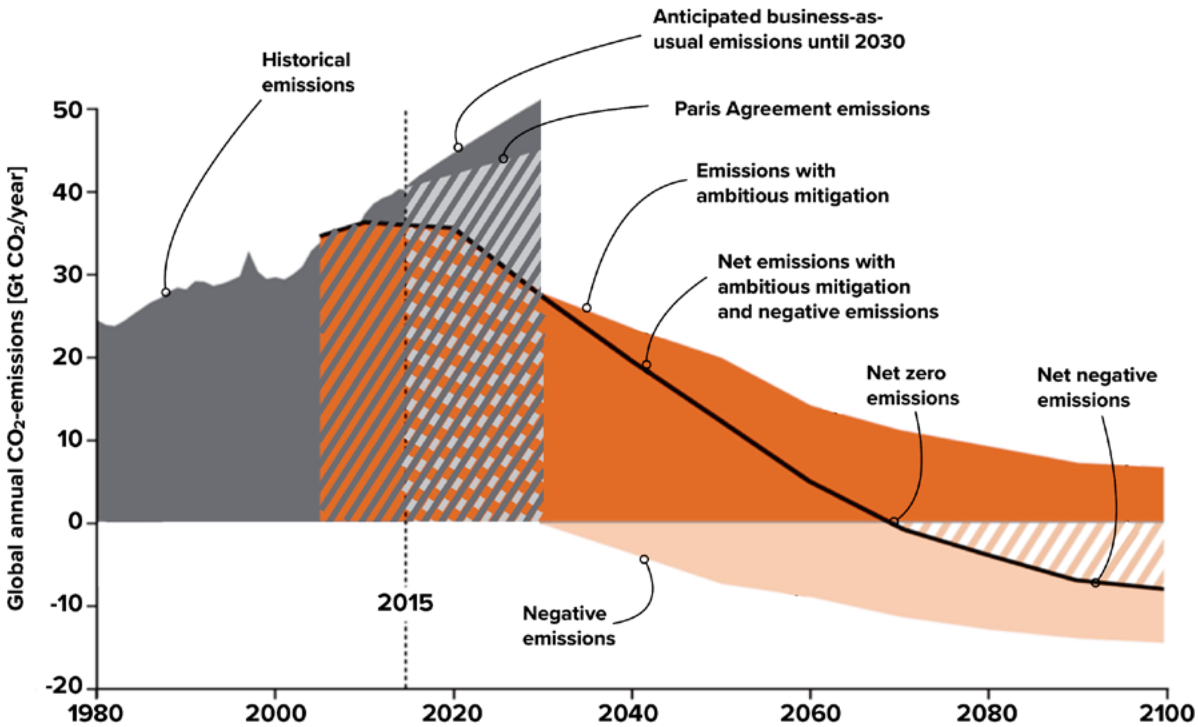
2. Potential scenarios for deployment

Before examining the potential implications that deployment of Carbon Removal and Solar Geoengineering technologies may have for delivering the SDGs, it is first useful to consider the different scenarios in which these technologies might be deployed.

2.1. Carbon Removal

A typical pathway to reaching the 2°C target includes significant deployment of Carbon Removal starting in just over a decade from now (around 2030), with a gradual increase over several decades eventually reaching annual removal rates in the order of up to half of current global annual emissions (i.e. 10-20 billion t CO_2)[55] (see **Figure 3**).

Figure 3: Median of IPCC[56] scenarios (black line) achieving 2°C by ambitious GHG emissions reductions (dark orange area), and rapid CR upscaling from 2030 onwards (light orange area). Carbon Removal rates in such scenarios eventually exceed the rates of remaining emissions (here this occurs around 2070). (Honegger et al., 2017, adapted from Anderson and Peters, 2016[57]).



This figure only shows cumulative annual removals without indicating how much different types of Carbon Removal would contribute and assuming there was a carbon price[v]

v The United Nations Global Compact (UNGC) has called for a minimum internal carbon price level of US$100/t$CO_2$-eq by 2020 in order to be consistent with a 1.5—2°C pathway — **UNGC (2016) Put a price on carbon — leading the way to a low-carbon future.**

sufficiently high to incentivise deployment[58]. It is also debatable that any single type of Carbon Removal approach could alone achieve the scale necessary (of 10-20 billion t CO_2 per year)[59 60 61].

Theoretical estimates of the technical potential of different types of Carbon Removal technologies often do not take into account socio-economic or political barriers (e.g. lack of attractive business cases, lack of public or political support, or opposition by particular interests). In view of such large scales of presumed Carbon Removal deployment, it is likely that socio-political and economic challenges would impose additional costs or constraints which must also be considered. Trade-offs would also likely increase with the scale of deployment and could already become a serious barrier to further deployment at comparatively small deployment levels, if past experience from e.g. biofuel production or Carbon Capture and Storage deployment serve as an indication[62].

The current emissions reductions pathway indicated by current Nationally Determined Contributions pledged by Parties to the Paris Agreement results in a substantial decline of global greenhouse gas emissions by 2030 but still leads to an approximate median global warming of 3°C by the end of the century[63]. Greater or lesser warming is also possible, given that uncertainty surrounding climate sensitivity and carbon budgets remains high[64 65 66 67]. Independently, the available global carbon budget for 1.5°C will in all likelihood be largely or completely depleted by 2030[68]. Any emissions occurring later would have to be removed from the atmosphere, if 1.5°C is to be achieved via emission reductions and Carbon Removal.

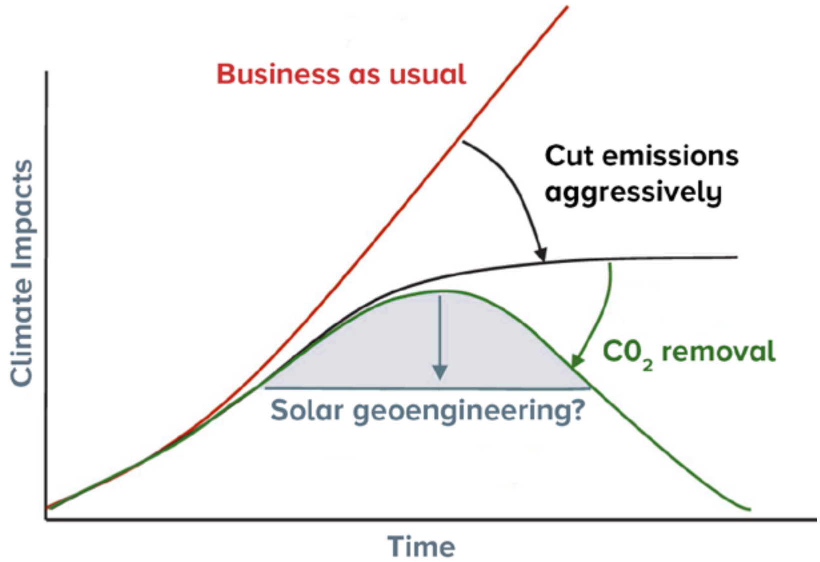
Understanding the potential contributions each type of Carbon Removal approach may make will require substantially more bottom-up assessment and exploration of realistic potentials informed by a diversity of perspectives including those of academics and practitioners. It is even conceivable that such exploration reveals realistic potentials of several Carbon Removal approaches being smaller than expected and that as a consequence, GHG emissions need to be mitigated and eliminated even more rapidly than is currently assumed[69]. In view of the ubiquitous trade-offs with other objectives, collaborative design of policies that can mobilize a portfolio of Carbon Removal approaches will take time.

2.2. Solar Geoengineering

The economic characteristics of Carbon Removal approaches are in most cases similar to existing mitigation techniques, their histories and expansion pathways. By contrast, Solar Geoengineering opens up some much more unfamiliar scenarios. It would likely take several decades until the understanding of regional and local outcomes, physical processes, technology development (delivery mechanisms), as well as the development of appropriate governance and societal responses would be sufficiently advanced for any serious and responsible consideration of Solar Geoengineering[70]. Independent of any of these, lack of social and political support for the large-scale manipulation of natural systems may prevent a legitimate deployment of Solar Geoengineering. The plausibility of Solar Geoengineering being deployed in a globally coordinated manner in the time window that is of primary relevance to the SDGs (pre-2030) appears rather limited. However, a small but relevant risk of unilateral, ungoverned deployment of some Solar Geoengineering techniques even before 2030 does exist. Given the potential risk that the global community misses the Paris temperature target, particularly in light of significant policy challenges of Carbon Removal deployment, the repercussions of potential Solar Geoengineering deployment on Sustainable Development beyond 2030 need to be understood.

Deployment of Solar Geoengineering could seek different outcomes depending on the timing and amount of warming to be counteracted by it. **Figure 4** indicates a scenario in which Solar Geoengineering is used to "shave off" the peak of climate impacts corresponding to warming temporarily exceeding 2°C before aggressive greenhouse gas mitigation and CO_2 removal result in lower greenhouse gas concentrations. Note that, as described in figure 4, climate impacts scale with greenhouse gas concentrations (not emissions).

Figure 4: Peak-shaving Solar Geoengineering deployment scenario[71]



Another possible use of Solar Geoengineering could be to slow the rate of warming, by gradually phasing in Solar Geoengineering and later slowly phasing it out again in order to reduce climate change impacts as societies and ecosystems would have more time to adapt[72].

Finally, a third potential use of Solar Geoengineering would be in a case where earth systems respond more rapidly to rising greenhouse gas concentrations than expected due to a high climate sensitivity and reinforcing feedbacks triggering a major shift in the climate system. Some types of Solar Geoengineering deployment could potentially slow or halt such developments, but uncertainties are very large in such extreme scenarios and it is debatable whether the international community would be capable of coming up with appropriate governance measures under such circumstances[73]. Climate change-related implications for SDG delivery varies greatly depending on the level and rate of warming and the scenarios in which Solar Geoengineering might be deployed.

3. Potential implications of deploying Carbon Removal

In this chapter we explore each of the six major types of Carbon Removal examined for this report, explaining key characteristics and discussing possible implications their deployment may have for delivering the SDGs.

3.1. Afforestation and Forest Ecosystem Restoration

Forestry-based Carbon Removal can be achieved by either increasing forest area, enhancing forest density or the carbon content of forest soils through reforestation (planting trees in deforested areas), afforestation (planting trees in historically treeless areas), and forest management.

Afforestation can have opportunity costs for land-use (such as displacing agricultural land) and while some types of locally adapted forestry (e.g., agroforestry) can provide important benefits for local communities and ecosystems, others can displace indigenous communities or isolate people from ecosystem services, e.g. when commercial plantations prevent local communities from harvesting wood or other forest products[74].

Afforestation and commercial reforestation projects often use monocultures of fast-growing species such as pine and eucalyptus[75] and significant albedo changes can result from afforestation with certain species, resulting in additional warming, potentially counter-acting any benefits from the CO_2 removed[76]. While targeted afforestation projects have the potential for slowing or halting desertification, large-scale afforestation in unsuitable areas can lead to nutrient and water limitations as well as fertilizer runoff with implications for local ecosystems and communities[77].

Climate policy around forestry and land-use has seen limited success to date. Restoring carbon stocks previously lost through land-use changes takes decades and policy instruments have so far failed to consistently achieve such reversals due to increasing pressure on these resources in developing countries and limited willingness among industrialized countries to support ambitious policies in developing countries[78].

As for all forms of Carbon Removal, a key challenge for implementation is ensuring the permanence of CO_2 storage. In the case of forestry, the risk of 'carbon leakage' from future land-use changes or forest fire are key challenges[79].

The issue of scale is key to what implications this type of Carbon Removal may have for SDG delivery. Large-scale monoculture plantations executed in a top-down, non-participatory manner are likely to result in negative implications for delivering many of the SDGs[80 81] whereas other community driven approaches could be scaled-up in ways to ensure substantial net positive implications for SDG delivery. Effective governance will be essential to balance the crucial contribution of afforestation and forest ecosystem restoration with other Carbon Removal and climate mitigation options to maximise the benefits to SDG delivery.

3.2. Bioenergy with Carbon Capture and Storage (BECCS)

Bioenergy with carbon capture and storage (BECCS) is a technology that so far has not been implemented at large-scale, although its two technology components: (i) Bioenergy; and (ii) Carbon capture and storage (CCS) are already well known[82]. In most future mitigation policy scenarios BECCS plays a significant role, often accounting for several hundred billion tCO_2 cumulatively being removed by 2100[83]. Sustainable Development considerations are largely missing from the corresponding literature and only now, the research community is paying increasing attention to the potentially significant implications of large-scale BECCS applications[84].

A first observation with regard to implications for SDG delivery, is that the primary reason for these models to anticipate such large amounts of BECCS is a general trend toward more energy being sourced from biomass[85]. Achieving an annual CO_2 removal rate of 10 billion tCO_2 through BECCS would require a global increase in power generation capacity from biomass by an order of magnitude and equipping all these plants with CCS technology[86]. Both requirements represent a serious departure from current trends, especially considering the lukewarm acceptance and support for CCS projects to date[87]. CCS has faced significant challenges regarding its costs which are exacerbated if it is to be applied in a decentralized manner, as may be necessary due to limited availability of reliable geological storage in the vicinity. There will be significant regional differences in the availability of suitable geological repositories for reliable CO_2 storage, which could have implications on aspects of fairness of accruing revenues or resource-conflicts. If storage sites are unavailable close by, transportation of compressed CO_2 through dedicated pipelines or on roads, rails or water needs to be undertaken, with corresponding risks. Past experiences with geological storage of CO_2 have raised concerns over potential toxicity of CO_2 leaking into underground water resources[88]. While some literature suggests these impacts may be manageable[89], overall, CCS implementation has been much less successful than hoped for by many experts in the mid-2000s[vi]. Technically, captured CO_2 could also be used as a resource for long-lived carbon-based products (e.g. in construction), however the demand and potential market for such products pales in comparison to the CO_2 that is to be removed from the atmosphere.

Importantly, a distinction is to be made between BECCS fuelled by waste-biomass compared to BECCS drawing on dedicated biomass plantations. While the former would affect nutrient cycles due to the removal of residual biomass from natural cycles, the latter would have more far-reaching implications due to the necessary land-use change.

vi For the optimistic estimates in the mid-2000s see IPCC (2005).

Most IPCC scenarios achieving 2°C include large volumes of plantations, requiring a change in land-use for massive amounts of productive lands (around one third of current global cropland)[90]. Changes in land use at such scales would have significant implications for delivery of numerous SDGs, most notably due to conflicts over land-use, water, and changing nutrient cycles. The impacts of BECCS on life on land depends largely on local conditions, for example where dedicated plantations replace primary forests, biodiversity is almost inevitably reduced[91]. Furthermore, large impacts on water use are likely[92], requiring in some scenarios up to 3 percent of the fresh water currently appropriated for human use[93].

There could be significant indirect social implications depending on policy design, where for example, top-down, non-participatory approaches to planning and implementing BECCS may impair delivery of some SDGs compared to other more participatory approaches[94].

Another second-order implication of this technology is that the CCS component will always remain an additional cost factor, rendering BECCS less economically attractive than bioenergy without CCS in the absence of dedicated financial incentives. Creating such incentives could redirect resources from other activities with implications for delivery of related SDGs. In addition to potentially displacing primary forests and thus releasing much of the stored carbon content, bioenergy plantations are vulnerable to unintended carbon loss through disease, pests and fire as well as potential impacts of future climate change[95].

Given the current conceptual reliance on mitigation pathways that include large-scale BECCS deployment, technological and institutional challenges must urgently be addressed[96].

3.3. Enhancing Soil Carbon Content (e.g. with biochar)

Soil carbon sequestration aims to increase soil carbon stocks through land management practices such as reducing agricultural tillage, planting species with deep roots or by incorporating biochar which can result in long-term storage[97] [98]. Soil carbon sequestration through agricultural practices could in theory result in Carbon Removal with substantial benefits for the delivery of various SDGs, but its capacity to do so varies regionally and is limited once soil carbon reaches an equilibrium[99] [100]. In principle, a significant amount of soil carbon sequestration is possible by partially restoring the levels of carbon lost from historic land use[101], which are estimated at 840 billion t CO_2e in the last 10,000 years[102]. However, the maximum global removal rates have been estimated at approximately 1 Gt CO_2 per year[103] with further potential limitations associated with changing agricultural production practices and corresponding trade-offs with economic productivity or efficiency[104].

There are a number of practices that can contribute to enhancing the soil carbon content including particular forms of vegetation management, nutrient management, cover crops, and crop rotation, minimum tillage and others. Carefully chosen combinations of such approaches can be beneficial in enhancing water retention capacities, reduce soil erosion, enhance crop production, sustaining soil fertility, but trade-offs also exist[105] [106] [107]. Yet a policy design that prioritises carbon sequestration above all other objectives could also negatively affect biodiversity due to changes in fauna and flora[108].

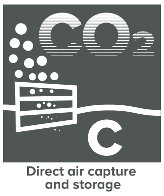
Large-scale deployment could have significant negative socio-economic implications. For example, production, transportation and handling of biochar is energy intensive and could endanger health of those involved in the process, due to potential exposure to airborne carcinogenic particulates[109]. Additionally, mandating biochar use in agricultural practices, could increase food prices while providing financial incentives could reduce them [110]. Soil carbon enhancements could potentially be implemented via participatory, community driven approaches, with benefits for a range of SDGs, whereas the opposite could also be true, if e.g. policies create incentives for large-scale and non-participatory agricultural changes.

3.4. Enhanced Weathering or Ocean Alkalinisation

Weathering of silicate minerals on land to form limestone in the ocean is a natural process that removes carbon from the atmosphere. Enhanced weathering aims to speed up this process by spreading crushed silicates onto the land surface — an effect that is in principle well known, but large uncertainties remain regarding the effective rate of weathering under varying conditions[111] [112]. Costs are estimated at US$ 60-200 per tCO_2[113] and the large-scale mining and grinding operations and physical distribution of the minerals required to scale up enhanced weathering could have substantial health, economic and ecosystem implications.

A related technique involves dispersal of alkaline powder (e.g. olivine, calcium carbonate, quicklime, or calcium hydroxide) directly onto the surface of the ocean, resulting in principle in dramatically higher chemical CO_2 uptake and storage (940 billion tCO_2 in one scenario[114]). Oceans represent the largest carbon sink globally, but ocean carbon uptake is slowing down due to surface water acidification and warming caused by climate change[115] — ocean alkalinisation would in principle counteract this trend. Regional differences of alkalinity enhancement in relation to dispersal points could result in substantial local changes in ocean water chemistry with impacts on marine ecosystems.

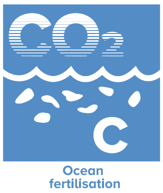
Enhanced weathering processes and ocean alkalinity enhancements would counter soil or aquatic acidification, which could to some degree be a positive outcome unless it resulted in uneven or overly rapid changes exposing ecosystems to stress[116]. Unwanted airborne dispersal of mineral dust could, however, cause respiratory problems both for miners engaged in their extraction and communities close to extraction and deployment sites. Additional pollution may in both cases also result from transportation of materials and additional energy requirements of grinding and transportation.



3.5. Direct Air Capture and Storage (DACS)

Direct Air Capture and Storage (DACS) describes the combination of direct air capture — a technology that removes CO_2 from ambient air via a chemical process — with carbon capture and storage. Capturing processes applied in pilot installations to date are very energy intensive with cost projections making DACS one of the highest cost Carbon Removal options at present[vii]. Some suggest costs could fall[117], enough to bring them into the range of potential future carbon prices[8] but all economic estimates remain highly uncertain in the absence of large industrial-scale pilot activities. Large-scale DACS deployment would therefore likely require significant public spending with large opportunity cost for support to other public-funded activities which may support SDG achievement. On the other hand, DACS' independence of biological or agricultural processes renders it a potentially attractive option to remove large quantities of CO_2 without major implications for ecosystems. But, similar to BECCS, DACS does not appear economically viable until financial incentives matching the combined cost of Direct Air Capture and Storage are made available.

In the absence of serious research and development spending that could lower the cost and improve cost-estimates, costs are currently crippling the potential role of DACS despite it largely avoiding key challenges that other Carbon Removal techniques exhibit, i.e. lesser concern over land-use conflicts, health implications or effects on ecosystems.



3.6. Ocean Fertilisation

The oceans are responsible for about half of the planet's natural CO_2 removal with a substantial contribution of phytoplankton living on or near the ocean surface: a small fraction of plankton biomass sinks to great depths before decomposing — a process known as the "biological carbon pump"[118]. Growth of such phytoplankton is often limited by lack of nutrients such as nitrate, phosphate or iron. Where this is the case, this biological carbon pump action could in theory be enhanced by a process of fertilizing surface waters with such nutrients. Ocean fertilization using iron has a natural analogue, where iron-rich desert dust or volcanic ash or dissolving iron-rich rocks have triggered accelerated phytoplankton growth[119 120 121].

Deploying Ocean Fertilizing using macronutrients (such as nitrate or phosphate) would require very large amounts of material and correspondingly very large mining and transportation operations with the corresponding challenges of large energy demands and potential environmental pollution. Such resource needs would also potentially compete

vii Estimates range between US$200/t$CO_2$ (**Lackner, 2009**; **Lackner, et al., 2012**;) to US$600-1000/t$CO_2$ (**Socolow et al., 2011**; **House et al., 2011**).

with agricultural fertilization[122]. Fertilizing with micronutrients (such as iron), would require considerably less mass and thus drastically reduce some implications further along the value-chain.

The efficacy of CO_2 removal by ocean fertilization is not yet determined as scientific research in the open ocean has yielded widely differing results. While evidence suggests that it is possible to enhance algal and plankton growth, there remain serious uncertainties regarding the actual volume of CO_2 removed from the atmosphere and in some cases responses in the oceanic food-chain have prevented additional biomass from sinking to sufficient depths[123, 124].

If ocean fertilization works as intended it could potentially have beneficial outcomes on fishery productivity, however, in view of significant uncertainties and likely regional differences, negative outcomes are also entirely possible.

4. Potential implications of deploying Solar Geoengineering

In this chapter we explore each of the three types of Solar Geoengineering examined for this report, explaining key characteristics and discussing possible implications their deployment may have for delivery of the SDGs.

Additional to examining these three types individually, a number of overarching general observations can also be made from the existing literature.

Firstly, Solar Geoengineering is often presented as distinct from greenhouse gas mitigation and Carbon Removal in three key ways[125]: (i) direct deployment costs are potentially low; (ii) effects are potentially very rapid and large; and (iii) evaluation may be better characterised as a risk-risk trade-off (namely, the risks of use are presented as potentially lower than the risks from climate change without use)[126]. However, confidence in such claims is relatively low given the limited body of research available to substantiate them.

Secondly, the climate-related effects of Solar Geoengineering would depend to a large extent on underlying greenhouse gas concentration levels[127] and the pace of deployment, with any kind of rapid phase-in or phase-out likely being harmful[128]. For example, a globally uniform deployment of Solar Geoengineering theoretically has the potential to keep the climate system close to its pre-industrial state (at levels where climate related risks are substantially reduced) [129]. It is essentially uncontested that limiting global warming to 1.5°C rather than 3°C by means of drastic emissions cuts and removal of CO_2 would significantly reduce climate change impacts detrimental to development outcomes[130]. Therefore, in a scenario where emissions cuts remained insufficient (resulting in 3°C or more of warming), it could be argued that limiting warming to 1.5°C through deployment of Solar Geoengineering would present a relatively lower overall risk to development outcomes[131] [132]. However, sudden termination of any such Solar Geoengineering deployment could cause a disruptive change in climate that would have potentially massive detrimental impacts on human development and ecosystems[133] [134].

Some forms of uneven deployment of Solar Geoengineering (e.g. solely in one hemisphere) could have serious impacts on atmospheric circulation and the hydrological cycle resulting in disruption to development outcomes across many regions. Similarly, as Solar Geoengineering is expected to affect changes across a range of earth system variables (e.g. temperature, precipitation, sea-level rise) at different rates, it appears to represent an imperfect limitation of climate change at best. Deploying Solar Geoengineering in a scenario of unabated emissions and very high atmospheric GHG concentrations (>1000ppm) to fully counteract the associated warming would likely result in substantial differences regarding precipitation in various regions[135] [136] [137].

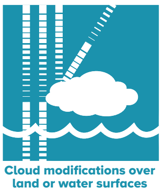
4.1. Stratospheric Aerosol Injection (SAI)

Stratospheric Aerosol Injection (SAI) seeks to increase the amount of aerosol particles in the lower stratosphere (at altitudes of around 20 km), thus increasing the reflection of sunlight back into space[138]. Particles could theoretically be injected directly or formed via injection of precursor gases such as sulphur dioxide (SO_2) which are then converted into particles.

Deployment mechanisms and the choice of substances that could be used for SAI would determine the direct physical side-effects and to date there is no sufficient empirical evidence to assess the feasibility of any specific delivery mechanism or substance. Theoretically, if SAI were undertaken with sulphate aerosols, these would likely contribute to acidification and elevated tropospheric sulphur content[139], as well as potentially delay in the recovery of the ozone layer[140]. However, if other substances were used, impact on delivery of some SDGs may even become positive. For example, using calcite aerosols might accelerate recovery of the ozone layer and counteract acidification of the oceans and soils caused by the use of fossil fuels[141].

Direct deployment costs of SAI have been estimated in the order of US$10 billion per year, globally[142]. However, overall costs of deployment would be higher due to the requirement for global policy coordination, large-scale observation and modelling efforts to monitor consequences, security measures to protect the deployment infrastructure, and redundancies in the delivery equipment[143]. Costs of large-scale public projects can also be expected to increase beyond early estimates, as e.g. seen for nuclear energy[144].

Even if Solar Geoengineering resulted in a net reduction of harm from climate change around the world, some areas would likely still experience negative environmental effects, potentially triggering demands for compensation[145]. For example, dispersal of light reaching the earth's surface would likely have significant implications for plant growth[146], with associated implications for agricultural productivity or food security and numerous cultural implications resulting from associated phenomena such as potential changes in the colours or visibility of the sky.



4.2. Cloud Modifications over land or water surfaces

Radiative energy from the sun (both visible and invisible) is scattered or reflected away by clouds to a greater or lesser extent depending on the size of the water droplets from which they are formed (observed in the differing colour of clouds).

Solar Geoengineering techniques aiming to modify levels of cloud reflectivity to influence global temperatures, could in theory be pursued by 'seeding' clouds with small particles that act as nuclei around which water vapour droplets form to create clouds. This mechanism could, in theory, be used to either brighten clouds to reflect more sunlight away (in particular over heat absorbing dark ocean surfaces) or to thin higher altitude (cirrus) clouds to enhance transmission of radiative energy from the earth's surface back into space. Particles could theoretically be delivered via ships to seed low-lying clouds above the oceans, or by airplanes to influence high-altitude cirrus clouds.

The direct physical effects flowing from the deployment of cloud modification techniques would be dependent on the particle types, the quantities of deployment and the location of deployment as well as potential emissions from ship or airplane operation. In the case of ocean-based cloud seeding using seawater, these impacts might be in large part indistinguishable from the natural fluctuations of sea-salt concentrations in the air above the ocean surface and in coastal regions. However, in some locations, local deposition rates might be sufficiently high to have corrosive effects on coastal infrastructure and negative effects on soils[147]. In the case of cirrus cloud thinning, the necessary amounts of seeding substance are thought to be relatively small[148], such that the impact of jet fuel emissions resulting from deployment might be more significant. Reliable estimates are currently lacking given vast uncertainties over various delivery mechanisms' efficacy[149].

Climate change related implications of cloud modification Solar Geoengineering are highly uncertain, given that cloud physics and chemistry are two of the most complex areas of climate science[150]. Unless a deployment mechanism is found that allows relatively homogenous cooling through cloud-based Solar Geoengineering, regional differences of impacts on the hydrological cycle[151] [152] as well as on temperature[153] [154] could pose a serious challenge[155]. Given the very limited work on potential delivery mechanisms, as well as very substantial uncertainties surrounding the physical and chemical properties of clouds, significant adverse implications on ecosystems and agricultural systems stemming from such regional differences cannot be ruled out.

The potential socio-economic implications of deploying cloud based Solar Geoengineering techniques would — in view of potentially considerable regional differences in effects — pose significant challenges for equity, governance and sub-national and international relations in potentially affected regions.

Surface albedo modifications

4.3. Surface Albedo Modifications

In theory, any land or ocean surface could be covered by reflective materials or with plants that have a higher reflectivity resulting in local or regional cooling. While increasingly considered for the purpose of local adaptation to climate impacts of e.g. counteracting urban heat islands[156], to reduce energy costs for cooling buildings or for preserving glaciers or polar ice-masses, these techniques are not always considered a geoengineering measure, as it is hard to conceive of covering sufficiently large areas with artificial materials or a particular breed of plants to achieve a globally significant cooling effect.

The direct physical implications of deployment at scale could be large. Covering significant land or water surfaces with artificial materials would directly affect a range of physical systems including hydrological cycles[157], plant growth and natural transportation of minerals (which play an important role in conveying nutrients into aquatic systems) among many others. Production of the necessary materials in large quantities (such as foils or paint), could also cause substantial environmental harm, and come with energy requirements resulting in additional GHG emissions. Furthermore, through natural erosion processes the materials would inevitably end up in numerous ecosystems including the oceans, where they would — depending on the materials used — potentially contribute to pollution.

The potential benefit to counteracting global climate change using Surface Albedo Modification is uncertain, given that large scale applications would likely be inherently patchy on a global scale they would likely result in significant regional differences[158]. Localised Surface Albedo Modification (e.g. painting buildings or road-surfaces white) could serve as a combined adaptation/mitigation measure with potentially substantial benefits. Where aligned with other objectives of agricultural or forestry practices, selecting particular crops for having a higher reflectivity can result in a local cooling effect, which can also potentially be beneficial in rural areas. Surface Albedo Modifications in the arctic region could potentially slow arctic ice melt, but the efficacy and feasibility of such interventions remain highly uncertain[159].

5. Potential implications for delivery of the SDGs

In this chapter we summarise the potential implications that deployment of Carbon Removal and Solar Geoengineering could have for reaching each of the seventeen Sustainable Development Goals (SDGs) based on analysis included in Appendix 1. They can be both negative or positive.

The potential implications identified for the SDGs are likely to differ strongly depending on the assumed scale of deployment as well as the policy pathways and broader governance contexts in which they would be deployed.

As stated earlier, it is important to note that while this report endeavours to present a balanced, impartial and evidence-based view of potential implications, significant gaps in knowledge mean that a comprehensive discussion of pros and cons for each technology (or combinations of technologies) is still far from possible at this stage.

Table 3 (page 31) provides an overview of the more detailed goal-by-goal review of potential implications presented in the appendix. For each of the technologies examined we highlight where current research and knowledge suggests a potential interaction or risk exists for each respective SDG and where implicit or explicit research gaps are identified. The summary presented in this table does not imply any comparison of relative magnitude or importance as this remains largely unclear in the literature.

While we present here some initial insights into potential interactions and risks of deploying Carbon Removal and Solar Geoengineering technologies, it is important to note that the decision not to deploy such technologies in future (i.e. Business as usual) will also have significant implications for delivery of the SDGs to a greater or lesser extent. Any kind of cost-benefit analysis to inform considerations of whether or not to deploy such technologies in future, will require considerably more detailed, transdisciplinary assessment of implications for SDG delivery, which far exceeds the scope of this report.

Table 3 (page 31): Initial exploration of potential (non-climate) interactions and research gaps identified in the literature review. Any benefits from reductions in climate impacts that would result from successful deployment are not included here given large uncertainties around efficacy and feasibility although these could potentially be very substantial in some cases.

Legend:

Potential research gap identified: No substantial interaction found in the reviewed literature — a potential research gap or may require policy impact assessments

Key research gap identified: gaps identified in the reviewed literature - likely requiring dedicated research efforts

Interaction identified: challenging interactions found in reviewed literature, requiring particularly careful policy design

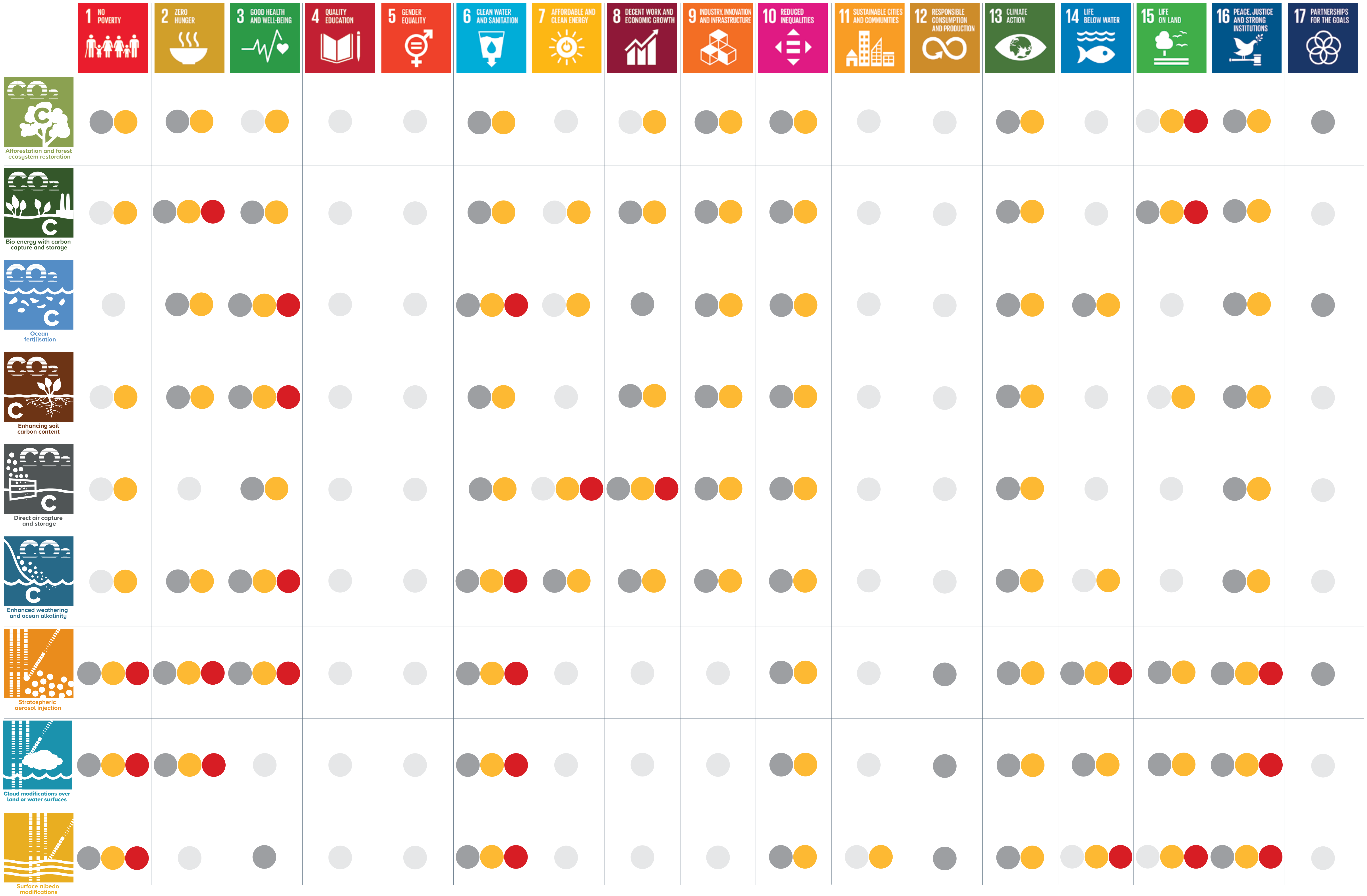
Risk identified: risks identified in the literature, which would require substantial dedicated research and assessments before considering deployment

Potential research gap identified

Key research gap identified

Interaction identified other than climate related

Risk identified



6. Conclusions and recommendations

While deployment of Carbon Removal may be needed to limit climate change to well below 2°C and while Solar Geoengineering technologies might potentially help mask climate change impacts, observations from the literature and expert review undertaken for this report suggest that these technologies would also have significant implications (physical, socio-economic and political) for delivery of most (at least 13 out of 17) SDGs. Whether these are negative or positive strongly depends on the specificities of technology deployment. Carbon Removal and Solar Geoengineering technologies could create risks for the successful delivery of more than half of all SDGs (at least 9 out of 17 SDGs) including: **SDG-6** (Clean Water and Sanitation), **SDG-3** (Good Health and Well-being), **SDG-1** (No poverty); and **SDG-16** (Peace, Justice and Strong Institutions). Further risks are also identified for delivery of **SDG-2** (Zero hunger), **SDG-14** (Life below water), **SDG-7** (Affordable and clean energy), **SDG-8** (Decent work and economic growth) and **SDG-15** (Life on land).

We have idenitified potential physical side effects and limitations of the technologies' capability to reduce or reliably mask climate change impacts, with implications including for:

- **Land use and food security** — where Carbon Removal could lead to conflict over land-use allocation and thus directly and indirectly impact on livelihoods or food security. Reductions in local precipitation from some forms of Solar Geoengineering could affect food security;
- **Water quality** — where Carbon Removal could result in ground water pollution from carbon storage or mineral mining processes. Land-use changes due to bioenergy and sequestration-oriented forestry could increase nutrient run-off. Stratospheric Aerosol Injection could change the chemistry of freshwater or ocean environments;
- **Water availability** — where Carbon Removal requires carbon capture processes or land-use changes for increased biomass with high water demand. On the other hand, some forms of land-use changes which increase upstream water retention could reduce downstream flood-risk.
- **Biodiversity** — where land-use changes for some Carbon Removal could cause pressure on land-areas rich in biodiversity, reduce water availability. However, if designed properly, in specific cases these land use changes could align with conservation or restoration efforts. Stratospheric Aerosol Injection could affect ecosystems sensitive to acidification or alkalinisation with potentially mixed — positive and negative — effects on plant growth and fauna.
- **Health** — where respiratory problems may result from exposure to substances and processes involved in production of biochar or minerals for enhanced weathering or production or Stratospheric Aerosol Injection particles. Solar Geoengineering could also have various impacts on the ozone layer and influence ultraviolet light levels affecting skin cancer and potable water quality.

- **Energy security** — where energy demands of most forms of Carbon Removal (geological storage of CO_2, Direct Air Capture, biochar production or grinding and transportation of minerals for alkalinity enhancement or ocean fertilisation) could lead to strong competition for energy. Stratospheric Aerosol Injection could potentially reduce yields of concentrated solar power and potentially enhance yields of solar photovoltaic cells. Solar Geoengineering might reduce energy demand for cooling and air-conditioning through temperature decrease.
- **Economic productivity** — where Carbon Removal technologies lead to competition over land, water or minerals driving up prices for key commodities. The high cost of many Carbon Removal technologies could require large public expenditure with opportunity costs and result in an economic burden (e.g. through increases in energy prices). Carbon Removal or Solar Geoengineering deployment could impact productivity of fisheries or agriculture or increase demands on transportation infrastructure. On the other hand, research and development of Carbon Removal and Solar Geongineering technologies could stimulate innovation.
- **Cultural impacts** — where for example Carbon Removal requires land-use changes or changes in agricultural practices with cultural implications for rural communities or where Solar Geoengineering leads to changes in the colours of the sky. Deployment of large-scale Carbon Removal or Solar Geoengineering would also mark a fundamental shift in human-environment relations.

We also identified a number of critical political implications including:

- **Opportunity costs of technology development and deployment** — where focus on Carbon Removal or Solar Geoengineering could shift political attention and public spending away from emissions reductions or other priorities for achieving the SDGs.
- **Political tensions** — where negative effects of Carbon Removal technologies and Solar Geoengineering as described above affect countries or regions unevenly, and extreme weather events potentially come to be seen as blameworthy. This may require a governance system that allows for some form of compensation, which may be exceedingly difficult. Coming to agreement on how to share costs of and control over Solar Geoengineering or Carbon Removal deployment would be challenging.
- **Governance demands** — where there is limited understanding of how to globally coordinate any potential deployment of Carbon Removal or Solar Geoengineering, or how to anticipate and manage the risk of transboundary impacts. Governance needs to manage political and economic interests which may influence governance in ways which create or exacerbate inequalities.

Given the current relative immaturity of Carbon Removal and Solar Geoengineering technologies[160], substantial uncertainties remain and the breadth of scientific understanding is limited. Furthermore, no comprehensive assessments of what implications these technologies could have for SDG delivery have yet been undertaken. We identify research gaps which could warrant further investigation, including:

- **Overall effectiveness of Solar Geoengineering at reducing climate change impacts —** Can Solar Geoengineering technologies be effective in achieving their intended outcome: reducing climate change impacts consistently and across regions and climate variables without substantial adverse changes to local weather patterns, also taking into account economic, political, cultural and ethical prerequisites for this?
- **Overall feasibility and scalability of Carbon Removal** — To which extent will economic costs, societal and political support and environmental implications allow for scale-up of Carbon Removal technologies to result in a substantial contribution to mitigating climate change?
- **Agriculture and food security impacts** — What net impact could different Carbon Removal or Solar Geoengineering technologies have on agriculture and food security of various regions, also in light of expected reductions in agricultural productivity due to climate change impacts? How would these Carbon Removal technologies interact with other mitigation measures including large increases in biomass-based energy generation?
- **Environmental impacts** — What are net local environmental impacts of Carbon Removal or Solar Geoengineering on aquatic and terrestrial ecosystems?
- **Socio-economic impacts** — What are regional and global socio-economic implications of Carbon Removal-related land, energy, mineral and water resource needs? How would prices of resources be affected by different Carbon Removal or Solar Geoengineering technology combinations? What are potential impacts on the poorest or on women and girls in various cultural, economic and social contexts from Carbon Removal / Solar Geoengineering-induced changing land-use practices, increasing land-use pressures or altered precipitation patterns? How could Carbon Removal or Solar Geoengineering affect efforts to shift economies to more sustainable consumption or production patterns?
- **Regional differences** — How might physical side effects of Carbon Removal or regional differences in climate parameters generated by Solar Geoengineering impact on social and economic parameters (e.g. poverty eradication, reduction of inequality, well-being, economic and food productivity etc.) within various local contexts including under different water, energy, land, mineral, transport, geological storage potential and infrastructure availabilities and needs?
- **Health impacts** — What are the potential impacts from increasing exposure to specific airborne particles resulting from Carbon Removal or Solar Geoengineering? Could such impacts be effectively mitigated? What are safe potentials for geological storage of CO_2, taking groundwater quality and human health into account?
- **Policy instruments** — What conditions, financial incentives and policy designs could ensure Carbon Removal or Solar Geoengineering research or deployment could positively contribute to SDG achievement? Could policies be designed to balance trade-offs across issue areas? Could innovation and scaled-up action beneficial to other areas of SDG delivery be stimulated through policies relating to Carbon Removal or Solar Geoengineering research, development or deployment?

- **Governance** — Would Solar Geoengineering or Carbon Removal strengthen or challenge collaboration across institutions involved in governing climate change action at multiple levels? Would they strengthen or weaken political support for greater mitigation efforts? What implications might they have for important principles such as equity and burden sharing of mitigation action? What forms of governance might work best (e.g. more centralised or more polycentric and dispersed)? What forms are more likely to help or hinder SDG attainment? How to ensure public interests prevail over private interests? Which stakeholders should be engaged in designing effective governance and how? How to address power inequality and conflicting interests?

Given the complexity of these research questions and the salience of getting robust answers, future research exploring deployment scenarios would need to incorporate insights across a broad range of disciplines and practical expertise in various policy areas. If research and development of Carbon Removal or Solar Geoengineering technologies comes to be pursued more actively, ensuring that any potential benefits from reduced climate change impacts are not outweighed by negative environmental, social, economic and political effects would be crucial. As a consequence, it would be important for researchers to start more systematically engaging with more diverse groups of stakeholders in an ongoing, reflexive process of mutual learning. At the same time, the geographical balance of the research needs to be enhanced. Currently, research on this subject is pioneered by a small number of research institutions in the global North and efforts to strengthen participation of researchers in the global South are emerging only slowly[161] [162]. There is broad agreement within the scientific community that North-South, South-South and triangular regional and international cooperation is crucial when further exploring and researching Carbon Removal and Solar Geoengineering. Suspicions of conflicting national motives in research and assessment could arise very easily in a wider debate on Carbon Removal and Solar Geoengineering — not least due to potentially significant implications for national priorities. It would thus be important to ensure that the science is broadly based, not least to enable public debates in various cultural contexts that inform respective political leadership[163].

The observations presented in this report also have important implications for governance of the research or potential deployment of these technologies. To date, despite a limited number of multilateral conventions having begun to address certain aspects of governance (such as decisions taken under the Convention on Biological Diversity[viii] and amendments to the London Convention/London Protocol[ix]) no comprehensive international framework for governing these technologies currently exists. Given the vast implications of Carbon Removal and Solar Geoengineering technologies for delivery of the SDGs, there is an urgent need to ensure sufficient attention is paid to such Sustainable Development implications in any future governance arrangements.

viii The Convention on Biological Diversity (CBD) provided guidance to countries for considering conditions under which to undertake (or not) climate-related geoengineering activities. See: **www.cbd.int/climate/geoengineering/**

ix The London Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter addressed specific marine geoengineering processes, such as ocean fertilization, first as a nonbinding decision of the Conference of the Parties and later as binding amendments. See: **www.imo.org/en/OurWork/Environment/LCLP/Pages/default.aspx**

This report has described key types of Carbon Removal and Solar Geoengineering technologies currently under consideration, and examined what possible implications they might have for delivery of the SDGs if they were ever deployed (including identifying areas for further research to help better understand these implications). We conclude here with a number of recommendations:

- **More transdisciplinary and geographically diverse research is required on the interconnections between Carbon Removal and Solar Geoengineering and delivery of Sustainable Development, which may include development of common assessment principles or metrics.** There is hardly any literature addressing Carbon Removal and Solar Geoengineering implications for Sustainable Development and given the high levels of complexity and interactions between SDGs[164] and climate change, research on interconnections will be important (as emphasised in the context of biodiversity by the Convention on Biological Diversity (CBD) decision XIII/14[165] calling for more transdisciplinary research (i.e. involving non-academic stakeholders) and sharing of knowledge about climate engineering). This could be achieved through novel collaborations across research communities, development of common assessment approaches that cover the full range of the SDGs and could be strengthened by corresponding design of collaborative, international research programmes. Increasing the representation of women and enabling researchers in various geographical, cultural and disciplinary contexts to engage on such research could help reduce blind spots, strengthen understanding of sensitivities around regional differences, allow building up decision-making capacities in countries involved and avoid creating or exacerbating inequalities through research, policy design, governance or potential deployment.
- **Comprehensive quantitative analysis of potential risks and benefits of Carbon Removal and Solar Geoengineering is needed to avoid under- or over-estimating climate and Sustainable Development impacts.** This should include scenario development co-created with involvement of practitioners, scholars of various disciplines and systems-based modelling which provides insights at various levels, ranging from the global to the local. Such modelling could draw upon, be aligned with, or even incorporated into existing climate and development modelling tools.
- **More social science and humanities research is needed, including critical reflection on the role of science and technology in the context of the SDGs.** This should include historical, cultural, political and other forms of critical academic investigation of the expectations and assumptions underlying scenarios of Carbon Removal and Solar Geoengineering, and the speculative promises made on their behalf.
- **Integrated policy impact assessments are needed to understand potential policy designs to mobilise Carbon Removal and Solar Geoengineering and what implications they would have for delivery of the SDGs.** In particular, for Carbon Removal the overall potential rates of CO_2 removal and potential for stable, long-term storage is a crucial variable for global and national decision-making.

- **Governance of research and any potential future deployment of Carbon Removal or Solar Geoengineering will need to be carefully designed to ensure its support for Sustainable Development and to reduce the risk of negative impacts.** The quality of governance will be decisive and will need to consider critical issues: How can research on these technologies complement rather than distract from strengthening emissions reductions efforts? At which point should one embrace or reject technologies so as to prevent premature lock-in or exclusion? How can policy instruments be designed to mobilize technologies while ensuring their compatibility with Sustainable Development? How should decision-making and public dialogue be structured to allow informed decisions on whether and how to proceed with basic and applied research programs? How can relevant governance capabilities be built within countries of widely differing capabilities? How should responsibilities be differentiated between national and international institutions?

Appendix 1: Potential implications for each SDG

For each SDG, we highlight current knowledge of the potential physical side-effects, climate-related, socio-economic and political implications that Carbon Removal or Solar Geoengineering could have for delivery and suggest possible areas for further research. The issues listed under each SDG are by no means exhaustive and as noted in the introduction are intended more as a conversation starter, rather than a final word.

Limits to current knowledge around these technologies render detailed assessment of potential implications highly challenging at this stage and in many cases the issues presented here rely on expert opinion and extrapolations based on broader understanding of physical, socio-economic, and political processes.

SDG-1: End poverty in all its forms everywhere

Potential physical side-effects:

- Land-based Carbon Removal could lead to conflicting demands for land and water, disproportionately effecting poorer communities especially those that lack formal ownership titles or access to means to enforce ownership rights.
- Processes for producing substances used in some forms of Carbon Removal (e.g. DACS, biochar or enhanced weathering) may have health implications for poorer communities engaged in or exposed to the production of such substances.
- Effects on the ozone layer resulting from SAI might affect poorer populations with less means to protect themselves disproportionately.
- Deployment of Carbon Removal or Solar Geoengineering might be planned or deployed in ways that maximise the benefits for wealthier populations while physical side-effects for poorer ones are not sufficiently considered. This might apply cross-country as well as within countries.
- Energy demands of some forms of Carbon Removal could potentially weaken energy access for the poorest.

Potential climate-related implications:

- Climate change impacts (especially if global temperature increase exceeds 2°C) pose serious threats to eradicating poverty by disrupting livelihoods and economic systems[166], disproportionately affecting the poor and reversing gains made toward eradicating poverty[167]. Carbon Removal and Solar Geoengineering could potentially play important roles in reducing the impacts of climate change on the poor, although such benefits rely on efficacy and feasibility at scale, on effective governance and on the ability to maintain a focus on reducing GHG emissions.

- Solar Geoengineering could in the best-case scenario help directly maintain conditions that avoid some of the threats climate change pose to the poorest and most vulnerable.
- Significant challenges in participation or representation of the poorest in international decision making processes could, however, also lead to unwanted climatic outcomes in poorer regions

Potential socio-economic and political implications:

- Increases in the price of commodities whose production is reduced or demand for which is increased due to Carbon Removal and Solar Geoengineering might disproportionally weigh on the poor.
- Land-based Carbon Removal (afforestation, biochar or enhanced weathering) may be done in a manner that would enable smallholder farmers to profit from enhanced yields as well as potential financial revenues. Policies for large-scale land-intensive techniques might, however also be put in place in a way that harms smallholder farmers through land- and water conflicts in competition with larger corporations.
- Regulatory requirements that impose certain practices on smallholder farmers or constrain the crops grown or their use could harm farmers' ability to generate income.
- There is a risk that the significant public spending required to operate large-scale Carbon Removal technologies could displace funding for poverty-alleviation.
- Pursuit of Carbon Removal and Solar Geoengineering could lead to reductions in overall spending on climate change mitigation and adaptation, which could lead to expansion of poverty due to increased climate change impacts on the poor. A successful deployment of Carbon Removal or Solar Geoengineering as part of an ensemble of mitigation measures to reach 1.5 to 2°C, could on the other hand reduce overall public spending needs on greenhouse gas mitigation and climate change adaptation.

Areas for further research:

- Overall resource needs of production chains necessary for Carbon Removal approaches and their indirect impacts on poorer societies have to date hardly been studied.
- Region-specific climate change impact pathways on the poorest — and correspondingly the potential attenuation through Carbon Removal and Solar Geoengineering — are not well understood.
- Repercussions from large new public expenditure programs at national or international levels for Carbon Removal / Solar Geoengineering on public spending for eradicating poverty require dedicated study.

SDG-2: End hunger, achieve food security and improved nutrition and promote sustainable agriculture

Potential physical side-effects:

- Increased soil acidification from the release of sulphate aerosols deployed in Stratospheric Aerosol Injection[168] could affect yields of food crops or lead to additional costs (e.g. requiring farmers to enhance alkalinity of their soils) athough other types of aerosols might attenuate or counter this effect[169].
- Stratospheric Aerosol Injection could have an impact on plant growth due to scattering of light, rendering certain species more and others less productive[170].
- Stratospheric Aerosol Injection could slow the recovery of the ozone layer which could adversely affect agriculture, although this effect might depend on the types of aerosols deployed.
- Should ocean fertilization lead to significant disruptions in ocean ecosystems, fisheries could be affected and complex food-chain interactions altered.
- Leaks from storage sites could reduce plant growth and impact negatively on livestock.

Potential climate-related implications:

- Solar Geoengineering may potentially be deployable in ways that effectively limit climate change impacts on food production (temperature and precipitation patterns) as well as a potential reduction of extreme weather events and thereby help maintain agricultural yields.
- Some Solar Geoengineering deployment scenarios (e.g. completely masking large amounts of warming or rapid changes) could lead to local changes in climate parameters with consequent reductions in agricultural productivity.
- Large local decreases in precipitation due to Solar Geoengineering could significantly decrease crop yields.

Potential socio-economic and political effects:

- Land-use and other resource conflicts could pose a significant challenge, e.g. where large-scale land-use changes displace food production systems — especially in the case of subsistence farming where large-scale afforestation, BECCS and perhaps to a lesser degree also biochar could pose significant challenges[171]. However, the effect on achieving food security strongly depends on the policy design. For example, the challenges of land-use conflicts may be attenuated by policy instruments that seek to insure that those most vulnerable to food insecurity benefit financially from Carbon Removal activities and have access to food markets[172].

- Some agroforestry practices and biochar applications[173 174] might increase agricultural yields and at the same time achieve Carbon Removal. Limited quantities of BECCS and biochar could be sourced from waste-biomass limiting negative impacts on food production. Certain areas of dedicated plantations for BECCS might be possible without infringing on food security if policies are carefully designed[175].
- Impacts of land-based Carbon Removal significantly depend on broader trends such as dietary shifts (limiting meat consumption would e.g. increase land productivity besides cutting GHG emissions)[176].

Areas for further research:

- Given complex implications for agricultural productivity particularly via climate change impacts, more research is needed to establish, which effects — including positive and negative impacts on food production — might dominate under specific climate change and Carbon Removal or Solar Geoengineering deployment scenarios globally as well as in various regional conditions and depending on particular policy designs.
- Understanding the effects that different aerosols deployed in Stratospheric Aerosol Injection could have on acidification and the ozone layer and corresponding impacts on food production requires more research.
- Identifying volumes of particular Carbon Removal that may be undertaken without infringing on food production or access to food requires bottom-up research and assessment that takes socio-economic and cultural conditions of food production and access to markets etc. into account.
- Locally rooted research needs to explore various — locally appropriate — policy designs compatible with food security informed by an understanding of local cultural and socio-economic conditions which will require involving a diversity of stakeholders.

3 GOOD HEALTH AND WELL-BEING

SDG-3: Ensure healthy lives and promote well-being for all at all ages

Potential physical side-effects:

- Both Carbon Removal and Solar Geoengineering could affect drinking water quality. Aerosol particles and dust and changes in UV radiation can impact water quality, and geological CO_2 storage can affect groundwater chemistry and the quality of drinking water for surrounding communities[177].
- Dust particles could induce respiratory problems if they become airborne along the production process of land- or ocean-based Carbon Removal options including biochar (pyrolysis), BECCS (combustion of biomass), enhanced weathering and ocean fertilization (pulverised minerals).

- Airborne particles for cloud seeding or sunlight reflection (such as sulphate or other aerosols) could also be a concern for respiratory health[178].
- Delay or acceleration in the recovery of the ozone layer due to SAI and the associated changes in ultraviolet radiation would likely have significant health implications[179, 180].
- Large-scale transport of material related to Carbon Removal or Solar Geoengineering could cause traffic-accident related casualties and injuries.

Potential climate-related implications:

- Climate change is recognized as a major threat to human health[181, 182] and some have argued that the potential health hazards from side effects described above might largely be surpassed by benefits due to reduced climate change / extreme event impacts (e.g. avoided deaths from malnutrition, avoided forced migration and associated health risks, reduced pervasiveness of malaria, diarrhoea and heat stress).
- Local albedo modification could reduce city heat islands and help limit adverse health effects of heat waves.

Potential socio-economic and political implications:

- If consideration of Carbon Removal or Solar Geoengineering resulted in lessened political will to reduce fossil fuel use, substantial health benefits due to reductions in respiratory disease from particulate matter pollution would be reduced or lost.

Areas for further research:

- Health effects of potential leakage of geological CO_2 storage are highly site-specific. More research is required to identify the volumes of storage that could be mobilized without posing a health hazard including site-specific risk assessments.
- Effects concerning airborne particles from biochar, ocean fertilization, and enhanced weathering may very much depend on technical design specifics of production, transportation and application procedures.
- Health impacts from various potential Solar Geoengineering particulates likely vary depending on particle type, quantities and injection points. More research is needed to analyse the potential health implications of various substances and processes.
- Should materials be proposed in forms that do not naturally occur in environmental systems, testing health implications may have to meet or exceed the standards for testing novel medical procedures.
- Implications — positive or negative — from various potential particles used for SAI on the ozone layer and by extension ultraviolet radiation and associated issues surrounding skin health require further study, in particular to fully understand how certain substances might accelerate or slow the recovery of the ozone layer under real-world conditions.

- The drivers for phasing out fossil fuel use need to be better understood, to judge whether Carbon Removal or Solar Geoengineering would endanger the health benefits of that transition.
- How to design a transport system for Carbon Removal or Solar Geoengineering technological interventions that minimizes negative health side effects.

SDG-4: Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all

Potential physical side-effects:

- Should physical side effects of Carbon Removal or Solar Geoengineering negatively affect living conditions and health, there could be a risk that access to education would be adversely affected, particularly for populations at a high risk of displacement.

Potential climate-related implications:

- Carbon Removal or Solar Geoengineering might reduce the impacts from extreme weather events, heat waves, health problems and other adverse impacts that climate change can have on education opportunities (e.g. damage to school and transportation infrastructure, nutritional and health issues and increased displacement causing interruptions in school attendance)[183].
- Local albedo modification might help limit adverse effects of heat on learning particularly for children — especially in cases of urban heat islands, which could otherwise disrupt school attendance during heat waves.

Potential socio-economic and political implications:

- Many effects discussed with regard to SDG 1 could also indirectly impact on SDG 4.
- The potential climate-related implications for education highlighted in the previous section could have long-term impacts on social and economic development.

Areas for further research:

- Given that many implications of Carbon Removal or Solar Geoengineering are likely to be indirect (resulting e.g. from health and well-being implications of physical side-effects and climate change limitation effects), a better understanding of such second-order implications on school attendance and quality is needed.
- Furthermore, policy effects concerning e.g. allocations of funding to education require more study, to understand whether funding of Carbon Removal or Solar Geoengineering activities could potentially enhance or diminish funding for education in certain socio-economic or political contexts.

SDG-5: Achieve gender equality and empower all women and girls

Potential physical side-effects:

- Carbon Removal or Solar Geoengineering resulting in changes to agricultural practices, forest management, precipitation patterns or access to drinking water (due to e.g. biomass plantations) could affect women disproportionately, particularly in indigenous, marginalised and traditional agricultural communities.
- Some impacts could particularly affect women who lack access to typical adaptive coping mechanisms, such as migration to cities, access to capital, or educational opportunities to pursue different types of work[184].

Potential climate-related impacts:

- Successful reductions in climate change impacts via Carbon Removal or Solar Geoengineering could benefit women disproportionately as it is widely recognised that women are particularly susceptible to the negative effects of climate change[185 186].

Potential socio-economic and political implications:

- Women are currently underrepresented among Carbon Removal or Solar Geoengineering researchers and research quality and policy design would potentially benefit from better gender balance, broadening the range of assessment metrics in use beyond cost-benefit and risk categories, and by introducing a broader range of ethical concepts to the dilemmas posed by these technologies[187].

Areas for further research:

- Understanding how differences in the design of Carbon Removal policies could mean significant changes in land-use or access to natural resources affecting women and girls is insufficient and requires further applied research.
- Research needs to address how specific regional changes in precipitation and temperature from particular Solar Geoengineering deployment scenarios would affect conditions and livelihoods for women and girls in light of local socio-economic and cultural conditions.
- Research on Carbon Removal and Solar Geoengineering as well as international governance processes needs to become more gender-balanced to avoid overlooking important areas of research and governance that may be relevant for SDG delivery.

SDG-6: Ensure availability and sustainable management of water and sanitation for all

Potential physical side-effects:

- Land-based, biomass-reliant techniques of Carbon Removal are expected to have significant implications on water availability — both positive and negative[188] [189].
- In areas of high-intensity biomass production, water consumption of plantations could limit availability to other uses[190] in other instances enhanced water retention from ecosystem- or soil restoration and afforestation may help preventing flash-floods and even out water availability in case of irregular precipitation[191].
- Water use in CCS operations needed for BECCS and DACS could potentially exacerbate water scarcity in dry regions, though globally the energy sector's overall water consumption might not necessarily increase due to CCS[192].
- Geological storage of CO_2 can potentially affect groundwater chemistry and thus the quality of drinking water sourced from local groundwater wells[193].
- Some forms of SAI could contribute to the acidification of lakes and streams[194], although others might do the opposite[195].
- Mineral-based processes that are reliant on mining, grinding and transportation of large quantities of minerals (alkalinity enhancement, enhanced weathering, ocean fertilization), could result in additional and unwanted material flows into aquatic systems, which could change their chemistry in unintended ways.

Potential climate-related implications:

- Carbon Removal or Solar Geoengineering could have substantial implications on water availability due to their potential impacts on precipitation and evaporation. Solar Geoengineering is likely to reduce precipitation on aggregate which would indirectly reduce water availability.[196].
- Large-scale afforestation has the potential to increase precipitation regionally[197] and some scenarios of global Solar Geoengineering suggest precipitation changes triggered by climate change could be counteracted to some degree[198].

Potential socio-economic and political implications:

- The social, economic and political imperative to maintain integrity of water resources at a national or local level could be significantly compromised or supported depending on the specifics of different types of Carbon Removal or Solar Geoengineering.

Areas for further research:

- Potential effects of involuntary mineral dispersal in rivers and lakes require dedicated study.
- Potential effects of cloud modification through seawater spraying on coastal freshwater availability are not well understood.
- Better understanding of the suitability of geological storage sites in light of potential effects on groundwater requires a regional assessment of potential sites. An emerging understanding of regional potentials could change estimates of global potentials e.g. for technical potentials of BECCS and DACS.
- Local and regional implications of water demand of Carbon Removal deployment remain largely unexplored.
- Local and regional precipitation effects of various Solar Geoengineering techniques remain a key subject for earth system modelling research, which may need to be complemented with broader impact assessments regarding socio-economic and environmental factors.

SDG-7: Ensure access to affordable, reliable, sustainable and modern energy for all

Potential physical side-effects:

- Carbon Removal energy requirements and reduced solar energy yields due to reduced solar irradiation from Solar Geoengineering as well as losses in wind energy yields due to reduced average windspeeds are likely to have implications for energy access and land-use trade-offs.
- Some Carbon Removal options have large requirements for low-carbon energy, which would likely compete with other uses for energy. This includes grinding of mineral rocks for alkalinity enhancements or ocean fertilisation, transportation of large volumes of minerals as well as the physical/chemical processes used for DACS.
- As some types of Solar Geoengineering would result in more scattered light, they could potentially reduce yields of concentrated solar power and increase yields of solar photovoltaic cells[199].

Potential climate-related implications:

- Carbon Removal or Solar Geoengineering might have benefits for energy access in light of substantial energy sector vulnerability to climate change impacts such as constraining water availability for hydropower or for cooling of thermal or nuclear power stations, potentially lowering energy generation capacity up to 60-90% as well as increasing energy demands[200]. If precipitation is locally reduced by Solar Geoengineering, hydropower yield could somewhat decrease.

- Some forms of surface albedo modification might reduce energy demand for air-conditioning due to local cooling effects.

Potential socio-economic and political implications:

- Some forms of Carbon Removal, such as adding CCS to existing bio-energy power generation would entail a cost and substantial energy penalty.
- BECCS could potentially be used to enhance energy access in places identified for bioenergy generation without previous access to electricity.
- While an increase in biomass for energy production could displace imported fossil fuels and strengthen energy security, an exaggerated push for bioenergy could provoke political pushback as already observed in the case of bioenergy production without CCS, which might also challenge energy security[201].

Areas for further research:

- Regional implications of energy requirements of Carbon Removal options are not well understood, this would require bottom-up regional assessments of mineral and energy resources that are informed by an understanding of local circumstances.
- Further research may also be required to understand regional vulnerabilities of energy infrastructure to climate change impacts and how Carbon Removal or Solar Geoengineering could attenuate or aggravate these.

SDG-8: Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all

Potential physical side-effects:

- Carbon Removal or Solar Geoengineering requires the setup of physical infrastructure and occupation of land, sea or air space that prevents use of the same area for productive economic activities.

Potential climate-related implications:

- Regional differences of Solar Geoengineering impacts on temperature, precipitation and extreme weather events could result in regional redistributions of climate-dependent productivity and damages to assets.
- Successfully avoiding climate change impacts through Carbon Removal or Solar Geoengineering would provide substantial economic benefits especially in poorer regions, which are expected to be especially hard-hit from climate change at 2°C or more[202] [203] [204].

Potential socio-economic and political implications:

- Carbon Removal or Solar Geoengineering could have implications for economic growth or employment due to competition over land, water and mineral resources or due to effects on fisheries or land ecosystems affecting dependent economic activities. Indirect effects through the reduction of supply of these resources and propagation of related price shocks through the economy would be negative.
- Most Carbon Removal or Solar Geoengineering technologies are currently far away from presenting economically viable business cases for deployment. In the absence of trustworthy, long-term global carbon pricing pathways returns on investment are unlikely to materialize. Demand for commercial uses for captured CO_2 and CO_2-rich minerals and compounds at present appear vastly insufficient to cover the CO_2-supply that large-scale Carbon Removal would offer. It is thus unclear to what degree deployment of Carbon Removal or Solar Geoengineering would contribute to inclusive and sustainable growth in light of their dependence on public spending. A particular concern is the opportunity cost of public spending on Carbon Removal or Solar Geoengineering that would otherwise be available to provide infrastructures and public goods necessary for sustained economic growth and employment.
- Carbon Removal technologies such as BECCS and DACS would in particular require much higher incentives than current mitigation policies offer, by one or two orders of magnitude[205 206].
- For Solar Geoengineering, the expected financial costs per unit of radiative forcing reduced might be orders of magnitude lower than of classical mitigation, but nevertheless — the atmosphere being a public good — no business case for deployment has been demonstrated to date without public investment. Furthermore, costs increase proportionally with the duration at which Solar Geoengineering needs to be maintained and full cost assessments will have to include funding for accompanying policies (e.g. monitoring of results or compensation for and adaptation to induced regional changes)[207].

Areas for further research:

- Research on potential policy instruments to mobilize Carbon Removal or Solar Geoengineering deployment has just started. As a consequence, little is known concerning the potential implications of such policies on economic growth and employment.
- More sophisticated and broad-based assessment methods need to be developed to quantify and compare how changes in prices and availability of different resources that are potentially affected by Carbon Removal or Solar Geoengineering (e.g. energy, food, water, ecosystem services etc.) might interact to impact on inclusive and sustained economic growth.

SDG-9: Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation

Potential physical side-effects:

- Carbon Removal or Solar Geoengineering will increase the need for dedicated infrastructure and increase pressure on existing transport infrastructure.
- Large-scale Carbon Removal would require planning, constructing and operating production plants and a substantial dedicated transportation infrastructure, which would compete with resource and transportation requirements of other industrial and infrastructure activities.

Potential climate-related implications:

- Carbon Removal or Solar Geoengineering could potentially mitigate the destructive forces of extreme weather events on built infrastructure and a corresponding reduction of public and private spending required to restore crucial infrastructure and build resilience to higher levels of warming[208].

Potential socio-economic and political implications:

- The potentially significant levels of additional infrastructure spending required for large-scale Carbon Removal — and to some degree Solar Geoengineering — could represent a significant additional cost for infrastructure investment;
- Investment in Carbon Removal or Solar Geoengineering could stimulate industrial innovation.
- Increased freight transportation resulting from most Carbon Removal technologies could adversely affect transport systems.

Area for further research:

- Regional infrastructure and transportation requirements of potential Carbon Removal or Solar Geoengineering deployment are not well understood. More research is therefore needed to better understand the potential implications for different types of infrastructure in different regions and economic contexts.
- Further research into the potential Carbon Removal or Solar Geoengineering may offer for stimulating industrial innovation which serves the public interest.

SDG-10: Reduce inequality within and among countries

Potential physical side-effects:

- Any harmful side-effects such as those described elsewhere in this report including from particulate pollution on health, degraded natural environments or reduced agricultural and economic productivity that affect disadvantaged populations within or between countries and regions could lead to an increase in inequality.

Potential climate-related implications:

- By reducing climate change impacts, Carbon Removal or Solar Geoengineering could contribute to improving development outcomes for the most disadvantaged both within and between countries[209].

Potential socio-economic and political implications:

- How the costs of potential large-scale Carbon Removal are shared between regions or countries could exacerbate or ameliorate existing inequalities.
- Side-effects of Carbon Removal or Solar Geoengineering may be unevenly distributed in ways which could further exacerbate economic inequality.
- The type of Carbon Removal deployed could accentuate inequalities between different regions and countries, e.g. if a country is vulnerable to food-price fluctuations it could be particularly susceptible to Carbon Removal deployment that displace food-crops[210].
- Carbon Removal or Solar Geoengineering research is predominantly funded by- and executed in countries of the global North, thus risking biases towards those countries' interests and overlooking key issues for developing countries.

Areas for further research:

- Further research is needed to understand how Carbon Removal or Solar Geoengineering could be distributed in ways that avoid increasing inequalities both within or between countries.
- More research is also needed to understand how the side-effects of Carbon Removal or Solar Geoengineering could be managed to avoid increasing inequalities.
- More analysis is needed to better understand how different types of Carbon Removal or Solar Geoengineering could impact on different countries, regions or localities both socially and economically.
- Strengthened efforts to enable involvement of developing country research institutions and a broad range of stakeholders in Carbon Removal or Solar Geoengineering research could be important to avoid exacerbating or creating new inequalities.

SDG-11: Make cities and human settlements inclusive, safe, resilient and sustainable

Potential physical side-effects:

- Carbon Removal through trees or Solar Geoengineering through roof albedo increase could potentially contribute to reducing urban heat-island effects.
- Forestry-based Carbon Removal could help to build resilience to precipitation changes by increasing water absorption and reduce downstream flooding as well as improve continuity of water availability in cities and human settlements.

Potential climate-related implications:

- Reducing climate change impacts could result in significant benefits to city dwellers as cities are often found in particularly vulnerable places, e.g. on low-lying coastlines and rivers.
- Reducing impacts of extreme meteorological events and reduced agricultural yields in rural areas could reduce migration pressure and thus urbanization rates.
- Using surface-albedo modifications as a means to counteract urban heat islands could substantially improve local conditions of urban populations during heatwaves.

Potential socio-economic and political implications:

- Cities and networks of subnational government entities would likely demand to be involved in developing governance mechanisms for local or regional Carbon Removal or Solar Geoengineering and could substantially contribute to global and regional governance efforts.

Areas for further research:

- Uncertainties with regard to Carbon Removal or Solar Geoengineering impacts on cities include their potential for altering key climate variables (e.g. sea level rise, extreme temperature and precipitation events) as well as implications on resource availability (e.g. drinking water) affecting urban communities.
- Local and regional implications of substantial urban surface albedo modifications (e.g. on wind and precipitation) are not well understood and may require bottom-up research that takes local conditions into account.
- More research may be needed to better understand and enable the potential role of subnational governments in sub-national, national or global governance of Carbon Removal or Solar Geoengineering.
- Potential contributions of urban design and management — if scaled up globally — are to be explored further[211].

SDG-12: Ensure sustainable consumption and production patterns

Potential physical side-effects:

- Energy requirements of Carbon Removal and land-use could limit the potential for sustainable production practices in agriculture and industrial production as well as limit availability of low-carbon energy for transportation.

Potential climate-related implications:

- By attenuating real or perceived climate impacts, deployment of Carbon Removal or Solar Geoengineering could potentially reduce pressures toward changing lifestyles and industrial production, thus weakening support for sustainable consumption and production patterns.

Potential socio-economic and political implications:

- Anticipating adverse physical side-effects resulting from Carbon Removal or Solar Geoengineering might enhance support for sustainable consumption and production of some populations.
- Consideration or deployment of Carbon Removal or Solar Geoengineering could potentially reduce political support for pursuing sustainable consumption and production patterns among some populations.

Areas for further research:

- Further social science research could help inform understanding of the conditions under which consideration of Carbon Removal or Solar Geoengineering might weaken efforts to undertake a transformation toward sustainable consumption and production patterns — and under which conditions the opposite effect could be the result. This includes addressing questions around the framing of these issues in international discussions as well as evolving institutional responsibilities.

SDG-13: Take urgent action to combat climate change and its impacts

Potential physical side-effects:

- Risks from unreliable storage of CO_2 or generating additional GHG emissions from land-use changes or secondary effects in ocean ecosystems.
- Physical side-effects of Solar Geoengineering could include unexpected regional differences in climate outcomes as well as secondary cooling effects from avoiding crossing of ice-melt, permafrost methane emissions or other earth systems tipping points.

- Energy systems transformation from fossil fuels to BECCS in principle result in decarbonisation, except when plantations displace old-growth forest that holds large amounts of carbon.
- Physical risks of Solar Geoengineering on climate action also include the risk of abrupt termination of its deployment and corresponding impacts from rapid changes in climate[212 213].

Potential climate-related implications:

- For Carbon Removal to contribute to climate action — particularly in developing countries — policy instruments may be needed that resemble those seeking to mobilize GHG emissions reductions while addressing particular challenges of Carbon Removal such as high natural resource demands, cost, limited co-benefits and significant research and development funding needs[214 215].
- The efficacy of Solar Geoengineering to combat climate change and its impacts is debated: Many have serious objections against considering Solar Geoengineering as a potential means to reduce climate change risks. However, some consider Solar Geoengineering to hold serious potential for contributing to reaching the 1.5°C to well below 2°C target. Evidence from computer models suggests that partial compensation of moderate GHG-induced global temperature increase through SAI could limit climate change impacts across regions and key climate variables[216].

Potential socio-economic and political implications:

- Climate action may be one of the most interlinked dimensions of Sustainable Development and there may be a very high risk for missing key goals, in the absence of ambitious climate policy that limits warming to 1.5/2°C[217].
- There are some concerns that Solar Geoengineering could obstruct emissions reduction efforts[218].

Areas for further research:

- Whether or not Carbon Removal or Solar Geoengineering can effectively contribute to limiting climate change and its impacts is the subject of ongoing research and cannot be resolved without substantial research efforts across a broad range of disciplines as well as substantial public discussion and deliberation.
- The international governance of climate change is already intricate and complex, with many regimes and institutions beyond the UNFCCC involved. Serious consideration of Solar Geoengineering and to a lesser extent Carbon Removal could both strengthen or challenge collaboration across institutions involved in these global governance processes and more research is needed to understand these opportunities and risks toward

addressing climate change, especially in the context of the Paris Agreement, being driven by voluntary national contributions.

- Research in particular is needed to understand how discussion of Carbon Removal or Solar Geoengineering would affect political support for reducing GHG emissions and how strategic communication could help ensure mitigation ambition is raised over time.
- Research might also explore whether introducing Carbon Removal or Solar Geoengineering might have implications on interpretation of important principles such as equity and burden-sharing given that Carbon Removal represents a removal of historical GHG emissions as opposed to reducing current emissions.

SDG-14: Conserve and sustainably use the oceans, seas and marine resources for Sustainable Development

Potential physical side effects:

- Carbon Removal or Solar Geoengineering may have potential effects on ocean chemistry and ecosystems resulting from the effects of ocean-based technologies such as fertilization or accelerated weathering or via Solar Geoengineering due to particles precipitated in SAI or changes in algal growth due to scattering of solar irradiation.
- Large-scale land-use based Carbon Removal techniques could cause changes in water and nutrient run-off affecting coastal marine biology.

Potential climate-related implications:

- Climate change affects ocean ecosystems largely through increasing water temperature and acidification resulting from carbonation[219]. Enhancing ocean alkalinity could help counteract acidification and ocean fertilization could in an ideal scenario revitalize fisheries and oceanic ecosystems. Ocean fertilization might however also alter ocean ecosystems in less fortunate ways e.g. by increasing plankton productivity in one regions and reducing nutrient availability elsewhere. Uncertainties with regard to such effects are large, as these are highly dependent on dynamics of ocean currents and corresponding nutrient transportation processes.
- Large-scale Carbon Removal on land could potentially counteract ocean acidification by reducing atmospheric CO_2 concentrations.
- While not directly counteracting acidification, SAI and marine cloud brightening could counteract warming of ocean waters — thus alleviating one of two key stressors to oceanic ecosystems[220].
- Solar Geoengineering may have the potential to slow or halt the crossing of earth systems tipping points such as accelerating ice-melt and its effects on ocean currents and nutrient distributions as well as the destabilization of ocean methane clathrates[221].
- Cloud modification through spraying of sea salt could require large fleets of ships cruising the world's oceans and could thus have a negative impact on marine life.

Potential socio-economic and political implications:

- Effects of various Carbon Removal approaches on ocean nutrient compositions could impact on fisheries as a source of food and income.
- Governance of ocean-based Carbon Removal or Solar Geoengineering in or above international waters is likely to pose a challenge to the pertinent governance bodies. This includes questions such as whether policy instruments to incentivize beneficial applications can be created and in which institutional context. No governance body currently seems to envisage developing policies that could actively counteract ocean acidification and enhance oceanic CO_2 uptake[222 223].

Areas for further research:

- Further research is required to understand how Carbon Removal or Solar Geoengineering may affect the complex interactions within ocean food-chains and oceanic chemistry, as well as the associated impacts on fisheries.
- Further research is needed to understand under which conditions some forms of Solar Geoengineering might be capable of slowing polar ice-melt and attenuate its effects on ocean currents and ecosystems.

SDG-15: Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss

Potential physical side-effects:

- Land-use changes required for Carbon Removal (e.g. for large-scale biomass plantations and their associated water use) as well as potential changes in nutrient availability or particulate pollution could severely impact on terrestrial ecosystems.
- Nature-(or Vegetation-) based Carbon Removal can potentially contribute to the protection of biodiversity and livelihoods if addressed via careful and locally appropriate policy design[224].
- Large-scale monoculture plantations for BECCS or afforestation could negatively affect life on land by competing with other land uses and degrading natural ecosystems. However, socio-economic scenarios that exclude BECCS still rely heavily on bio-energy production[225].
- Policy instruments or programmes for afforestation and reforestation, if locally-appropriate and well-designed can ensure sustainably sourced biomass that does not result in significant pressures on land-ecosystems, but options may be more limited than technical potential assessments currently suggest[226].
- Solar Geoengineering could have an indirect effect on land-based ecosystems due to an

increase in diffuse light, which could enhance photosynthetic productivity of some plants and reduce it for others[227].

- Solar Geoengineering SAI based on sulphur dispersion could harm ecosystems sensitive to acidification.

Potential climate related implications:

- Carbon Removal or Solar Geoengineering could potentially reduce the pressures to land-based ecosystems caused by climate change.
- Regional temperature increases might result from afforestation in northern latitudes as forests have a lower reflectivity than other land-surfaces.

Potential socio-economic and political implications:

- Land-based Carbon Removal requires careful assessment of conditions, financial incentives and policy design to ensure deployment does not negatively impact on land-based ecosystems[228].
- Assumptions over future BECCS or bioenergy use in current mitigation pathways may need to be adjusted, as a growing number of studies suggest the corresponding scales might not be reached without significantly impacting land-based ecosystems.

Areas for further research:

- Despite growing research on land-use implications of large-scale BECCS knowledge of what could constitute integrally beneficial practices and regionally appropriate scales of deployment is still very limited.
- More research may also be required to understand socio-economic effects of particular policy designs that would seek to mobilize potentially beneficial practices such as biochar or other soil enhancements in a way that supports SDG-15.
- Ecological effects of potential involuntary or purposeful dispersal of pulverised minerals for Carbon Removal are not well understood as are the potential land ecosystem effects from various particles that could in theory be used for Solar Geoengineering.

SDG-16: Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels

Potential physical side effects:

- Transboundary side-effects of Solar Geoengineering in particular (and to a lesser extent potentially also of large-scale Carbon Removal) could create tensions and pose challenges for international institutions, and justice if for example, extreme weather events that occur after deployment might be attributed or even perceived to be linked to such an intervention and strain diplomatic relations[229]. In such as scenario, unilateral Solar Geoengineering might be counteracted through various technical means[230], the release of potent industrial GHGs or even destruction of deployment equipment by military intervention.

- In the event of regional differences in side-effects, serious legal challenges might emerge in attributing causality and agency rendering claims for compensation for relative gains or losses very difficult.

Potential climate-related implications:

- In the event of Solar Geoengineering deployment, the need to agree a common temperature goal that would accommodate diverging national interests could test the capability of international institutions to come to agreement and operationalize it via coordinated deployment. Some see this as a potential new source of international conflict and disagreement[231].
- Carbon Removal and Solar Geoengineering could reduce climate change impacts that pose increasingly serious threats to disrupt stability and peace (e.g. by triggering resource conflicts and large-scale migration flows);

Potential socio-economic and political implications:

- The potential political and commercial interests bound up in Carbon Removal and Solar Geoengineering proposals could pose a challenge to international governance.
- Significant differences of opinion and differing interpretations of ethical and equity implications of Carbon Removal and Solar Geoengineering techniques could pose serious political and social challenges.

Areas for further research:

- There is a broad range of questions requiring the attention of scholars, practitioners and decision-makers concerning implications of Carbon Removal and Solar Geoengineering techniques for governance and institutions at all levels. For example, will Solar Geoengineering require more centralised or dispersed forms of global governance and will this have further concentrate power globally, or could it disperse it, e.g. due to the relative affordability of the technology?[232]
- Is Solar Geoengineering inherently anti-democratic[233] or can it be governed and potentially deployed via democratically-mandated decision-making processes?
- Can large-scale Carbon Removal be effectively deployed through participatory decentralised modes, or would policy instruments inevitably be captured by corporate interests? How far do public and private interests diverge?
- If geoengineering demands global coordination and strong global governance institutions would that help or hinder achievement of other SDGs?

SDG-17: Strengthen the means of implementation and revitalize the global partnership for Sustainable Development

Potential physical side-effects:

- Variation in regional redistribution of side-effects and associated trade-offs in outcomes from Carbon Removal and Solar Geoengineering deployment could lead to a loss of trust and collaboration between networks of international institutions working toward human development and reducing climate impacts.

Potential climate-related implications:

- The growing realization of the international climate regime's reliance on Carbon Removal and observation of more serious discussion on Solar Geoengineering could challenge current narratives, reduce impetus and destroy existing partnerships toward Sustainable Development.

Potential socio-economic and political implications:

- Potential reallocations of public funding upon implementation toward Carbon Removal and Solar Geoengineering policies and away from other important areas such as the humanitarian sector is a concern often voiced[234]. Such changes may be inconsistent with hard-won understanding of global roles, expected contributions and the meaning of partnerships in pursuit of Sustainable Development.
- Carbon Removal approaches are considered in economic models for their potential reduction of the optimal social cost of mitigation, thus theoretically freeing up resources for delivery of other SDGs compared to socially optimal pathways to reaching the Paris temperature goal without the option of Carbon Removal. However, this will only be the case at much higher levels of mitigation ambition than existing today.
- The emergence of a largely new and urgent coordination challenge that can only be addressed within a framework of global agreement and cooperation might create linkages and solutions that offer potential for direct or analogous approaches elsewhere in the Sustainable Development field[235]. Strengthened public consultation and deliberation processes that many are calling for[236] [237] would be particularly welcome in this context.

Further research needed:

- Implications of Carbon Removal and Solar Geoengineering on global partnerships and their governance will require engaging various perspectives, including national governments, industries, investors and other private sector players, and civil society including the defenders of various ecosystems and rights of indigenous peoples.
- Contrasting economic studies regarding efficient CO_2 reduction paths with different approaches to policy assessment might result in a constructive reflection in the context of international climate governance regarding means of implementation.

- Issues of collective monitoring and verification of the impact of Carbon Removal and Solar Geoengineering initiatives would pose considerable technical challenges that by necessity might lead to strengthening international collaboration. However, this might also strain international collaboration.
- In view of the importance of the local context (such as socio-economic, political, cultural, and climatic factors as well as differences in the natural resource availability), inclusive and broad-based research and deliberation is a necessity for gaining better understanding of the implications of Carbon Removal and Solar Geoengineering.
- Given that institutions based in developing or under-developed economies may not prioritise such activities over other urgent issues of concern, financial support from the global North may be required to enable the necessary participation [238] [239].
- Further research areas include in particular questions of potential implications and trade-offs for public budget allocations such as toward technology development, funding for climate change adaptation, humanitarian work or disaster relief.
- As work toward Sustainable Development transformations as well as debate on Carbon Removal and Solar Geoengineering advances, a better understanding of the potential for constructive decision making, partnerships and synergies between various goals could be gained through political science research.

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