EPFL

Unedited version – 15 June 2020

Report

International governance issues on climate engineering

Information for policymakers

Commissioned by the Swiss Federal Office for the Environment (FOEN)

International Risk Governance Center

irgc

Imprint

This report was prepared under contract from the Swiss Federal Office for the Environment (FOEN). The contractor bears sole responsibility for the content.

Commissioned by: Federal Office for the Environment (FOEN), International Affairs Division, 3003 Bern, Switzerland. The FOEN is an agency of the Federal Department of the Environment, Transport, Energy and Communications (DETEC).

Contractor: EPFL (Ecole polytechnique fédérale de Lausanne), International Risk Governance Center (IRGC)

Author: Marie-Valentine Florin (Ed.), Paul Rouse, Anna-Maria Hubert, Matthias Honegger, Jesse Reynolds

To cite this report:

> Florin, M.-V. (Ed.), Rouse, P., Hubert, A-H., Honegger, M., Reynolds, J. (2020). International governance issues on climate engineering. Information for policymakers. Lausanne: EPFL International Risk Governance Center (IRGC).

Individual chapters:

> [name of author], '[title of chapter]' in Florin, M.-V. (Ed.), *International Governance of Climate Engineering. Information for policymakers* (2020), Chapter [nr], Lausanne: EPFL International Risk Governance Center (IRGC).

DOI:10.5075/epfl-irgc-277726

For any questions, please contact: irgc@epfl.ch

Cover photo by USGC on Unplash

Abstract

Some climate engineering technologies are being developed to remove CO_2 from the atmosphere (carbon dioxide removal, CDR), which is expected to contribute to reducing and preventing climate change. Some other technologies (solar radiation modification, SRM) would artificially cool the planet and could reduce some symptoms and risks of climate change. Meaningful steps may need to be taken soon to lay a foundation for a decision process regarding research, policy, regulation and possible use.

Driven by questions and needs from the international policymaking community to better understand the potential benefits as well as opportunities, risks, uncertainties and other challenges of CDR and SRM, at both technical and governance levels, this report reviews and compares technologies and their potential contributions, costs, risks, uncertainties, before surveying the current legal and institutional landscape of governance regarding climate engineering. It then addresses trade-offs between risks and discusses possible options for international governance, including criteria for evaluating options. The need for more inclusive approaches and the pros- and cons of institutional fragmentation are emphasized. Options for sites of international governance are discussed, for various technologies, as well as general principles and specific recommendations to: distinguish between CDR and SRM as well as among CDR techniques; accelerate authoritative, comprehensive, and international scientific assessment; encourage the research, development, and responsible use of some CDR techniques; internationally build capacity for evaluating CDR and SRM; facilitate non-state governance; and explore potential further governance of SRM while remaining agnostic concerning its use.

Executive Summary

This report addresses issues of international governance of climate engineering, as composed of two families of technologies, carbon dioxide removal (CDR) and solar radiation modification (SRM), as technologies to address causes and consequences of climate change. The field is marked by complexity, uncertainty and ambiguity. A range of different governance arrangements would be beneficial at various levels, but political input will be necessary for the conversation to produce an effective outcome. Altogether, the four chapters in this report offer a review of techniques and governance instruments and issues, to provide information and options for international policymaking.

Chapter 1: Review of technologies for CDR and SRM

by Paul Rouse

Chapter 1 provides an overview of two classes of emerging climate-altering technologies: Carbon Dioxide Removal (CDR), and Solar Radiation Modification (SRM). Further, approaches to the permanent sequestration of the billions of tonnes of carbon that may be removed are reviewed. For each technique, the chapter explains the principles that underlie them, their technological readiness, their potential to contribute to reducing CO_2 concentrations or temperature warming, the economics and social responses to each and their possible impacts. The technologies discussed in this chapter are:

CDR

- Nature-based approaches: afforestation and reforestation, carbon sequestration in soils; restoring wetlands, peatlands and coastal habitats; macroalgal cultivation
- Hybrid approaches: biochar production and deposition, ocean fertilization, enhancing ocean alkalinity with terrestrial weathering
- Engineered approaches: Direct air carbon dioxide capture and storage (DACCS); bioenergy with carbon capture and (BECCS)
- Other CDR techniques
- Sequestration: sequestering carbon in the oceans; crop residues oceanic carbon sequestration, mineralization of injected CO_2 within geologic structures

SRM

- Stratospheric Aerosol Injection (SAI)
- Marine Cloud Brightening (MCB)
- Other SRM techniques

This chapter highlights the breadth of uncertainties and ambiguities involved in climate-altering technologies, which gives rise to a complex set of agenda for the policy debate. Whether it be CDR or SRM, whether it be the planting of trees, or bold proposals to change the stratosphere – there are no simple solutions. New research should inform decisions about techniques. However, science alone cannot provide answers. As such, any future decisions about climate-altering technologies, or prioritization of techniques will require a rebalancing of the debate away from expert analysis alone, toward a plural, socially situated deliberation. This is necessary to help better understand the challenges and opportunities, and guide the choices we must make collectively. At the heart of these deliberations must lie governance.

Perhaps the only certainty is that almost all facets of climate-altering technologies are uncertain, and within those uncertainties reside ignorance and ambiguities, in which actors' own interpretive and normative responses will affect perspectives on the tolerability of risks. Continued dialogue and deliberation, informed by robust research, may be the only way forward currently available.

Chapter 2: International Legal and Institutional Arrangements relevant to the Governance of Climate Engineering Technologies

by Anna-Maria Hubert

Given its potential for far-reaching consequences, climate engineering has the potential to intersect with many different subject areas of international law, including international human rights, international development, international peace and security, intellectual property, and food security. This chapter focuses on the potential application of international law related to the protection of the environment, and provides an overview of (1) general norms: duty to Prevent Transboundary Environmental Harm, Precautionary Principle, Transboundary Environmental Impact Assessment and Duty of International Cooperation, (2) key instruments: 1992 UNFCCC and 2015 Paris Agreement, 1985 Vienna Convention for the Protection of the Ozone Layer and its 1987 Montreal Protocol, 1992 UNCBD, 1996 Protocol to the 1972 Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, 2013 London Protocol Amendment on Marine Geoengineering, and others; (3) international institutions relevant to the governance proposed for climate engineering technology: United Nations Security Council, United Nations General Assembly, UNEP, ILC, United Nations High-level Political Forum on Sustainable Development, UNESCO and IOC, WMO, IPCC and ISO, and (4) some development of soft-law principles and instruments.

With few exceptions, international law remains largely silent on the regulation of climate engineering measures and their development. Though dependent on the overarching aims and objectives of governance, this chapter points to potentially significant gaps in existing legal regimes, suggesting the need for further cooperation at the international level to promote effective, legitimate and fair governance of these emerging technologies. In addition, the analysis in this chapter also points to how existing instruments and institutions that have expressly addressed geoengineering regulation and governance to date, also reflect a "limited" approach in line with their specific objectives, scope and mandate, leading to a one-dimensional perspective on climate engineering rather than a comprehensive and integrated approach to its governance. At the same time, this survey of the existing international legal landscape shows that there are a number of general norms of international environmental law, treaties and soft-law instruments and international institutions with relevance to geoengineering. The international legal and institutional landscape relevant to climate engineering thus presents a complex 'patchwork' of overlapping norms and institutional mandates. Taken together, these underscore the need for some degree of international governance for climate engineering measures.

Though issues of climate engineering governance are only now breaking onto the international agenda, it is already apparent that fragmentation is a concern. As such, no treaty or institutional organization is likely to provide a 'one-size-fits-all approach' for climate engineering measures as a group. Regime conflicts are generally to be avoided, since a 'doubling of efforts' can erode the effectiveness of international law, waste scarce resources, give rise to concerns about forum shopping, risks of conflicts between actors, legal uncertainty, and issues of overlapping or conflicting legal obligations. The principle of systemic integration of international law stands for the proposition that 'when several norms bear on a single issue they should, to the extent possible, be interpreted so as to give rise to a single set of compatible obligations. Top-down intergovernmental processes may also be complimented by bottom-up soft-law governance initiatives by academics, scientific bodies, NGOs and corporate actors within a polycentric governance framework.

Chapter 3: Addressing risks and trade-offs in governance

by Matthias Honegger

Climate change and climate-altering technologies pose an emerging risk governance challenge involving risk-risk trade-offs both regarding potential outcomes as well as governance choices. Trade-offs characterize not only various emergent governance and policy design choices but also how research is conducted and communicated. This chapter identifies several risks and trade-offs and offers approaches that could be pursued in the near- to medium-term to gradually overcome trade-offs, by strengthening opportunities for governance strategies that attenuate multiple risks. Strategies aim at improving capacities for anticipation, cooperation, and joint decision-making, which are essential qualities for addressing the risk-risk trade-offs posed by climate change and countervailing risks associated with potential CDR and SRM applications.

Risk and trade-offs related to policy design and governance include inclusive governance versus governance efficiency at the global level; sovereignty of domestic policies versus transboundary effects of CDR approaches; maximizing mitigation versus ensuring sustainable development; centralized governance versus polycentric governance – effectiveness versus diversity; and preventing uncoordinated or premature application of SRM. Suggested measures include strengthening capacities for international inter-agency collaboration, coordination, and learning; proactively exploring how specific governance challenges match particular international agencies' mandates; and conducting policy impact assessments in the context of national mitigation policy planning.

Risks and trade-offs related to research include focused authoritative knowledge generation versus a diversity of assessment approaches; CDR research moral hazard versus mitigation underprovision; SRM research moral hazard versus risk of ignorance; risk of transboundary impacts from SRM research; insufficient interdisciplinary and international research causing a risk to governance cooperation; and risk of uneven research capacities fueling unfair power differentials. Suggestions for addressing research-related risks and trade-offs include enabling more diverse, transdisciplinary research; supporting the international exchange of expertise; enabling continuous science-policy conversations; and conducting research to generate insights on potential interlinkages in the context of the Sustainable Development Goals.

Chapter 4: Elements and steps for global governance

by Jesse Reynolds

This chapter evaluates possible options and approaches for potential future regimes on the international governance of climate engineering. Developing international governance of CDR and SRM – especially in case of their large-scale use – will be a long process across several decades. However, meaningful steps may need to be taken soon to lay a foundation for this lengthy, uncertain process. Furthermore, some shorter-term international governance actions – including of CDR's and SRM's research – could be beneficial.

The chapter offers explicit criteria for the assessment of governance options, including to reduce climate change and its impacts, contribute to sustainable development, support greenhouse gas emissions reductions, establish and maintain legitimacy, foster peace and stable international relations, and reflect current knowledge and adapt to changing conditions.

Possible governance sites – including but not limited to intergovernmental institutions – are then discussed. Among possible candidates, it is difficult to imagine the international governance of CDR and SRM without the climate change regime having a central role. Because the IPCC aims to be neutral with respect to policy, it can and should contribute to, but not take the lead in governance. The biodiversity regime is well-positioned to legitimately contribute to international governance that prioritizes sustainable development and poverty eradication, although its governance would largely be limited to that concerning impacts on biodiversity. Notably, UNEP's mandate and capabilities include identifying emerging issues, conducting scientific reviews, and catalyzing international governance across issue areas and sectors. The creation of de-novo international process and decentralized governance should also be considered.

The chapter suggests possible substantive options for governance, which are to facilitate research; encourage the responsible use of carbon dioxide removal (CDR); regulate risks for sustainable development; further integrate with existing governance; build governance capacity; strengthen international cooperation; leverage the private sector; implement breakpoints, stage gates and moratoria; and establish a foundation for future decision-making.

The chapter closes with six specific recommendations:

- to distinguish between CDR and solar radiation modification (SRM) as well as among the diverse CDR techniques in their additional dedicated governance;
- to accelerate authoritative, comprehensive, and international scientific assessment;
- to encourage the research, development, and responsible use of some CDR techniques;
- to help build capacity for evaluating CDR and SRM in some of those countries that lack the resources to do so
- to facilitate the elaboration and implementation of non-state governance; and
- to explore potential further governance of SRM while remaining agnostic concerning its ultimate use.

Chapter 5: Concluding remarks

The report concludes with a summary of four cross-cutting themes that emerge from the four chapters: First, noting the pervasive uncertainty that characterizes both CDR and SRM and their governance, develop adaptive approaches to reducing uncertainty and deploying the most appropriate technologies; be very prudent and cautious, and avoid lock-ins. Second, separate CDR and SRM in policy discussions. Third, acknowledge that existing international arrangements lean toward or even in some cases create an obligation to engage in further research and cooperation. And fourth, combine top-down and bottom-up approaches to the national and international governance of CDR and SRM.

Elements to consider in a possible roadmap for research and broader conversation of CDR and SRM are then suggested, including a list of key themes for further research.

Table of Contents

Tables of Figures

Tables of Textboxes

Tables of Tables

Acronyms

BECCS	Bioenergy with Carbon Capture and Storage
CBD	Convention on Biological Diversity
CBDRRC	Common but Differentiated Responsibilities and Respective Capabilities (in the context of the UNFCCC)
CCS	Carbon Capture and Storage
CDR	Carbon Dioxide Removal
CMA	Group of countries who have signed and ratified the Paris Agreement. Full name: 'Conference of the Parties serving as the meeting of the Parties to the Paris Agreement'
CO_2	Carbon Dioxide
DACCS	Direct Air Capture with Carbon Storage
EIA	Environmental Impact Assessment
EMG	Environment Management Group [of the UN]
ENMOD	Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques
FAO	Food and Agricultural Organization
GHG	Greenhouse Gas
GGR	Greenhouse Gas Removal
ILC	International Law Commission
IMO	International Maritime Organization
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
LOSC	United Nations Convention on the Law of the Sea
LULUCF	[mechanism for] land use, land-use change, and forestry [of the climate change regime]
MCB	Marine Cloud Brightening
MCB	Marine Cloud Brightening
NBA	Nature-Based Approaches; same as Nature-Based Solutions (NBS)
NDC	Nationally determined contributions [to global mitigation measures], in the context of the Paris Agreement
NDC	Nationally Determined Contributions (in the Paris Agreement)
NET	Negative Emission Technologies (synonym to CDR)
OCCS	Ocean Carbon Capture and Storage
RTA	Risk Trade-off Analysis
SAI	Stratospheric Aerosol Injection
SAI	Stratospheric Aerosol Injection
SBI	Subsidiary Bodies for Implementation (UNFCCC)
SBSTA	Subsidiary Bodies for Scientific and Technological Advice (UNFCCC)
SDG	Sustainable Development Goals
SRM	Solar Radiation Modification
UN	United Nations
UNCLOS	same as LOSC
UNEA	United Nations Environment Assembly
UNEP	United Nations Environment Program
UNFCCC	United Nations Framework Convention on Climate Change
UNGA	United Nations General Assembly
WMO	World Meteorological Organisation

Introduction: Framing the Governance of Climate Engineering

by Marie-Valentine Florin[1]

Approaches to removing CO_2 from the atmosphere or to modifying solar radiation are often discussed under the term 'climate engineering' or 'geoengineering'. The two groups of approaches have in common that they refer to the idea of intentionally intervening in the climate system to address the problems of climate change induced by continued emissions of greenhouse gases (GHGs). However, they are so different that they require distinct consideration and any generalization may cause misunderstandings. This report aims to provide support to governments and international policymakers that wish to improve their understanding about various technologies for CDR and SRM, including the existing and potential opportunities, risks, uncertainties, challenges, and possible governance options and approaches that could be discussed in future international negotiations.

The report provides evidence-based information and considerations relevant to international policymaking:

- It reviews various technologies for Carbon Dioxide Removal (CDR) and Solar Radiation Modification (SRM)
- It reviews the leading international legal and institutional arrangements relevant to the governance of climate engineering technologies
- It considers trade-offs between risks in governance and in research
- It suggests elements and steps for global governance, suggesting possible criteria and options for potential future regimes on the international governance of climate engineering

Beyond the critical requirement to aggressively reduce GHG emissions, and the reminder that policy decisions must strive to be based on evidence and a shared, robust understanding across disciplinary and applied perspectives, this report highlights uncertainties, risks and trade-offs involved in climate engineering. It does not make any policy-prescriptive recommendations. It reviews technologies, their apparent potential to contribute to reducing climate change and tackling its dangerous consequences, their limitations and risks, and research needs. The report also highlights that, confronted with significant uncertainties and considerable ambiguities, both normative and interpretive, decision-makers are advised to adopt open processes and flexible mechanisms to facilitate the emergence of shared understanding and goals, which in turn can trigger successful and legitimate institutional processes and decisions. Open and unstructured processes are often better suited to technologies in condition of uncertainty. However, the full respect of structured institutional decision processes provides the legitimacy needed for certain decisions such as those to authorize or ban techniques with high levels of uncertainty and ambiguity. A combination and complementarity of open and structured governance processes can contribute to legitimacy and acceptability of decisions made with a goal to enhance responsibility and sustainability.

[1] EPFL International Risk Governance Center

Context of this report

Anthropogenic climate change poses severe risks to people and ecosystems, especially the most already-vulnerable among them. The Intergovernmental Panel on Climate Change (IPCC) indicates in its latest reports that, in order to comply with the global warming goals provided for by the Paris Agreement (limit the increase in the global average temperature to well under 2°C above pre-industrial levels), there is a need to reach global net-zero CO_2 emissions in the second half of this century, and perhaps sooner (IPCC, 2014, 2018b, 2019a, 2019b).

All emission pathways in the IPCC Special Report on 1.5°C warming (IPCC, 2018b) require engaging actively in actions to remove CO_2 from the atmosphere using CDR techniques. The IPCC top-level integrated assessment scenarios and underlying emissions pathways mentioned above indicate the need to cumulatively remove from the atmosphere by 2100 more than 600 Gt of CO_2 (100-1000 Gt CO_2 by 2100), taking into account that annual anthropogenic CO_2 emissions are today of the order of 40 Gt of CO_2, and depending on how soon net negative emissions is achieved. These scenarios demonstrate the necessity of rapid and unprecedented action; indeed, the apparent required amount of CDR is so enormous as to perhaps be infeasible. However, the IPCC reports provide little indication of the contribution potential of CDR.

Solar Radiation Modification (SRM) includes proposed approaches to limit the global temperature increase, and has thus far been included in neither top-level integrated assessment scenarios nor their underlying (emissions) pathways discussed in the IPCC Special Report on 1.5° warming (IPCC, 2018b).

Various existing international governance mechanisms – legal and non-legal, international and national, binding and non-binding – already contribute to the international governance of CDR and SRM. However, there is no international legal governance arrangement *specific* to either CDR or SRM.

Brief introduction to Carbon Dioxide Removal (CDR) and Solar Radiation Modification (SRM)

To the risk of being over-simplistic, this section begins with an analogy with a bathtub (see Textbox 1 below) that is often used by scholars to explain the role of CDR. Then, Figure 1 illustrates the range of human response options to the climate change problem.

Textbox 1 – The bathtub analogy

In analogy with water in a bathtub, greenhouse gases' natural concentrations are in equilibrium, and the rate of gases entering the atmosphere *(like the running tap)* roughly equal that leaving *(like the emptying drain)*. Human activities have increased the rate of gases entering the atmosphere (*opened the tap wider)*, causing the water level to rise. In the future, there will be dangerous climatic consequences such as caused by sea-level rise *(like water overflowing)*. In analogy with actions to avoid water overflow and its consequences, actions to combat climate change can target:

- Reduction of CO_2 emissions (reduce the flow of water that comes in the bathtub from the tap)
- Increase of CO_2 removal with CDR (increase the size of the drain or the number of drains)

In addition, actions to reduce vulnerability and prevent or avoid irreversible damage from climate change are or may be needed via various measures including SRM, adaptation and protection of essential assets *(widening the bathtub; installing waterproof floors and using mops to reduce consequences of overflow).*

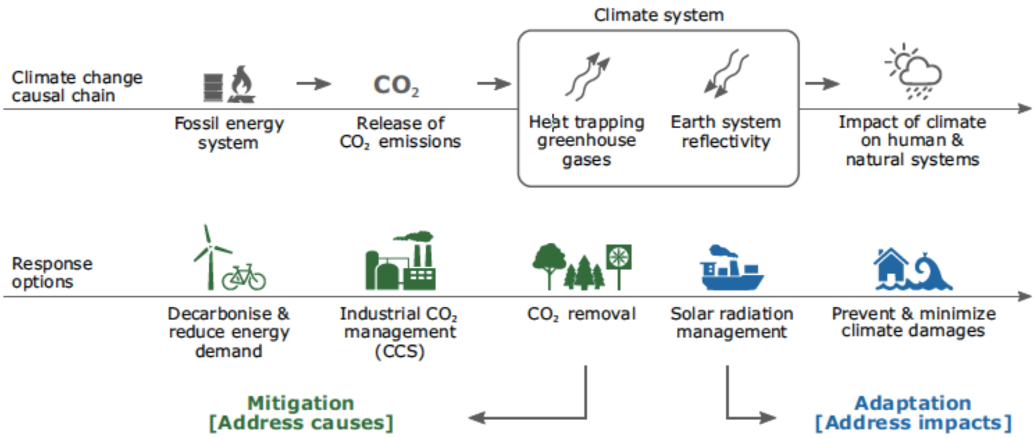


Figure 1 – Human response options to the climate problem.
Horizontal arrows in the top show the causal chain of the climate change problem. Vertical arrows and bottom row define locus and modes of intervention for climate policy. In this figure, all options are attributed to either mitigation or adaptation. Figure from Keith (2000), further developed by Minx et al. (2018). According to IPCC, technologies that enhance sinks are part of mitigation, and SRM is not part of adaptation.

Among the response options illustrated in Figure 1, the two families of techniques, CDR and SRM, are briefly introduced here and further described in chapter 1.

CDR: Sometimes called NETs (Negative Emission Technologies) or GGR (Greenhouse Gas Removal), CDR is defined by the IPCC (2018a) as 'anthropogenic activities removing CO_2 from the atmosphere and durably storing it in geological, terrestrial, or ocean reservoirs, or in products. It includes existing and potential anthropogenic enhancement of biological or geochemical sinks and direct air capture and storage, but excludes natural CO_2 uptake not directly caused by human activities.'

SRM: Sometimes called solar geoengineering, SRM refers to 'the intentional modification of the Earth's shortwave radiative budget with the aim of reducing warming. Artificial injection of stratospheric aerosols (SAI), marine cloud brightening (MCB) and land surface albedo modification are examples of proposed SRM methods. SRM does not fall within the definitions of mitigation and adaptation' (IPCC, 2018a). Note that in the literature, SRM is also referred to as solar radiation management or albedo enhancement' (IPCC, 2018b). Most SRM technologies would intervene to increase the reflectivity, known as the 'albedo', of the Earth's surface or atmosphere. An increase in the amount of sunlight returning to space would alter the Earth's radiation balance, working as a shade and cooling and countering some of the effects of climate change.

Chapters 1 will describe CDR and SRM technologies.

The problem of uncertainty and ambiguity

Technologies that aim to alter the climate system must be assessed as comprehensively as possible around matters of actual contribution to reducing climate change and its consequences, risks, and possible unintended consequences elsewhere. Risks and trade-offs concern not only the climate system but the broader natural environment (through impacts on biodiversity), the economy and society (through impacts on inter- and intra-generational equity, or ethics), which all contribute to sustainable (or unsustainable) development. In addition to the ***complexity*** of the climate system, there are many scientific ***uncertainties*** about intervention techniques and their outcomes. These uncertainties must be compared to the risks and uncertainties of not intervening in the climate system, and much of both sets of uncertainties will remain, probably for several decades.[2]

Policy decisions must be taken despite scientific uncertainty. They must acknowledge certainties (what we know is true), scientific uncertainty and uncertainty about the outcome of policy decisions. Managing risks marked by uncertainty requires a broader governance approach, using rigorous procedural methods, relying on multi-disciplinarity and involving a range of stakeholders and the lay public. While simplification is often possible and needed, the ability to fully embrace uncertainty, and to make decisions under uncertainty is a strength that policymakers can gain, if they can become 'comfortable' with uncertainty.

Ambiguity, i.e., the possibility of various meanings and interpretations of the same evidence, potentially leading to controversies or conflicts, must also be addressed upfront in the policymaking process. Participatory or inclusive governance can help deal with ambiguity. Addressing ambiguity in an international context requires identifying and evaluating potential conflicts, such as those between nation-states with different interests and capacities. This may lead, for example, to evidence for sharing but differentiating responsibility in the choice and implementation of CDR techniques that are most adapted to countries' own geographic or industrial specificities.

Chapters 1, 2 and 3 will delve into gaps, i.e. absence or imprecision of legal dispositions regarding certain questions of current interest, uncertainties and trade-offs among competing yet desirable objectives.

Is there a need to revisit the framing of 'climate engineering' for a productive conversation?

Discussion of climate engineering approaches may be and often is perceived as distracting or even diverting attention from the fundamental need to urgently reduce CO_2 emissions, preserve natural reservoirs of GHG, and capture CO_2 at source, such as with industrial Carbon Capture and Storage (CCS).

Moreover, it can be confusing and misleading when CDR and SRM are grouped under any overarching term such as 'climate engineering'. Umbrella terms are useful to focus on common characteristics, in this case *deliberate alterations of the climate system* to alleviate the impact of climate change (C2G, 2020). There may be contexts in which 'climate engineering' is the appropriate organizing term. However, there are arguably other underappreciated contexts in which 'mitigation' (including CDR) could be a more useful umbrella term, to purposely group emission reduction and all forms of CDR, while leaving aside SRM for its different goal and role and, above all, the many environmental and social risks that its deployment could cause, some of which with potential irreversible adverse consequences. Overarching terms are widely used, but there are indications that they can be confusing for policymaking and to the general public.

Revisiting the framing of climate engineering for research and communication purposes might be useful if it could help clarify the debate about the respective *roles* of various strategies:

(a) CDR is needed to complement the reduction of emissions, but few technologies are mature, some could have large adverse environmental and social impacts and many are presently very expensive.[3]

[2] Noting here that applying a precautionary approach can go both ways: against implementing certain climate engineering techniques - if they incur unacceptable risks -, and against *not* implementing these techniques - if the risk of climate change is expected to be higher than the risk of deploying the techniques.

[3] The overwhelming majority of scenarios for which models can solve for 1.5°C of warming by end of century include very substantial amounts of negative emissions (predominantly in the form of bio-energy with carbon capture and storage); to date just one study has offered an alternative scenario achieving 1.5°C with less reliance on negative emissions, but extreme global emissions reductions efforts including categories of organized social behavior change that have to date not been tested (van Vuuren et al., 2018).

(b) SRM may be needed some time in the future to reduce temperature increase, but deployment is far from ready and potentially dangerous and disruptive. In addition to physical risks, social and political challenges would have to be addressed upfront.

(c) None of the climate engineering options represent an alternative to GHG emissions reductions. Under the United Nations Framework Convention on Climate Change (UNFCCC) and Convention on Biological Diversity (CBD), and as reminded by several international organizations, climate change should primarily be addressed by reducing anthropogenic emissions by sources and by increasing removals by sinks of greenhouse gases (CBD 2016, para.3).

What we know

>> The immediate *goal* is to reduce GHG concentrations in the atmosphere, which will have broader benefits to protect people and ecosystems. This goal must be pursued by a combination of strategies:

- GHG emissions reduction to the furthest possible extent
- Protection and enhancement of existing natural sinks and reservoirs
- Removal of CO_2 with nature-based approaches
- Technological CO_2 atmospheric removal (engineered approaches).

>> Adaptation can help cope with some local consequences of climate change but may not be sufficient to address all problems caused by altered temperatures, precipitation patterns and increasing extreme events. Furthermore, some climate change impacts are not amenable to adaptation.

>> In light of high uncertainty as to the sufficient mitigation of climate change via emissions reductions, limitations of adaptation and potential of various and distinct CDR techniques, additional approaches may be needed. SRM has been discussed for more than a decade for its potential to slow or halt warming. SRM is framed as a way to 'buy time' to fight and adapt to climate change, or as 'an emergency measure of last resort', or to 'fill a gap' to avoid the climate system crossing a dangerous threshold, after which damage would be irreversible. These framings are not neutral (see chapter 3) and may contribute to ambiguity or confusion.

An alternative framing

Instead of contrasting and opposing techniques, an alternative framing would articulate inter-relation and complementarity of response options (as well as their distinct characteristics), perhaps in line with the suggestion made by Heyward in 2013 (see Figure 2). At this point in the conversation about climate engineering, breaking the boundaries between strategies and technologies with an overarching set of policy options might help the conversation going forward. The goal is to encourage holistic thinking about the global nature of the climate problem as a common concern, rather than oppose and fragment, while at the same time being specific about distinct features of the various technologies. International governance could strengthen the oversight of CDR and SRM by offering

Aim	Avoiding climate change			Avoiding "dangerous" climate change	Responding to dangerous climate change
	Avoiding a given level of atmospheric GHG concentration		Avoiding global average temperature increases	Ensuring that rising temperatures do not impact upon core interests	Providing redress for injuries to core interests
Strategy	**Mitigation** Reducing GHG emissions	**CDR** Drawing GHGs out of the atmosphere	**SRM** Increasing albedo	**Adaptation** Improved irrigation, flood defences, protection against disease	**Rectification** Financial compensation, symbolic reparation.

Figure 2 – Situating and abandoning geoengineering: a typology of five responses to dangerous climate change
Note that, in this figure from Heyward (2013), "mitigation" is limited to reducing GHG emissions.

guidance on how actions toward the Sustainable Development Goals can be pursued synergistically, rather than in conflict.

Does it make sense to speak of a portfolio approach to GHG concentration reduction (addressing the causes)?

Pacala and Socolow introduced in 2004 the concept of 'stabilization wedges' to address the climate change problem. While not all the technologies that they described at that time have proven net benefits (balancing their potential to contribute to climate change reduction and risks/costs) in the order of their estimates, their approach is still relevant. 'A portfolio of technologies now exists to meet the world's energy needs', and 'although no element is a credible candidate for doing the entire job (or even half of the job) by itself, the portfolio as a whole is large enough that not every element has to be used' (Pacala and Socolow, 2004). A similar portfolio approach may be relevant for GHG concentrations reduction. Adopting such an approach to CDR technologies suggests that all strategies should be considered, because each of them could contribute to reducing climate change, with various potentials, risks and costs, and time and spatial scales. Rockström et al. (2017) have proposed a 'global decadal roadmap' to make Paris goals a reality, and others have explored similar portfolio approaches to remove CO_2 from the atmosphere, which is also expressed in Figure 3 above. The United Nations Environment Programme (UNEP, 2017) and the US Academy of Sciences NAS (2019) also retain this approach, although at a global level and without specifying the potential role of possible technologies (cf Figure 3 below).

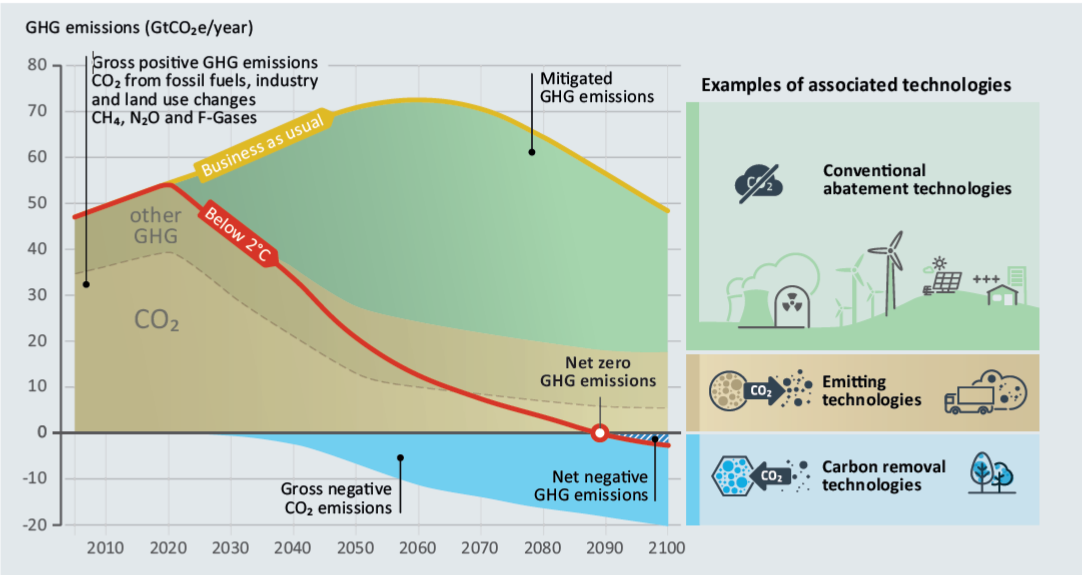


Figure 3 – Scenario of the role of CDR in reaching net-zero GHG emissions and then net negative GHG emissions

Note: This figure shows emission reductions from conventional mitigation technologies combined with CDR. This exemplary scenario is consistent with an at least 66 per cent chance of keeping warming below 2°C relative to pre-industrial levels. Emission reductions are shown against a business-as-usual scenario without any additional climate policies. Global net emissions levels turn to net negative towards the very end of the century, but carbon dioxide removal is already being deployed much earlier. Some residual greenhouse gas emissions remain at the end of the century, as they are too difficult to mitigate in the scenario. (UNEP, 2017; NAS, 2019)

A range of governance or regulatory strategies will be needed

The term governance refers to the range of actions, processes, traditions and institutions by which authority is exercised, and decisions are taken and implemented in order to direct behavior toward an explicit goal. In broad terms, governance is expected to support the delivery results as defined in the pursuit of this goal. Governance includes aspects such as social norms, practices, rules (regulation), institutions, and processes. In the traditional sense, regulation consists of legal instruments, international and national. In a wider sense, regulation also includes bottom-up and non-legal instruments such as codes of conducts, standards, altogether grouped under the term of 'transnational regulation'.[4] With regards to activities of states, subnational entities (regions), civil society and economic actors (e.g. NGOs), and their consideration of certain technologies, governance and regulatory strategies can have various purposes. They can prohibit the use of these technologies considering their proven or possible risks; organize and coordinate them; provide safeguards for e.g., sustainable and responsible research, development, and possible deployment; encourage or discourage them, using a wide range of policy and economic instruments to provide incentives or disincentives; or mandate their research, development, and possible deployment.

Chapter 2 will review the current and potential application of international norms and laws related to climate engineering.

Some binding rules may be less effective than non-binding rules. While binding rules are necessary, it is worth noting that non-binding rules may establish standards that all actors adhere to, especially when they provide the right incentive to reach a goal. There is both frustration about policy hesitation, which leads to an absence of appropriate formal public governance, and possible interest in other forms of arrangements that could be pursued and complement public regulation. Openness and creativity should be encouraged.

Governance and regulatory strategies can also be at various levels. Both the governance of CDR and SRM and the governance of the conversation about them are critically important. They need to take place at the local, national and international levels, depending among other reasons of the scope of impacts of the distinct technologies. Some technologies may incur inherently global risks, and their deployment only makes sense at a global climate-altering scale, which will require international governance. Other technologies may incur risks primarily at a local or regional level, and their deployment would first be subject to national governance.

Political input is needed to define the objective of 'good' governance of climate engineering, and how it should be structured. Implicit in any activity about architecture and functions of governance are values and political input. Engagement of a broader range of stakeholders could serve to develop awareness around technologies and their governance, and trigger government engagement.

A note about terminology

This report predominantly uses the overarching term 'climate engineering', except when a different term such as 'geoengineering' is used as a legal term of art. However, other terms such as 'climate-altering technologies' or 'emerging climate technologies' are also relevant. Some CDR technologies act closer to the causes of climate change (GHG emissions and their atmospheric concentrations), while SRM focuses more on the consequences (e.g., temperature increase or changes in precipitation patterns), and there is a large diversity within each category. All denote deliberate human interventions for the purpose of countering climate change.

Acknowledging the diversity of terms used in this field, it is worth noting again that both the use of any overarching term and the use of different terms may cause confusion and misinterpretations[5]. The right term should be used in the right context. What matters eventually for policy decisions are the details about each of the technologies, their potentials and risks, and governance arrangements such as regulation and economic incentives, rather than the choice of any specific overarching term. Arguments about definitions do not help, unless they are necessary to bring more clarity. Terminology should not be an obstacle to dialogue and international collaboration.

---

[4] According to Djelic and Sahlin-Andersson (2006, p.10). 'Transnational regulation is a mode of governance in the sense that it structures, guides and controls human and social activities and interactions beyond, across and within national territories. However, transnational regulations are embedded in and supported by other modes of governance. As a concept, therefore, governance captures better than regulation the reordering patterns of our contemporary world'

[5] Academics, experts and commentators have used the politics of terminology to advance their agenda (see Gupta and Möller, 2018).

Structure of the report

This report is composed of four chapters

- Chapter 1, by Paul Rouse, reviews the main technologies and their technological readiness, their potential to contribute to reducing CO_2 concentrations or temperature warming, the economics and social responses to each, and their possible impacts.
- Chapter 2, by Anna-Maria Hubert, reviews international legal and institutional arrangements relevant to the governance of climate engineering technologies.
- Chapter 3, by Matthias Honegger, evaluates and discusses risks and trade-offs in governance.
- Chapter 4, by Jesse Reynolds, discusses elements and steps for global governance: possible options and approaches for potential future regimes on the international governance of climate engineering.

Chapter 1 | A Review of Climate-Altering Technologies

by Paul Rouse[1]

Abstract

Two classes of climate-altering technologies, Carbon Dioxide Removal (CDR) and Solar Radiation Modification (SRM) are reviewed, alongside some approaches to the sequestration of carbon. The principles that underlie each technique are explained, and their technological readiness, potential economic costs and environmental implications are explored, along with potential social responses to each technology.

The range and breadth of the uncertainties revealed in the review of techniques expose a complex agenda for governance and policy debate. The analysis demonstrates that there are no simple solutions, and that before any decisions about the direction of travel or prioritisation of techniques can be taken, a plural, socially situated deliberation is required to help better understand and guide the choices we must make collectively.

[1] Carnegie Climate Governance Initiative (C2G), Carnegie Council for Ethics in International Affairs, 170 E 64th St, New York, NY 10065, United States.

1.1. Introduction

This chapter provides an overview of two classes of climate-altering technologies[2], Carbon Dioxide Removal (CDR) and Solar Radiation Modification (SRM). Further, approaches to the permanent sequestration of the billions of tonnes of carbon that may be removed are reviewed. For each technique the principles that underlie them are explained, and their technological readiness, potential, the economics and social responses to each and their possible impacts are explored.

1.2. Carbon Dioxide Removal (CDR)

CDR, also known as greenhouse gas removal or negative emissions technologies, seeks to remove and permanently store the primary driver of climate change, carbon dioxide (CO_2), from the atmosphere. This removal of CO_2 is not a recent idea. It has been part of global climate policy since at least 1992 when the United Nations Framework Convention on Climate Change (UNFCCC) established that mitigation included both emission reductions and removals. The scale and speed at which removals are now required are challenging. All IPCC pathways keeping warming to under 1.5°C require that between 100 – 1000 billion tonnes of CO_2 are permanently removed from the atmosphere by 2100 (IPCC, 2018).

CDR methods include a range of approaches. Some would use nature, such as afforestation and enhancing wetlands; other techniques would use natural systems in conjunction with industrial processes or, alternatively, engineered systems would directly capture CO_2 from ambient air. Each technique varies in its potential, readiness, permanence, cost, and risks of adverse side-effects and all give rise to, as yet, unresolved issues. At present, no CDR techniques are ready to deploy at the scale necessary to significantly contribute to meeting the Paris Agreement goals. Even if they were available for deployment, because the impact of CDR on the climate would not be immediate, any CDR measures that might be taken are unlikely to reduce temperatures for decades. Here CDR techniques are grouped as being either 'nature-based or hybrid' or 'engineered', and a subsection explores how carbon might be permanently stored. Each technique is discussed using the following headings:

- The technique
- Potential contribution to mitigation
- Delivery time scale
- Cost of deployment
- Environmental impact
- Socio-political and policy considerations
- Research issues

Table 1 summarizes the potential theoretical maximum capacity and estimated costs of the CDR approaches discussed in this chapter. It should be noted, however, that the potential and costs indicated cannot be considered settled, because, firstly, to date there has been an insufficiency of systematic and comprehensive assessment of the approaches (Fuss et al., 2018), secondly costs fundamentally depend on technique, policy design and local geographical conditions, and thirdly, indirect economic costs, such as compensation for harms or loss, or those arising from social frictions have been excluded.

[2] Climate-altering technologies is the Carnegie Climate Governance Initiative's (C2G) preferred term. It is broadly synonymous with climate engineering or geoengineering

Table 1 – Potential sequestration capacity and costs of CDR techniques

Technique	Theoretical sequestration capacity (per annum) [3]	Potential cost per tonne of sequestered CO_2 (CHF)
Afforestation And Reforestation	3 to 18 Gt	2.4 to 179
Carbon Sequestration In Soils	1 to 11 Gt	-3* to 12 *Improved soil quality may increase crop profit.
Restoring Wetlands	1 Gt (+ 1 Gt of avoided emissions)	10 to 100
Macroalgal Cultivation	19 Gt	Not available.
Biochar	2.6 to 4.8 Gt	17 to 158
Ocean Fertilisation	Up to 3.7 Gt	10 to 450
Enhancing Alkalinity With Terrestrial Weathering	Theoretically unlimited	51 to 460
Direct Air Carbon Dioxide Capture and Storage (DACCS)	0.5 to 5 Gt (by 2050)	30 to 950
Bioenergy With Carbon Capture And Storage (BECCS)	2.4 to 10 Gt	67 to 240
Artificial Upwelling	Less than 0.25 Gt	400 to 700

1.3. Nature-based and hybrid approaches to CDR

1.3.1. Introduction

Ecosystems and the natural environment play critical roles in the carbon cycle. Protected terrestrial areas contain 15% of global carbon reserves, and deforestation and soil loss currently produce almost 20% of greenhouse gas emissions (IUCN, 2016). The oceans also play an important role in the climate system, not only as a carbon, but also a heat sink – they have, for example, absorbed 93% of the additional energy generated by the enhanced greenhouse effect (IPCC, 2014) and, in the ten years to 2016, they absorbed the equivalent of a quarter of all anthropogenic CO_2 emissions (RS/RAE, 2018).

The Nature-Based Approaches (NBA) – sometimes referred to as Nature-Based Solutions (NBS) – reviewed here seek to exploit natural systems capacities to absorb and store carbon through actions such as planting trees and improving soils. This section also reviews hybrid CDR approaches, which rely on industrial processes to enhance natural systems capability to remove CO_2 from the atmosphere.

The measures discussed here can not only remove carbon but may also provide other human well-being, ecosystem and biodiversity benefits. Whilst the techniques may, with the right policy, political and governance environment in place, make important contributions to constraining climate change, it is unlikely

[3] Gt = Gigatonne, 1 billion or 1 000 000 000 tonnes

that they will be sufficient in their own right to resolve the climate change challenge (Griscom et al., 2017; IPCC, 2014; Smith, 2013; Houghton, 2013; Pacala and Socolow, 2004).

The natural systems that NBA and hybrid approaches would change provide essential services, including carbon storage but also oxygen production, flood and storm protection and food and income generation (IPCC, 2018). Any consideration of these techniques should then be conducted in the context not only of their carbon sequestration capacity but also these wider consequences. Further, nature is fundamental to many cultures and faiths (Thomas, 2018) such that any measures to intentionally change it may be vigorously contested. This, coupled with questions, such as: who would monitor, pay for and insure against harms; how would captured carbon be verified; and how might trade, food production and other resource extraction be affected (NERC, 2016), suggest navigating the governance of these techniques will be complex.

1.3.2. Afforestation and reforestation

The technique

Afforestation and reforestation exploit photosynthesis which absorbs CO_2 from the atmosphere (for a review of photosynthesis and its importance, see Morton (2008). Afforestation is the intentional planting of trees in places where trees have not traditionally grown. Reforestation consists of replanting trees where they have been cropped, died or been removed by other means. They are described here collectively as 'forestation'.

Potential contribution to mitigation

The global capacity of forestation mitigation is contested and uncertain. Griscom et al., (2017) suggest a removal range of 3 to 18 Gt per year, with the variation dependent on assumptions about the land availability ranging from 350 to 1780 million hectares. This upper estimate would require 1.2% of the total available land surface of the planet be planted every year. Smith et al. (2015) offer a more conservative estimate suggesting a maximum capacity of 12 Gt per annum by the year 2100.

Forestation is sometimes portrayed as something of a 'magic bullet' for climate mitigation. However, this is not the case. When a tree or forest reaches maturity, the uptake of CO_2 slows (Houghton, 2013) and when a tree's life cycle is complete, it decomposes, and some CO_2 is returned to the atmosphere (Read et al., 2009). Whilst, this CO_2 release may be avoided through forest management (mature trees being harvested and the biomass stored in long-lived wood products), important questions remain about the permanency of sequestration and how that might be insured through governance, see the section on sequestration below.

Further studies are required to develop a more comprehensive understanding of the potential for afforestation – for example, a recent study concluded that cloud cover and surface albedo changes caused by differences in atmospheric moisture created by the trees, and the darkness of trees absorbing more light, may effectively eliminate the mitigation contribution of northern European afforestation initiatives (Luyssaert et al., 2018).

Delivery times scales

Trees commence taking up CO_2 in their first growing season. However, they take up to 10 years to reach their peak sequestration capacity and reach maturity at between 20-100 years, after which they are no longer capable of net CO_2 removal (RS/RA, 2018). Large numbers of trees can be planted quickly – it is claimed, for example, that more than 350 million trees were planted in 12 hours as a contribution to Ethiopia's Green Legacy programme in July 2019. However, this may not be the environmental success it first appears. Previous mass plantings had a disruptive impact on land, causing soil acidity and the death of other established plants when inappropriate, non-indigenous saplings were introduced into native land.

Cost of deployment

In a meta-review of afforestation cost estimates, Fuss *et al*. identified a range of between 2 and 150 $ per tonne of CO2 (2018). The range of uncertainty is driven by multiple factors, including land price, location, accounting practice, the species of tree planted, ability to manage the resource and the long-term opportunity cost of tying up the land for forestry at the expense of other land uses (Popkin, 2019 and Fuss *et al.*, 2018). The management of soil quality, vulnerability to flood, drought, fire or disease and future effects of climate change may all add to the costs of afforestation over the long term.

Environmental impact

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

The locating of new forests is an important consideration. Temperature, albedo and precipitation locally and regionally can be affected in nontrivial ways, to the extent that they may either mitigate or even enhance the effects of climate change in the affected areas (Winckler et al., 2019, Luyssaert et al., 2018).

Socio-political and policy considerations

The REDD+ Programme suggests that considerable social justice issues may arise when projects are being sited (FCP, 2020). Negotiations among landowners, farmers and others with a cultural interest may be complex, and these processes will be within the context of wider international debates driven by, for example, the New York Declaration on Forests (UN, 2014).

Natural environments have an aesthetic amenity value and perspectives about forestation vary considerably (Thomas, Pidgeon and Roberts, 2018). Policymakers seeking to afforest may then have to navigate complex agenda before beginning to plant.

Research issues

The potential negative impact of forestation is being researched in large scale field trials to better understand the balance of the carbon sequestration and warming effects (Popkin, 2019). Studies are monitoring the carbon, water and other chemical fluxes of forests; and more work using climate models is required to better understand the effects of forestry cover changes (Winckler et al., 2019).

The effect of the chemicals that trees emit is subject to research. For example, methane and nitrous oxide, also greenhouse gases, are emitted by trees in upland forests (Welch and Sayer, 2019) and methane leaks from non-wetland trees in temperate forests (Covey et al., 2012). The extent to which afforestation may increase the emissions of these GHGs and what effects they may have requires further research.

There is also a range of social science questions, such as how to balance competing demands for food production, cropping and grazing, and bio-fuel production with forestation in the most equitable, economically viable and socially acceptable way.

1.3.3. Carbon sequestration in soils

Overview

Soils provide a significant store of CO_2 within the biosphere, meaning changes through disturbance or land management improvements can mitigate or worsen climate change (Powlson, 2011).

The technique

Changing the balance between carbon loss and uptake can be achieved by leaving materials such as roots, litter and other residues in the soil, or by adding manure (Lal, 2011). Depending on soil type, usage and resource availability, these changes can be achieved through crop changes, the use of novel biotechnologies, optimizing fertilizer, minimizing tillage, increasing grass density and the depth of roots and improving grazing management.

Potential contribution to mitigation

Estimates of the volume of carbon that may be retained are highly uncertain; results from modelling give a range of 1 to 11 Gt per annum (Lal, 2011, Lal, 2013, Minasny et al., 2017). It is known, however, that soils will eventually become saturated, and the IPCC has adopted a saturation horizon of only 20 years. Further, some uncertainty remains regarding how permanent carbon storage in soils may be over the long term.

Delivery time scales

There are no significant barriers to enhancing soils, the required practices are understood and in some cases already practiced (RS/RAE, 2018). Importantly, new machinery, tools or soil treatments are not required for deployment (UNEP, 2017), and their deployment requires few or no changes to land use (Smith et al., 2010). Additional support for farmers through incentives and information is however required if sequestration potential is to be maximized (Minasny et al., 2017).

Cost of deployment

Because of positive benefits that may arise, including improved soil fertility; enhanced land workability; increased crop yield; and, potentially, improved hydrodynamics (Keesstra et al., 2016), soil practices of this kind have the potential to create profit of up to CHF3 per tonne of CO_2 (Smith et al., 2016). In less productive soil and poorer environmental conditions, deployment may cost up to CHF12 per tonne.

Environmental impact

Soil sequestration is expected to be environmentally beneficial, and can improve soil fertility, water retention and crop yields – helping deliver some of the UN Sustainable Development Goals (RS/RA, 2019). However, the potential release of methane may reduce the net positive effect on GHG removal.

Socio-political and policy considerations

Knowledge of the benefits and techniques required is limited. This could usefully be addressed if scale-up is desired (Minasny et al.,2017). Work in this direction is underway as a contributor to the climate change goals of the Paris Agreement (UNFCCC, 2015) including the '4 per 1000 initiative' (Soussana et al., 2019). In addition, policy measures will be important to ensure good practice is maintained indefinitely to avoid the reversal of any achieved sequestration. Other practical policy considerations include global monitoring and accounting, although the approach is partially captured through the reporting requirements of the UNFCCC and the Paris Agreement (discussed in chapter 2).

Research issues

Research to better understand the potential of the technique to release additional soil methane is required (Lal, 2011), as is work on the effects of an expected increase of nitrogen mineralisation, which may become a source of another GHG – nitrous oxide (Smith, 2016). Better measurement and monitoring capabilities also require research (RS/RAE, 2018).

1.3.4. Restoring wetlands, peatlands and coastal habitats

Overview

Wetlands such as mangrove forests, tidal marshes, seagrass meadows and peatlands comprise 9% of the global surface area and store up to 71% of Earth's terrestrial carbon (Zedler, 2005). They can sequestrate 200 $MtCO_2$ per annum with between 50 – 90% per cent of this stored in perpetuity (Howard et al., 2017). However, one-third of global wetlands had been lost by 2009 (Hu, 2017), and this loss is accelerating (Page, 2016). Measures to reverse this have significant carbon sequestration potential.

The technique

Wetland restoration requires little technology (Zedler, 2005); requiring only the rewetting of environments by ceasing excessive draining through, for example, dam construction, managing vegetation, and plant restocking (SNH, 2019). Measures to protect the ecosystems against future degradation will also be important (Bain et al., 2011) and may require incentives and adequate land-use planning.

Potential contribution to mitigation

The sequestration potential of wetlands depends on the nature of the wetland, the condition from which it is restored and how the restoration is conducted. Following restoration, the on-going availability of surplus-water will be a key factor in its long-term viability. The restoration of wetlands not only sequesters carbon, but it markedly diminishes emissions from degraded land that would otherwise have happened. Current estimates of sequestration indicate a potential of between 0.4 and 18 tonnes of CO_2 per hectare per annum, scaling to a global potential of approximately 1Gt per annum by 2030 (Griscom et al., 2017). In addition, restoration may, by 2030, reduce about 1 Gt per annum of emissions that are currently being emitted from degraded land (Griscom et al., 2017).

Delivery times scales

Peatlands restoration can take in the order of five years before significant quantities of carbon are sequestered (SNH, 2019), other wetland systems may be expected to respond differently to restoration with timescales dependent on the approach to restoration, longer term management and ecosystem types among other factors. Currently, there is no generic estimate for how long it would take to reach peak sequestration

Cost of deployment

Restoring wetlands costs are estimated between CHF9 to CHF95 per tonne of CO_2 (Kayranli et al., 2010). However, restored or new wetlands can be monetised through opportunities such as water provision, flood management and tourism. These have been valued at up to CHF14 000 per hectare per annum (Junk et al., 2013).

Environmental impact

Restoring wetlands can deliver multiple environmental benefits, including enhancing resilience to flooding and storms. They may also improve water quality and preserve or enhance biodiversity (Zedler, 2005).

Socio-political and policy considerations

The critical barriers to wetland restoration are mainly financial. Frequently, the direct economic value of wetland restoration is insufficient to offset the value of the loss of land, which may be used for food production (RS/RAE, 2018). However, wetlands can create employment and new recreational benefits including tourism.

Research issues

The release of methane and nitrous oxide from wetlands creates between 20% to 25% of global emissions (Whiting, 2001). However, such releases can be reduced significantly by appropriate planting. Further research on how to minimize these GHG would make a useful contribution, as would work to protect against natural drying, or the effects of sea-level rise (RS/RAE, 2018). The effects of restoration on albedo dimming, identified by Rouse (2000), also warrant study, as do monitoring, verification and reporting of achieved sequestration, cost-effective monitoring of fluxes, and the effects of land-use change (Kayranli et al., 2009, RS/RAE, 2018).

Social science is required to inform improvements in land-management practices, and how to protect restored wetlands against future development or land-use change.

1.3.5. Macroalgal cultivation

Overview

Macroalgae farmed at sea to capture carbon through photosynthesis would be harvested for sequestration or used as a biofuel or food with carbon capture (Sondak et al., 2017).

The technique

Macroalgal aquaculture is well-established in China, Japan and South Korea (Pereira, 2013) and may already account for ~0.8 Mt of carbon removal annually (Sondak et al., 2017).

Potential contribution to mitigation

A scaling up to where 9% of the oceans were converted to macroalgal aquaculture could, theoretically, capture 19 gigatonnes of CO_2. The farmed biomass, it is estimated, could also produce 12 gigatonnes per annum of biodigested methane. This could be used as an energy source, and, if the methane were burnt for electricity production and the emissions were captured and stored permanently, an additional 34 gigatonnes per annum could be captured (N'Yeurt et al., 2012). This biomass could then be deposited in the deep seabed (Sondak et al., 2017) or used as a carbon donor for biomass conversion into biogas or fuels (GESAMP, 2019).

Delivery time scale

It is uncertain what rate of removals might be possible, although a South Korean study demonstrated that 10 tonnes of CO_2 per hectare per annum is possible, indicating the approach can ramp up sequestration significantly in one growing season (Chung et al., 2013). The capacity for macroalgae may be reduced by the increasing acidification of the oceans.

Cost of deployment

Currently, the costs of deployment for carbon removal purposes are uncertain. However, GreenWave, Oceans 2050, ClimateWorks and 3Degrees are working with industry, scientists and NGOs on a kelp carbon credit protocol for certification by international carbon credit agencies. The potential economic returns from such a scheme may offset the capital investment needed for new farms, large processing plants, aerobic combustion and CCS facilities.

Environmental impact

If macroalgae production diversifies into new species and geographical areas, there may be risks to biosecurity from the spread of disease and non-indigenous pests, (Cottier-Crook et al., 2016). Such risks can have significant environmental and economic impacts. For example, the shrimp farming industry loses over CHF900 million per annum to viral diseases. The effects of these outbreaks on natural biodiversity are unknown but are likely to be large (Cottier-Crook et al., 2016). Were very large-scale deployment to be taken forward, oxygen levels in the mid-water ranges could be significantly depleted through enhanced remineralization of organic materials, and increases in nitrous oxide and methane may also occur (Williamson et al, 2012)

Socio-political and policy considerations

A proliferation of the technique in the Asia-Pacific region is unlikely to be challenging (Chung et al., 2013) and the economic value from sale for nutrition, energy and fertiliser may help diversification to other regions.

Research issues

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

1.3.6. Hybrid approaches to CDR

The following hybrid techniques would seek to use industrial or engineered materials or approaches to enhance or accelerate the capacity of natural systems to take up CO_2.

1.3.7. Biochar production and deposition

Overview

The addition of biochar involves situating organically derived carbon, once produced, within organic matter in similar ways, and with similar governance agenda associated with other NBA approaches.

The technique

Biochar is an understood and established method, and biochar products are commercially available as soil amendments in Europe and the United States. Biochar is formed by pyrolysis, when biomass is heated with little or no available air, to above 250ºC. In combination with sustainable biomass production, it can be carbon-negative, with potentially positive implications for mitigation. Biochar production can be combined with bioenergy production, using the gases given off during pyrolysis (RS/RAE, 2018). However, this energy production would itself generate carbon emissions (Shackley and Gaunt, 2015).

Because biochar can be applied directly to land, without changing its use, there are few restrictions to its deployment (RS/RAE, 2018). However, the availability of biomass for biochar production is an important limiting factor constraining the potential for global biochar use (RS/RA, 2018).

Potential contribution to mitigation

One tonne of biochar may remove between 2.1 to 4.8 tonnes CO_2 (Lehmann, 2015; Hammond and Brownsort, 2011). It is estimated that globally biochar has a maximum removals capacity of between 2.6 and 4.8 Gt per annum (Woolf et al., 2010).

However, the application of biochar to soil can reduce the surface albedo, with studies suggesting an application of 30 to 60 tonnes per hectare may reduce albedo by up to 40% (Genesio et al., 2012).

Delivery timescales

Biomass, as noted, is available for deployment currently. However, to achieve the full potential of biochar, significant investment in infrastructure and efforts to increase knowledge about the value of biochar may be appropriate.

Cost of deployment

Biochar production costs range from CHF17 to CHF158 per tonne of CO_2 (Woolf et al., 2010). The price is affected by the costs of cultivating and sourcing biomass; feedstock preparation; storage and transport; capital and operating costs of technologies; yield engineering; post-production processing; and, the packaging, marketing and selling of products (Shackley and Barrola, 2011).

Environmental impact

Biochar can improve plant yields, reduce fertiliser requirements (Cowie et al., 2017), and improve water quality and soil nutrient levels (Smith, 2016). Biochar may also stabilise heavy metals in soils, stopping them entering food chains (Woolf et al., 2010).

Socio-political and policy considerations

There are limited incentives to encourage investment in, and take up of, biochar. New measures to facilitate a guaranteed market for biomass or for biochar may positively affect the development of biochar (Alexander, 2014). The International Biochar Initiative (2019) is seeking to encourage biochar uptake through the promotion of research, development, demonstration, deployment, and the commercialisation of biochar.

There are not expected to be major social concerns about the use or scale-up of biochar (Smith et al., 2010). Were transboundary trade in biochar to become common, certification schemes, like those associated with forestry products, might be appropriate for policy consideration.

Research issues

Research is exploring what constitutes 'good' biochar in agronomic and environmental management applications, for example, at the UK Biochar Research Centre (UKBRC, 2020). Other areas of current research include exploring decomposition rates of biochar, whole systems analysis (Sykes et al., 2019), standards, the impacts of biochar on plants and soil fauna and biogeological cycling. For a comprehensive review of biochar research, see Wu et al. (2019).

1.3.8. Ocean fertilisation

Overview

Photosynthesis by oceanic plankton removes around 40 Gt CO_2 per annum from the ocean surface and transports it to depth (RS/RAE, 2018). The volume of sequestration is limited by the availability of photosynthesising life, which is constrained by the supply of micronutrients. Ocean fertilisation seeks to accelerate carbon uptake by addressing this shortage.

The technique

Ocean fertilisation is technically feasible, and the industrial infrastructure required to deliver the materials to the oceans is well understood. Ships would transport industrially produced fertilisation materials, in the form of iron, nitrates or phosphate fertilisers, and place them into the ocean's surface. At least 12 experimental fertilisations have been conducted, with ambiguous CO_2 uptake and environmental results (Boyd et al., 2013). So, while modelling suggests that the subarctic Northern Pacific, the Eastern Equatorial Pacific and the Southern Ocean may be the most productive locations in which to deploy the techniques (Bopp et al., 2013), science lacks an understanding of how much additional carbon may be transported to the deep ocean as a result of a deployment.

Potential contribution to mitigation

Clarity regarding the potential capacity for ocean fertilisation to remove carbon is lacking. Strong et al. (2009) suggest a maximum sequestration capacity of not more than 1 Gt per year. However, assuming continuous fertilisation of all suitable areas of the ocean, others have suggested up to 3.7 Gt per annum may be possible (Williamson et al., 2012. One study concludes it is unlikely there will ever be the capacity to reduce mean temperature with iron fertilisation (Zhang and Zhai, 2015).

Delivery times scales

It would be possible to commence ocean fertilisation, if there were an amenable governance environment, immediately. However, there is currently insufficient infrastructure to support a climate-altering scale deployment (RS/RA, 2019), meaning it is uncertain how quickly large-scale removals might commence, if it were ever decided that it was appropriate.

Costs of deployment

Costs estimates per tonne of CO_2 removed by iron fertilisation vary widely from between CHF10 and 450CHF (Harrison, 2013), depending on how a range of uncertainties are accounted for in the calculation of costs. Although it has been suggested that nitrogen fertilisation – when additional costs including manufacture, transport and distribution by vessels on the ocean are included – is potentially more cost-effective, again the estimates are subject to considerable uncertainty (Harrison, 2017, Matear and Elliott, 2004).

Environmental impact

Environmental harms have been recorded during the initial experiments, including population increases of toxic species of diatoms (Silver et al., 2010, Trick et al., 2010) and increased concentrations of atmospheric methane and nitrous oxide (Law, 2008). Moreover, algal blooms create oxygen depletion in the water, which may pose a risk to other marine life. If phosphorus were to be chosen as the fertilising agent, that might have other environmental effects given its importance for crop fertilisation and its scarcity.

Socio-political and policy considerations

In 2012, 120 tonnes of iron sulphate were placed into the ocean near the Alaskan panhandle by the Haida community and became a case study for social and governance responses to the technique (Gannon and Hulme, 2017). This event and subsequent research suggest the public are broadly unaware of the technique, and when informed about it they view it negatively, describing concerns about pollution and other deleterious environmental consequences (Corner et al., 2014).

If fertilisation were ever to be used at large scale, the policy community would have to resolve complex governance issues (see chapter 2), but also agree an international ocean carbon accounting mechanism to monitor, report and verify achieved sequestration.

Research issues

Research about biological processes, supply chain infrastructure and market mechanisms that might underpin deployment is required, as are research assessments of carbon transfer, generated by fertilisation, in large-scale experiments (Williamson et al., 2012).

Research is being addressed both by universities and the private sector. For example, Ocean Nourishment Corporation Pty Ltd (ONC, 2019) is currently working in partnership with academic institutions to better understand how carbon transfers to and is stored within the ocean. Oceaneos, a marine research organization in the United States, is researching nutrient enrichment technology in waters off Peru (Oceaneos, 2019).

1.3.9. Artificial downwelling or upwelling

Overview

Engineering interventions would transport large volumes of water up or down the water column to either take CO_2 saturated water down to the deep ocean or bring nutrient-rich water up toward the surface to stimulate plankton growth.

The technique

There are no available techniques for downwelling at present. It is suggested the scale of the engineering challenge and the likely low carbon uptake capacity, estimated to be 0.01 Gt per annum per million m^3 per second 'pump' installed (Zhou and Flyn, 2005), makes downwelling an unlikely candidate for further development.

It may, however, be possible to bring deeper, nutrient-rich waters up toward the surface through upwelling. Modelling and field experiments, using devices that have been successfully deployed for several months, have reported positive effects on CO_2 sequestration (Pan and Zhang, 2016). Scaling up, however, remains challenging.

Potential contribution to mitigation

The maximum theoretical sequestration of this technique is estimated to be less than 20 Gt by 2100, equivalent to a mean 0.25 Gt/yr, however, 'there is no evidence that upwelling leads to local [net] uptake of CO2 from the atmosphere' (GESAMP, 2019). As upwelled waters would cool the surface waters and increase their capacity for heat absorption from the atmosphere at local scales (Marchesiello et al., 2010), upwelling may have the potential to provide localised 'air-conditioning' for coastal cities nearby.

Delivery timescales

Climate-scale effects would require the multi-decadal operation of upwelling (GESAMP, 2019) although Pan et al., (2016) suggest localised cooling could function on a seasonal time scale, cooling coastal cities during heat stress events.

Costs of deployment

Limited costs analysis is available to date, and estimates are necessarily uncertain. However, Eisaman et al. (2018) suggest a cost range of CHF400 to CHF700 per tonne of CO_2 removed.

Environmental impact

The potential extent of any environmental impacts of the technique is unknown. However, upwelling at large scale would be a significant disturbance to the environment, and while uncertainties regarding the potential effects on ecosystems remain, the technique can be expected to have impacts (Pan and Zhang, 2016). It is known, for example, that upwelling would bring up high levels of dissolved CO_2 and nutrients (GESAMP, 2019), which would have effects on phytoplankton growth, which may lead to oxygen depletion, were very large blooms to occur.

Socio-political and policy considerations

The state of uncertainty about this approach leaves multiple unresolved issues such as how might decisions be taken regarding who would operate systems, and why and by whom, where might installations be located and how might risk management be organized.

Research issues

Research is limited to modelling (Pan et al., 2016, 2018), laboratory-scale prototyping and small-scale projects to test upwelling 'tubes' in the Pacific Ocean and the East China Sea (White et al., 2010, Pan et al., 2019). More research is required to better understand the feasibility of the large-scale engineering required and the associated economics.

1.3.10. Enhancing ocean alkalinity with terrestrial weathering

Overview

Adding alkalinity in the ocean surface will decrease the relative pressure of CO_2 in the water, increasing its uptake from the atmosphere and reducing ocean acidification.

The technique

Lime put into surface waters would dissolve and consume CO_2 in a well-known and understood process. However, the very large carbon and energy footprint of lime manufacture is a constraint. Were this to be resolved, liming would have CDR capability.

Alternatively, an enhancement of carbonate and silicate mineral weathering on land, creating surface and groundwater run-off could avoid the environmental and financial implications of transporting materials to and across the oceans. A range of approaches have been suggested in the literature, including electrochemical enhanced weathering, ocean or land-based dissolution of reactive silicate material (e.g., olivine) and enhanced weathering of mine wastes – for a detailed analysis, see the comprehensive GESAMP review (2019).

Potential contribution to mitigation

If materials could be safely processed, distributed and deployed at sufficient scale, the combined (on land and in the oceans) mitigation capacity of this process is theoretically unlimited (IPCC 2013). Estimates suggest that if two-thirds of cropland soils were treated with 10 to 30 tonnes of basalt per hectare per annum, between 0.5 and 4 Gt of CO_2 could be removed by 2100 (Smith et al., 2015).

Delivery time scales

Materials could be deployed using existing farm machinery and the technology for mining and preparing rocks for distribution is currently available. However, environmental uncertainties and infrastructure shortcomings require resolution. Plus, economic, social and policy analyses are yet to be conducted.

Costs of deployment

Cost estimates cover a wide range with detailed assessments estimating between CHF51 to CFH460 per tonne of captured CO_2. Increases in crop productively may partially offset some costs (RS/RA, 2019; Renforth, 2012).

Environmental impact

Although mineral weathering, with associated run-off, is the primary way in which CO_2 is removed from the atmosphere over geologic timescales, the environmental impacts of enhancement are uncertain. Additional impurities that would be carried into or be placed into the oceans would have unknown biogeological and the ecological effects. Crop responses are expected to be positive, although more evidence is required.

Socio-political and policy considerations

Corner et al., (2014) suggest publics may not support ocean-based interventions, although some support has been shown for enhanced weathering, despite low levels of understanding about the approach (Pidgeon and Spence, 2017, Wright et al., 2014). Enhanced weathering does not feature in any carbon accounting regimes, and inclusion would require new monitoring and verification mechanisms, plus environmental assessment.

Research issues

With the current knowledge, informed decisions about the approach cannot be taken. Further research is required about materials choice, the likely impacts, the longevity of sequestration and the economics and resource efficiency of the technique.

Multiple research projects are exploring the challenges, including an interdisciplinary programme in the United Kingdom (UK) bringing together five universities across six disciplines. However, no field-scale trials have been undertaken.

1.4. Engineered approaches to CDR

1.4.1. Introduction

Engineered CDR techniques, such as Direct Air Carbon Dioxide Capture and Storage (DACCS) would develop new engineering systems or exploit industrial techniques to remove carbon from the atmosphere. These may all have environmental impacts and other uncertainties, which are not common to NBA. The techniques discussed here do not include carbon capture and sequestration (CCS) techniques. CCS, whilst a potentially important measure as part of the effort to tackle climate change would not result in a net-negative outcome. For example, CCS on a natural gas-fired power plant may reduce the plant's CO_2 emissions by 90-95%, but there is still a net increase in overall atmospheric CO_2, rather than a reduction. For a review of CCS literature, see Leeson et al. (2017).

1.4.2. Direct Air Carbon Dioxide Capture and Storage (DACCS)

Overview

DACCS seeks to separate CO_2 from the atmosphere and store or, in some cases, use the sequestered gas without contributing to warming. The volume of ambient air that must be processed to remove meaningful quantities of CO_2 is large and the amount of energy required to power the processes is high, meaning the efficient delivery of global cooling will require considerable technical capability.

The technique

Two extraction approaches are under consideration. Adsorption, in which a chemical gathers molecules on to its surface from another substance, or absorption, in which material is taken up into the volume of another material.

Absorption is well understood and DACCS would use processes similar to those used in the paper industry for over 120 years (Sanz-Pérez et al., 2016). The absorption would use hydroxide-based solvents such as potassium hydroxide and calcium hydroxide (Daggash et al., 2019), in a stream of air, producing a carbonate and exhaust air. The exhaust air would be unchanged, aside from having a lower CO_2 density. To isolate the captured carbon and regenerate the absorbent, the energy that binds the CO_2 and hydroxide must be overcome requiring a large energy input of heat at between 900 and 1000°C (Samari et al., 2019).

Adsorption DACCS is likely to use amines derived from ammonia. Amines hold CO_2 onto their surface without a chemical reaction taking place. To regenerate, amine has lower energy input requirements, requiring a temperature in the order of 120°C (Sanz-Pérez et al., 2016). Adsorption DACCS would build on known technologies that work at smaller scales, such as air purification systems in hostile environments, for example, within submarines or spacecraft.

Given the rate of air mixture globally is fairly efficient (Goeppert et al., 2012), it would be possible to co-locate multiple DACCS facilities, realising economies of scale, without having detrimental environmental effects. Multiple plants could therefore be located near renewable energy sources to power the process, and in areas that are neither environmentally sensitive nor densely populated (Wang et al., 2013).

Potential contribution to mitigation

It is suggested that DACCS may have a global capture and sequestration potential of 0.5 to 5 Gt per annum by 2050 (Fuss et al., 2018). Although to achieve this may require a large, dedicated power infrastructure.

Delivery times scales

Currently, DACCS development is between pilot and prototype demonstration stages. There is an increasing number of DACCS related patents, with at least 18 around the world (Viebahn et al., 2019), reflecting a growing commercial interest in the technology. Conservative assumptions suggest DACCS may not be viable on a large-scale before 2030 (Viebahan et al., 2019).

A 20-year roadmap for DACCS has been set out by the Innovation for Cool Earth Forum (Sandalow et al., 2018), as a well as Goeppert et al. (2012), Koytsoumpa et al., (2018), Sanz-Pérez et al., (2016). These suggest the key areas for DACCS research are:

- achieving greater energy, heat and water efficiency
- developing understandings of any sustainability impacts
- resolving carbon cycle uncertainties
- improving renewable fuels production
- delivering safe permanent carbon storage
- the economics and policy of a DACCS compatible carbon market
- the social acceptability of DACCS, and
- global carbon accounting and governance.

A summary of currently active DACCS developers known to the author is in Table 2. Research gaps have been identified in a number of studies.

Cost of deployment

The costs of large-scale deployment are uncertain. The power requirements of DACCS are significant. Noting that global nuclear power generation was 2,563 TWh in 2018 (WNA, 2019). The electricity requirements of absorption and adsorption to capture and isolate 1 Gt of CO_2 are estimated at 220 to 500 TWh and 200 to 1,000 TWh respectively. In addition, thermal energy requirements are 1,000 to 2,500 TWh and 640 to 1,700 TWh (Daggash et al., 2019). This suggests an uplift in total global energy provision may be required to achieve large scale DACCS. Additional costs include:

- where liquid sorbents are used – between 1 and 30 m^3 of water per tonne of CO_2 is required (Smith et al., 2016)
- sorbent replacement and other maintenance (Fuss et al., 2018)
- CO_2 sequestration costs – preparation for deposition, transport and storage costs
- capital investment and opportunity costs.

Estimates of DACCS costs range from CHF30 to CHF950 per tonne captured (Sanz-Pérez et al., 2016), with the variation driven by differential assumptions about processes, energy and thermal costs and sorbent regeneration. Some estimates include long-term CO_2 storage costs, whilst others do not.

In the light of the costs, energy demands, current carbon prices and the absence of credit for CDR, DACCS may not be commercially viable in the short term (Daggash et al., 2019). However, DACCS development is currently immature and costs may reduce as both technologies evolve and future markets mature.

Environmental impact

Aside from the effects of plant footprints and any water resource issues – which are unlikely to create harm if plants are constructed in areas without water stress – DACCS is unlikely to harm ecosystems. However, a full life cycle assessment of DACCS technologies is required before a definitive environmental assessment can be made (RS/RAE, 2018).

Socio-political and policy considerations

DACCS plants are likely to have a footprint comparable to medium-sized industrial facilities and are not expected to create land availability stresses. Further, because DACCS facilities need not be in sensitive areas, or close to populations, acceptability issues, aside from those of any medium-size industrial facility are not expected (RS/RAE, 2018).

Were DACCS to be viewed as desirable, the policy community may need to consider introducing significant incentives given its theoretical potential, and assuming the sequestration can be done safely, DACCS may be more promising than other techniques.

Research issues

UK Research and Innovation is committing CHF42 million to DACCS over five-years, commencing 2021 (UKRI, 2019). Other important research sites are The Arizona Centre for Negative Carbon Emission, the VTT Technical Research Centre of Finland and, in the US, the Oak Ridge National Laboratory and the Naval Research Laboratory.

Table 2 – DACCS developers

Group or Company	Objective	Technique	Progress	Current permanency of sequestration	Energy efficiency per tonne CO_2	Cost per ton CO_2
Climeworks (2019)	To capture 1% of global CO_2 emissions and permanently store it as rock or use in horticulture or fuel synthesis.	Adsorption using amine functionalised sorbent.	Nine facilities, currently capturing up to 990 tonnes CO_2 per annum. Offers a CO_2 removal subscription service.	One facility using permanent geologic sequestration. The remaining CO_2 is used in greenhouses or the beverage industry.	Thermal energy of 2.3 – 6.2GJ and 200-1000 kWh of electricity.	Approximately CHF600. Target cost, under CHF100 (Beuttler & Wurzbacher, 2019).
Carbon Engineering (2019)	To capture 1 million tonnes CO_2 per annum.	Absorption using sodium hydroxide.	1 tCO_2/day demonstration plant functioning. Working toward an industrial-scale plant.	Exploring use of CO_2 in synthetic fuels. Otherwise, not known.	8.81 GJ of natural gas, or 5.25 GJ of gas and 366 kWh of electricity.	Currently CHF90 to CHF221 (Keith et al., 2018).
Global Thermostat (2019)	To enable profitable re-use of captured CO_2.	Adsorption using amine functionalised sorbent.	Commercial demonstration-scale products to date.	Not currently permanently stored. CO_2 used in greenhouses.	Not known.	Approximately CHF50 (Breyer et al., 2019)
Infinitree LLC (2019)	To concentrate ambient CO_2 for enclosed agricultural applications to enhance crop growth.	Utilizes an ion exchange sorbent material to concentrate CO_2.	A free-standing modular system, powered by a 120-volt supply is planned.	Not currently permanently stored. CO_2 used in greenhouses.	Not known.	Not known.
Skytree (2019)	A system for citizens to produce fuel at home from CO_2 and water.	Adsorption and conversion of CO_2 into methanol for storage, heating or power.	Patents awarded and in-house testing in hand.	Not known. Exploring use of CO_2 in synthetic fuels.	Not known.	Not known.

1.4.3. Bioenergy with carbon capture and storage (BECCS)

Overview

Biomass is combusted to produce power and the exhaust carbon is captured and permanently sequestered.

The technique

Biomass is grown as feedstock and burnt in generators, producing energy or heat. Gasses released from combustion are then captured at source and sequestered permanently (e.g., in geological formations), effectively taking the emissions out of the carbon cycle. BECCS requires a secure, regular supply of biomass, which may be grown for the purpose or derived from waste, sourced locally to minimise emissions from transport. Rapid growing, cropping and gathering and crop replacement is required.

Potential contribution to mitigation

Models suggest a global storage capacity of between 2.4 and 10 Gt per annum, with the upper figure derived from the mean estimates of the IPCC WGIII AR5 scenarios (IPCC, 2014). It is interesting to note that the IPCC Special Report on 1.5°C (IPCC, 2018) includes pathways to achieve the 1.5°C goal that require BECCS removals of 0–1, 0–8, and 0–16 Gt per annum in 2030, 2050, and 2100, respectively – targets which current evidence suggest are not achievable.

Delivery times scales

Biomass-derived energy is a mature technology, whilst carbon capture and storage (CCS) is largely at the demonstration stage. There are currently 19 CCS plants in operation globally and 51 in a near-ready state (CCS, 2019). However, the ramp-up required in both biomass production and CCS infrastructure is significant, if globally meaningful removals are to be achieved (RS/RA, 2019). Other constraints include limited energy efficiency – BECCS plants are estimated to run at up to 33% efficiency whilst gas turbines currently achieve 61% – and limited financial or other incentives

Cost of deployment

Estimated BECCS costs are in the range CHF67 to CHF240 per tonne of CO_2, with price variation driven by different assessments of plant life, efficiency, biomass and transport costs (Bhave et al., 2017).

Environmental impact

A range of environmental considerations arise from large scale BECCS. Land-use change will be required for crops, freshwater and nutrients will be required to enable crops to flourish (potentially creating food production and sustainable development target tensions), and the nitrogen cycle may be affected (RA/RA, 2019). A linkage to forestation as a biomass source may also have environmental impacts (as discussed above). CCS may create air-quality issues due to sulphur dioxide, nitrous oxide, nitramines and nitrosamines release during the process. Comprehensive whole systems analysis of scaled-up BECCS infrastructure may reveal further environmental issues.

Socio-political and policy considerations

Competition for land-use change may create tensions and policy will have to carefully balance the demands for land against needs for settlements, energy, carbon removal and food. Given that several countries already have national policy commitments and BECCS deployment strategies (RS/RA, 2019), these, and the environmental implications need urgent resolution.

Research issues

Whole systems assessments of BECCS are required to better understand the full carbon cycle within the process and its wider environmental, economic and social effects (Fuss et al., 2018). Such assessments must be conducted in the context of the evolution of CCS, feedstock production and combustion techniques. Energy and CCS efficiencies should be sought (RS/RA, 2019).

1.5. Other CDR techniques

In addition to those discussed above, several other techniques have been explored in the CDR literature. These are all underdeveloped, and there is limited reliable information available regarding their climate-altering capabilities and associated uncertainties and risks. These are briefly reviewed here. For those interested in additional information, other reviews are suggested (e.g., GESAMP, 2019; C2G, 2020).

Ocean carbon capture and storage (OCCS) seeks to remove carbon dissolved in the oceans, increasing the capacity of the oceans to absorb more CO_2 from the atmosphere. The removed carbon would subsequently be sequestered into safe, permanent storage, as disused below. Carbon removal from water is an understood technique and is regularly undertaken in laboratories during seawater analysis and experimentation (Willauer et al., 2017). However, work on scaling up the process from the laboratory to the oceans is very limited. Outstanding fundamental research questions include resolving potential sequestration capacity, understanding the energy and infrastructure requirements and the environmental impacts (Eisaman et al., 2018).

Marine methane capture and processing. Methane's warming potential is 30 times more potent than CO_2 over a 100-year timeframe, although it persists in the atmosphere over a shorter time-frame than CO_2 (IPCC, 2013) and oceanic and permafrost warming is expected to generate large methane releases (Shakhova et al., 2010, Whiteman et al., 2013). Despite methane being an important GHG, there has been very limited work on methane capture and processing, a point reflected in the terminology of CDR, which explicitly excludes GHG other than carbon dioxide. Reviewing the literature Lockley (2012) and Stolaroff (2012) have suggested covering areas of the ocean with a film to capture methane releases for subsequent 'flaring off' or some form of storage. They have also suggested sieving methane bubbles, released from the seabed, through porous materials at the point of origin, causing them to dissolve into the water column before reaching the surface. Given the immaturity of this area of study, it is not possible to estimate the potential, impacts, costs or risks of these theoretical propositions.

1.6. Sequestration

1.6.1. Introduction

The safe and cost-effective permanent sequestration of captured carbon or any other GHG will be critical. An accidental release of multiple gigatonnes of a GHG due to storage failure, whatever the emission reductions or removals that may have been achieved through, for example, afforestation or DACCS could be very damaging.

1.6.2. Sequestering carbon in the oceans

It has been suggested, for example in the GESAMP review of marine techniques (2019) and the IPCC special report on carbon dioxide removal (IPCC, 2005), that it may be possible to inject liquid CO_2 into the oceans at a depth of greater than 2800m, where it would be expected to dissolve into inorganic carbon and remain indefinitely. Whilst the theory was explored in the IPCC Special Report (Metz et al., 2005), there has been minimal research since. Although some experimental trials had been proposed in Norway and Hawaii, these were not undertaken in the light of considerable negative public responses to the plans (Adams et al., 2002; Gewin 2002). There are no estimates of this method's capacity to store carbon in perpetuity, i.e., millennial time scales, and the environmental impacts are unknown (GESAMP, 2018). Economic modelling of costs suggests a range of between CHF5 and CHF24 per tonne of CO_2 (Anderson et al., 2005 and Livermont et al., 2011).

An alternative to injecting CO_2 onto deep waters may be to place it in seabed depressions, trenches or in sediments at depths greater than 3,000m (GESAMP, 2019, IPCC, 2005). Very limited field trails indicate CO_2 deposited in this way would remain stable in perpetuity (Brewer et al. 2005). However, currently there are no deployable technologies available to safely deliver the volumes required, although analogous techniques used in the offshore oil industry may be adaptable (GESAMP, 2019).

Economic assessments suggest a cost of placing CO_2 in the substrate of in the order of CHF24 per tonne (Goldthorpe, 2017). House et al. (2006) have demonstrated that the total storage capacity in such reservoirs is vast compared to current emissions. With good mapping, it is unlikely that the stores would be disturbed by human activity such as deep-sea mineral extraction, although geological disturbance could be disruptive, with consequent uncertain environmental impacts.

1.6.3. Crop residue oceanic carbon sequestration

There are no technological constraints to crop residue sequestration which would involve the dumping of ballasted crop residue, biochar, timber and other organic matter into the deep ocean or off the deltas of large rivers. Strand and Benford (2009) indicate that two gigatonnes of residuals could be available, without harming soils. However, Lenton and Vaughan (2009) suggest the methods would make a modest contribution. Further, the environmental impacts are uncertain and there is a dearth of knowledge about its environmental impacts (GESAMP, 2009).

1.6.4. Mineralisation of injected CO2 within geologic structures

Underpinning this theory is the capacity of carbon to react with available materials to form new rocks or minerals (Matter and Kelemen, 2009). Commonly found basalt and peridotite rocks, for example, would create stable carbonate minerals from a reaction between CO_2 and magnesium and calcium ions (Matter and Kelemen, 2009). The theoretical storage capacity of this technique may be sufficient to sequester all of the CO_2 that would be emitted by burning all known fossil fuels reserves (Goldberg et al., 2008).

Research, such as the EU funded CarbFix project has demonstrated a viable complete mineralisation process, and the US CarbonSAFE project is currently conducting onshore research using a demonstration project. It aims to have 50 operational 50 Mt facilities by 2026.

The risks associated with this approach relate to industrial process harms, the majority of which can be assessed and mitigated. The environmental impacts are, with appropriate site selection to access green or renewable energy (Sigfússon et al., 2018) and to avoid impacts on water resources, likely to be minimal. A small-scale project by Climeworks (2019), using technology developed by their CarbFix2 project (Beuttler et al., 2019) is now offering a subscription service for individuals who wish to offset up to 600kg of carbon emissions per annum through the mineralisation of emissions, framing those taking up the service as 'Climeworks Pioneers'.

1.6.5. Building with biomass

As noted*,* plants' capacity to continually take up new carbon declines as they age, if those with diminished capacity were cropped and used in construction, the contained carbon could be sequestered for between several decades and several hundred years and vacated land could be replanted. Harvested fibre would be used in buildings, providing frameworks, walls and insulation, sequestering carbon (RS/RA, 2019).

McLaren (2012) has suggested between 0.5 and 1 Gt per annum could be sequestered whilst Oliver (Oliver, 2014) indicates the approach could save between 12% to 19% of global fossil fuel use due to the reduction in the use of carbon-intense building materials such as concrete. However, to achieve this, between 34% and 100% of the Earth's sustainable wood growth would be required to service the building industry, requiring a new global industrial and supply infrastructure.

Although a full environmental and risk assessment is required (Ramage et al., 2017; Gustavsson, 2011) there are indications that the approach is gaining some policy support. For example, wood building codes in Canada, China and the United States have recently changed allowing greater flexibility for the inclusion of wood in builds, partly in the light of its sequestration potential (Cecco, 2019). Grey literature has suggested that the construction community may be responding to stimulus (Roberts, 2020)

1.7. CDR discussion

All of the techniques discussed have multiple uncertainties associated with their capacity to remove carbon, costs, environmental effects and social acceptance. Table 3 provides a brief overview of some of these uncertainties.

CDR will be required to meet the 1.5° Paris Agreement goal, requiring the removal of in the order of 100 to 1000 billion tonnes of CO_2 from the atmosphere in the next 80 years. Yet, to date, the policy community has not responded sufficiently to the challenge – neither in terms of research support, incentive provision, nor, as will be shown in chapter 2, CDR's governance (Mace et al., 2018). As more and more national net-zero targets emerge, this problem will become increasingly acute (Honegger et al., 2019).

Currently, no CDR techniques are comprehensively understood and developed, nor is a policy environment yet available to underpin climate-relevant CDR deployment. Whilst some techniques, such as forestation, can be deployed today, even tree planting requires further study to fully understand its environmental, climate and sustainability impacts and how we might achieve robust reporting, monitoring and verification (Zakkour, 2014).

Reporting, monitoring and verification of removals will require a global accounting system that accounts for the complexities of monitoring, reporting and verifying gas fluxes across many techniques that are, simultaneously, a sink for and source of GHG (Welch et al., 2019). Currently, carbon taxes, cap-and-trade and carbon credit offsets only fund very specific CDR approaches at the global scale and a centrally coordinated mechanism or body, that includes financial capability, may be required to maximize the benefits, and minimize any harms of afforestation.

It is unclear how the international community might agree, set and stabilise, over the long-term, atmospheric CO_2 concentrations and other mitigation measures. Nor how this process, and the outcomes of the decisions taken, can balance the individual interests of nation-states with the global need to reduce CO_2 concentrations in the atmosphere.

In addition to the many unresolved research, environmental and policy challenges that remain, as explored in relation to the various techniques discussed here, multiple other issues are yet to be resolved. It is unclear how the required scale and speed of implementation might be achieved. The incentives to secure this rapid change, in terms of new research investment, financial and policy options do not exist. Plus, of particular importance, are considerations about how CDR's implications on, for example, food and water security may affect the delivery of the Sustainable Development Goals.

The social acceptability of CDR cannot be assumed (Blackstock & Low, 2018) and there are no acceptance studies for many of the potential techniques. Opposition to CDR-driven land-use change and real or imagined effects on crop productivity and agriculture more widely could frustrate the rapid scale-up required (RS/RA, 2018) and, moral hazard could delay other climate change mitigation efforts (Mace et al., 2018).

This review of CDR techniques suggests policy and financial support, in the form of appropriate incentives and support for basic, strategic and applied research is required, alongside focussed efforts to guarantee the permanency of carbon storage. In the light of the large body of broader innovation literature, which consistently demonstrates long time lags between the development of new techniques and technologies and their scaling-up to deployment (Gross, 2018) – and the needs for CDR to be adopted quickly and globally – the urgency around CDR is growing.

Table 3 – Summary of uncertainties associated with the CDR techniques discussed

	Cost or Affordability	Climate uncertainties	Other environmental uncertainties	Permanency	Social acceptability	Energy requirements
Afforestation and reforestation	Costs of very long term management	Dependent on scale & type	• Biodiversity loss • Positive effects on erosion or flooding • River and lake acidification	Potentially limited without very long-term land and wood management	Competing demands for land use may create tension. Otherwise broadly accepted.	
Carbon sequestration in soils		Dependent on scale	• Extent of soil fertility, water retention and crop yield improvements	Very long term	No major concern.	
Restoring wetlands	Costs of very long term management	Dependent on scale & type	• Extent of enhanced resilience to flood and storm and improvements in water quality and biodiversity	Very long term with long-term land management	Competing demands for land use may create tension. Otherwise broadly accepted.	
Macroalgal cultivation	Capture and sequestration	Dependent on scale & type	• Extent of biodiversity loss or potential spread of disease and non-indigenous pests	Limited without appropriate capture and sequestration	The willingness to support expansion	
Biochar		Dependent on scale	• Extent of improvements to crop yield, water and soils quality. • Scale of benefits from stabilising heavy metals in soil	Very long term	No major concerns	

	Cost or Affordability	Climate uncertainties	Other environmental uncertainties	Permanency	Social acceptability	Energy requirements
Ocean fertilisation	Unknown	Unknown	• Scale of increase in toxic diatoms, and of methane and nitrous oxide emissions • Effects of algae blooms on biodiversity	Very long term with a proportion unlimited	Limited research suggests it is not welcomed	
Enhancing alkalinity with terrestrial weathering	Unknown	Unknown	• Uncertain bio-geological and ecological effects	Very long term	Insufficient evidence	Requirements for material preparation and distribution
Direct air capture with carbon storage (DACCS)	Unknown	Dependent on scale	• Water resources may be affected with uncertain effects	Potentially unlimited with appropriate sequestration	No major concerns	The capacity for the global energy system to deliver the energy required
Bioenergy with carbon capture and storage (BECCS)	Opportunity cost of land use and large-scale plants	Dependent on scale	• Effects on biodiversity, freshwater and nutrients • Effects on sustainable development • Process emissions	Potentially unlimited with appropriate sequestration	Competing demands for land use may create tension.	What future BECCS generation might contribute to global need
Artificial upwelling	Unknown	Unknown	• Unknown	Very long term with a proportion unlimited	Unknown	Unknown

1.8. Solar Radiation Modification (SRM)

Introduction

Solar Radiation Modification (SRM), also known as Solar Radiation Management or Solar Geoengineering, would aim to reflect sunlight back into space, or allow more heat to escape Earth's atmosphere. Increasing solar radiation would alter the Earth's radiation balance, working as a shade on a sunny day and countering some of the effects of greenhouse warming. Estimates suggest that we would need to reflect 2% of sunlight to counter the warming potential of a doubling of CO_2 concentrations in the atmosphere (Shepherd, 2009).

There are a number of potential approaches to SRM, ranging from the thinning of cirrus clouds to brightening clouds in the marine environment or injecting aerosols in the stratosphere. Some SRM methods appear able to effectively, rapidly, and inexpensively reduce warming. However, modelling suggests that they would imperfectly compensate for climate change and might pose environmental risks and social challenges. Further, SRM cannot be a substitute for emission reductions because it does not address the causes of global warming, increased GHG concentrations, meaning underlying risks would continue to grow whilst CO_2 concentrations increase. Neither would SRM have any more than minimal effects on ocean acidification. Despite these caveats, interest in SRM's potential is growing (Asayama, 2019).

There are multiple complex technical, socio-political and governance challenges associated with SRM and, although SRM techniques may be theoretically effective, there are large uncertainties and knowledge gaps, substantial risks and important institutional and social constraints to deployment (Keith, 2013, Robock, 2018). Whilst the approaches to SRM vary considerably in their technique, scale and the location of deployment, they do share several common characteristics. Modelling suggests that, if deployed, they would all be fast-acting, reversible although with some negative consequences, and are likely to be low-cost compared to the costs of mitigation. However, despite those common factors, there are important differences in the details of each technique, which are individually described below.

Table 4 – SRM potential cooling and costs

SRM Technique	Theoretical maximum capability	Potential cost per unit radiative forcing per annum[1]
Stratospheric Aerosol Injection (SAI)	Greater than the warming effect of all anthropogenic carbon emissions since the industrial revolution	Between CHF16.5 and CHF96 billion per -W m^{-2} (Smith and Wagner, 2018, Robock, 2020)
Marine Cloud Brightening (MCB)	-4 W m^{-2} (large uncertainty)	CHF190 million per -W m^{-2} (large uncertainty) (Lenton and Vaughn, 2009)

[1] The doubling of CO_2 concentration from pre-industrial values generates a radiative forcing of 3.7 W m^2 (IPCC 2007).

1.8.1. Stratospheric Aerosol Injection (SAI)

Overview

SAI seeks to increase the amount of reflective aerosol, a suspension of fine solid particles or liquid droplets, in the stratosphere. The cooling potential of this is demonstrated by volcanic eruptions, such the Mount Pinatubo event in 1991, which ejected in the order of 20 million tonnes of sulphur dioxide cooling the global climate by an average of 0.5˚C for two years.

SAI would deploy aerosols in the stratosphere, a relatively stable zone in the atmosphere meaning particles could remain in situ, reflecting light for a period measured in years (Keith, 2013, Stavins and Stowe, 2019).

The technique

To date, there are no available deployment techniques. Aircraft delivery of the aerosols is expected to be the most practicable and economic method (Robock et al., 2009; Keith, 2013; Stilgoe, 2015). However, to be fully effective, planes would need to fly at approximately 20,000 metres with a heavy cargo and be fitted with appropriate spraying kit to deliver particles (Keith, 2013). Nozzles to eject aerosols of the desired size are feasible but have not yet been developed or tested. No current aircraft can fly at the required height with a heavy payload for extended periods of time (Smith & Wagner, 2018).

It has been suggested that a fleet of 20 appropriate aircraft could deliver sufficient radiative forcing to produce detectable climate cooling (Keith, 2013) although, because the particles will fall out of the stratosphere over time, they will need to be continually replaced to maintain the same cooling effect.

Potential contribution to cooling

SAI has the potential for large leverage over anthropogenic warming (IPCC, 2018b). One kilogram of sulphur optimally deployed may offset the warming effect of several hundred thousand kilograms of CO_2 (Keith, 2013). This suggests that the additional radiative forcing of the 240 billion tonnes of carbon released by human activity, since the beginning of the industrial revolution could be reduced by half with an annual injection of 1 million tonnes of aerosol (Keith, 2013).

Response timescales

Notwithstanding the considerable uncertainty about possible environmental and social effects, social acceptability and SAI governance, it is expected that, were deployment capability available SAI could deliver planetary-scale cooling within a year of deployment (Keith, 2013). Chapter 3 discusses deployment scenarios and timescales further.

Cost of deployment

Assessments have suggested that SAI may be delivered at a cost of between CHF9.5 billion per year for -2 W m^{-2} (McClellan et al., 2012) to CHF200 billion (Robock, 2020). For comparison, a doubling of CO_2 concentration from its pre-industrial value is expected to generate radiative forcing of approximately 3.7 W m^{-2} (IPCC 2007).

The most comprehensive cost models indicate that an investment of approximately CHF2.20 billion per annum would halve the current rate of global warming. However, an additional infrastructure investment for aeroplane research and design is required – priced at CHF1 to CHF3.4 Billion (Bingaman et al., 2020; Smith and Wagner, 2018). Further, these direct deployment costs may only represent a fraction of the costs of comprehensive policy development and deployment.

Environmental impact

Various deployment scenarios suggest SAI may affect weather systems and local climate phenomena, such as monsoon rains and subsequently, ecosystem functioning (Nalam et al., 2017, Keith et al., 2016, Mercado et al., 2009). For example, if deployed in a high environmental GHG scenario and to fully compensate global warming, SAI may lead to drying over Amazonia, parts of Africa and India with implications for ecosystems and crop productivity (Simpson et al., 2019). SAI may also alter the seasonal cycle in high latitude locations, causing warmer winters and cooler summers (Jiang et al., 2019), with potentially important environmental and other implications. However, one recent study (Irvine and Keith, 2020) suggests that a halving of warming with SAI might reduce key climate hazards substantially, while avoiding some of the problems associated with fully offsetting warming with SAI.

Changes in aerosols in the stratosphere, caused by some of the candidate SAI particles, could influence its chemistry and cause ozone depletion (Keith et al., 2016, Tilmes and Mills, 2014) while the ozone layer is still recovering from modifications by ozone depleting substances due to human activities (Heckendorn et al., 2009). Ozone effects are an important unknown because ozone protects all life on Earth from harmful ultra-violet rays (Williamson et al., 2014).

Some candidate aerosols may cause harm as they fall into the troposphere forming acid rain or air pollution, affecting the terrestrial environment (Keith, 2013). The resulting number of deaths or illnesses is uncertain, although they are likely to be far lower than those that might otherwise arise from the avoided warming.

If SAI were deployed, and then stopped quickly, a temperature increase may occur – known as 'termination shock'. This creates a potential for large-scale environmental, economic and social effects (Matthews and Caldeira, 2007). However, it is argued that there are no obvious scenarios under which a rapid termination of SAI might be allowed to occur (Parker and Irvine, 2018). In addition, given the risks of such warming and that the rate of particle fallout from the stratosphere would be sufficiently slow to limit warming initially, it is suggested that there would be sufficient time for the global community to respond with replacement SAI (Parker and Irvine, 2018). The termination shock would also apply to MCB, as discussed below, but with different effects and response times.

Socio-political and policy considerations

Public responses to the idea of SAI deployment have frequently been shown to be negative in research studies (Macnaghten and Szerszynski, 2013, Pidgeon et al., 2012, Merk et al., 2015, 2019, Braun et al., 2018). However, one recent study has suggested that some in the global south may be more positively disposed to the technique (Sugiyama et al., 2020). Other studies have conflated SRM techniques of widely varying nature under a generic term, such as solar-engineering, and report findings about publics' views of those, without any clarity regarding which technologies are being explored (Burns, 2016).

The most frequently referenced concerns about SAI relate to uncertainty about the effects, harmful outcomes and issues about 'playing God'. Awareness of these concerns among scientists is thought to be higher than in relation to previous technologies and researchers maybe being more cautious in their approach to taking forward SAI research (Sarewitz, 2010).

Within the policy community, there is limited knowledge about SAI and its potential benefits or risks (Wagner and Zizzamia, 2019). If informed decision-making is to be possible, this information gap must be addressed. Some actors are seeking to do this, for example, the Carnegie Climate Governance Initiative (C2G, 2020).

Research issues

Research to date has focused on climate modelling (Berdahl et al., 2014, Irvine et al., 2009), potential engineering solutions (Keith, 2013) and social, political and governance issues (Horton et al., 2018, Macnaghten and Owen, 2011, Bellamy et al., 2017, Stilgoe, 2015, Reynolds, 2019). Future research questions will likely relate to particle choice, environmental and climate effects, delivery systems and potential effects in the stratosphere on, for example, ozone as well as social acceptability and governance questions.

In December 2019 the US government authorised $4 million of new research funding (Temple, 2019) and an Atmospheric Climate Intervention Research Act (ACIRA, 2019) was presented to Congress which, if passed, will facilitate and fund SAI amongst other climate-altering technologies research.

Much of current SAI modelling is through the 'Geoengineering Model Intercomparison Project' (GeoMIP, 2020) supported through the World Climate Research Programme (Tilmes et al., 2015). The first SAI outdoors experiment is now in development. The Harvard University Stratospheric Controlled Perturbation Experiment (ScoPEx) plans to deploy a small instrument package in the stratosphere in 2020 (ScoPEx, 2019).

1.8.2. Marine Cloud Brightening (MCB)

Overview

Clouds over oceans would be engineered to be brighter, increasing albedo and creating cooling.

Techniques

MCB seeks to increase the number of cloud-condensation nuclei in relatively dust-free parts of the marine atmosphere by spraying fine particles – likely of saltwater – into clouds raising the host cloud's albedo and potentially cloud longevity (Albrecht, 1989, Russell et al., 2013). Deployment by both ship and aircraft has been suggested (Wood et al., 2018).

Potential contribution to cooling

The degree of confidence that MCB could deliver cooling of a similar scale to SAI is low with uncertainty driven by the availability of clouds which would be susceptible to brightening (Latham et al., 2012). Further, the uneven distribution of suitable clouds means MCB cooling would be inherently non-uniform, a characteristic which does not apply to SAI (Stavins and Stowe, 2019). Bearing this caveat in mind, if it were ever possible, which is highly unlikely, it has been estimated that a doubling of cloud-droplet concentration of clouds off western coasts of North and South America and the west coast of Africa might compensate for approximately a doubling of atmospheric CO_2 (Latham et al., 2009). It may be possible to adjust MCB over short timescales, which may offer some capacity for local or regional cooling on a day to day basis: a measure which may be useful during peak heat stress events (Stavins and Stowe, 2019).

Delivery timescales

Some small scale outdoor experimentation of technology took place early in 2020 (see Research issues below). However, larger-scale deployment should not be expected for some years, if at all. Once deployed, cooling in the affected area would be immediate and continue for such time as the cloud remained bright – how long this may be is unknown.

Cost of deployment

Costs estimates for MCB are uncertain, with limited research and considerable ambiguity about deployment techniques and results (Latham et al., 2012). However, in one estimate, a cost of CHF190 million per -1 W m^{-2} reduction in radiative forcing has been suggested (Lenton and Vaughn, 2009).

Environmental impact

The most likely candidate base material for MCB is seawater, which would not have wider health effects. However, its use would not be neutral with research suggesting that the chemistry of additional sea salt may reduce ozone at the sea surface and increase methane levels (Horowitz et al., 2020).

MCB would be spatially heterogeneous and difficult to control. It may affect dynamic transport of moisture and air, affecting weather systems and important local climate phenomena such as regional hydrologic cycles and ecosystem functioning (Park et al., 2019, Keith et al., 2016, Mercado et al., 2009). What the ecosystem effects of these changes might be are uncertain. Such disruptions could lead to dryland expansion or flooding, environmental degradation and food security concerns. As with SAI, were MCB ever deployed at very large scale, and then terminated, a termination shock would be expected. Given MCB has a days-long lifetime rather than the more prolonged duration of SAI aerosols in the stratosphere, the termination effect would occur far more rapidly, leaving a short timescale within which to respond or prepare (Parker and Irvine, 2018).

Socio-political and policy considerations

The policy community may wish to consider whether MCB is an appropriate research investment to inform future consideration and decision-making. This deliberation might take note of public perceptions and likely responses to MCB. However these are uncertain and there have, to date, been fewer studies of MCB's acceptability than of SAI. Of those studies that have explored the acceptability of MCB they tend to suggest that key concerns relate to the controllability of the technique (Bellamy et al., 2017).

There is no established nor theorised market that might encourage MCB research and development.

Research issues

The Australian government (RRAP 2020) is currently supporting MCB research on reducing seasonal heating over the Great Barrier Reef and, in April 2020, the first field trials of a one-tenth scale prototype spaying technology was tested 100km off the coast of Queensland (SCU, 2020).

The 2019 US $4 million commitment to solar climate interventions discussed above encompasses MCB. The current research agenda includes proposed field experiments into cloud-aerosol interactions; cloud physics; particle manufacture, delivery and observation; and, climate and environmental implications such as examining the impacts of local application on regional or wider climate.

1.8.3. Other SRM techniques

In addition to SAI and MCB, several other techniques are discussed in the literature, these are all at an early stage of consideration, with a number being theoretical with limited, or no reliable information to hand regarding deployment scenarios, costs and environmental impacts. The extent to which any of these techniques would be socially acceptable are uncertain. These are briefly reviewed here. Further information is available from several detailed studies such as the National Academy of Sciences and GESAMP reviews, (NRC, 2015, GESAMP, 2019) and materials produced by the Carnegie Climate Governance Initiative (C2G, 2020).

Some **space-based techniques** have been proposed which would place light scatters or reflectors in space, reducing the amount of sunlight entering the atmosphere. Options include large prisms or opaque disks, a solar sail, an iron mirror, trillions of micro spacecrafts or a ring of space dust (NRC, 2015). However, these contain such great uncertainties regarding technique, direct and economic costs, risks and effectiveness, as well as lengthy timescales until potential deployment, that their implementation may be impractical (NRC, 2015, Sanchez and McInnes, 2015).

Cirrus cloud thinning (CCT) would modify the structure of high altitude ice clouds which absorb and emit longwave radiation back down to Earth with a warming effect (Lohmann, 2017). CCT would seek to change this balance by reducing the longevity of the clouds and by changing their optical properties by 'seeding' the atmosphere. Currently, research is at an early stage and researching CCT in situ is very challenging (Lohmann, 2017). Currently, not enough is known about CCT to warrant a more detailed discussion at this time, although this approach should be considered to have some potential, not least given effective CCT would change long-wave radiation, which has significant climate effects.

The use of light coloured materials on new and existing structures, known as the **'white roof method'** (Zhang et al., 2015) would enhance albedo. However, the approach is probably the least effective and most expensive of all possible climate-altering approaches (Shepherd, 2009).

It may be possible to **enhance plant albedo** through selective breeding (Ridgwell et al., 2009), although costs have not been estimated in any detail and, the context of global food supply issues, diverting effort toward SRM in crops may not be practicable (Shepherd, 2009).

Large reflective polyethylene-aluminum surfaces could be deployed **over land** (Govindasamy and Nag, 2011). However, the manufacture, transport, installation and cleaning of materials that cover a sufficiently large area would create new carbon emissions and have uncertain environmental effects underneath the surface and regionally. Costs to achieve minimal cooling could be several trillion dollars per year (Shepherd, 2009).

Floating spheres on sea ice (Field et al., 2018), micro bubbles (Seitz, 2011), rafts of foam (Aziz et al., 2014) or water pumped onto ice to freeze, creating reflective surfaces have been suggested to **enhance ocean surface albedo** (Desch et al., 2016, King, 2019). Simulations indicate a 0.05% increase in ocean albedo may create 2.7 ^{o}C of surface cooling (Seitz, 2011) and small-scale studies are underway (ICE911, 2019). Research questions include how the surfaces would respond, behave, disperse or sink; and, what the effects on vertical mixing in the ocean, ocean circulation, photosynthesis, and other risks to the biosphere, coastal zones, the biota and food chain might be.

A number of engineering approaches to reduce ice melt have been theorised, including glacier engineering and artificial snow deposition (Moore, 2018). To understand if such engineering feats would ever be possible, cost-effective and environmentally safe requires considerable research, for which Moore (2018) has suggested an agenda.

1.8.4. SRM discussion

Table 5 – Summary of uncertainties associated with SAI and MCB

	Cost or Affordability	Climate uncertainties	Other environmental uncertainties	Permanency	Deployment mechanisms	Social acceptability
Stratospheric Aerosol Injection (SAI)	More clarity required	Potential regional precipitation effects Effects on seasonal cycles at high latitudes	Ozone depletion Implications for ecosystems and crop productivity Health effects of particle fall out	Termination shock avoidance Moral hazard	Aerosol choice Aircraft design Number of aircraft and sorties required Aerosol distribution kit design	Appetite for research investment
Marine Cloud Brightening (MCB)	More clarity required Implications of heterogeneous deployment	Implications for ecosystems and crop productivity	Potential pollution – methane and ozone Availability of suitable clouds Implications of heterogeneous deployment	Termination shock avoidance Moral hazard Longevity of brightened clouds	Deployment mechanisms – ship or aircraft Spray device	Appetite for research investment Limited evidence to date

SRM partially decouples the link between carbon emissions and temperature, meaning it could be theoretically possible to achieve the 1.5°C target without reducing emissions. This may create a 'moral hazard' in which a deployment could create a form of rebound effect where emissions reduction policies are diluted, undermining individual, collective or political incentives for delivering mitigation. Oceans would continue to acidify, and increasingly large SRM inputs would be required, potentially even creating opaque skies, high rates of pollution and, without strong governance, a very significant rebound effect threat (Lin, 2012). The extent, nature and scale of any 'moral hazard' conditions are uncertain, as are the nature of measures to mitigate the thinking and behaviors that might lead to and drive it. It may also be true that moral hazard could, in some circumstances, be acceptable. For example, if SRM were safely keeping climate change within acceptable levels, despite a degree of moral hazard generating slightly higher GHG emissions.

The geopolitical challenges of SRM are significant (C2G, 2020) and it is unlikely that SRM deployment could ever be regarded as optimal by all States. However, if a global consensus about temperature could be arrived at, there would likely be only limited disagreement about how much SRM would be required to deliver the target (Ricke et al., 2013). Not only do different countries have different perspectives on what a 'good climate' is, but the environmental effects of some approaches to SRM would be asymmetrical, creating winners and losers (Stavins and Stowe, 2019). It has been suggested that these create a risk of conflict (Chalecki and Ferrari, 2018; Kosgui, 2011), especially in case of unilateral deployment by a state or non-state actor. Whether or not conflict is a threat, it is likely that the potential risks, benefits, and associated transboundary equity and justice uncertainties that SRM could give rise to, would also create complex policy challenges, including around decision-making, monitoring and validation and about who, if anyone, might choose to deploy, with what authority and when. Alternatively, the potential for unilateral deployment may have positives in as much as, whilst international cooperation and collaboration is probably desirable, it could allow for rapid deployment in an 'emergency' scenario.

The ordering of any potential deployment of SRM in relation to mitigation is an important policy consideration. Might SRM, for example, commence after efforts to reduce emissions have been exhausted to deliver interim cooling, whilst CDR were ramped up, after which SRM could be tapered down. Or, should SRM run concurrent to emissions reductions, with a tapering down of SRM as CDR effects take hold? Given the speed of effect of SRM deployment, some have suggested that SRM might be needed and should be deployed as an 'emergency' tool to deliver cooling if a climate crisis unfolds. For example, if it appears that an irreversible tipping point has been crossed.

All SRM scenarios create risks, for which policy formulation and governance decisions will be required. Some examples might include: who, and using what evidence, should decide that emissions reductions and CDR have failed (or are not sufficient) and that it is timely to deploy SRM; or, how might SRM be monitored and verified and who will authoritatively assess SRM and decide when it is time to either deploy or taper down any deployment of SRM? Who should host such discussions and from where would their authority stem, and what might the role of scientists be in this?

There are also important questions regarding who might choose to deploy, and with what implications. Barrett (2019) and Parker et al. (2018) have explored this, discussing various scenarios in which large powerful states or smaller collectives of weaker and/or vulnerable states threaten to, or do deploy SRM. Alternatively, might crowd-funded initiatives occur (Morton, 2015) or could the corporations recently committing large sums to the climate challenge choose to work collectively toward SRM as their preferred solution?

1.9. Conclusions

The breadth of uncertainties and ambiguities that the climate-altering technologies discussed here give rise to create a complex set of agenda for the policy debate. Whether it be CDR or SRM, whether it be the planting of trees, or bold proposals to engineer the stratosphere – there are no simple solutions. Before any decisions about techniques can be made, new research is required. However, science alone cannot provide all answers. As such, before decisions about any future direction of travel or prioritisation of techniques can be taken, a rebalancing of the debate away from expert analysis alone, toward a plural, socially situated deliberation is required to help better understand and guide the choices we must make collectively. At the heart of these deliberations must lie governance.

Perhaps the only certainty is that almost all facets of climate-altering technologies are uncertain, and within those uncertainties reside ignorance and ambiguities, in which actors' own interpretive and normative responses will affect perspectives on the tolerability of risks. Continued dialogue and deliberation informed by robust research may be the only way forward currently available.

1.10. Bibliography of useful sources

The following is intended as a brief reading list for those interested in exploring the techniques discussed here further.

Carbon Dioxide Removal

RS/RAE (Royal Society and Royal Academy of Engineering) (2018) Greenhouse Gas Removal. London, UK: The Royal Society. Available at: http://royalsociety.org/greenhouse-gas-removal.

GESAMP (2019) High Level Review of a Wide Range of Proposed Marine Geoengineering Techniques, GESAMP Reports and Studies. Joint Group of Experts on the Scientific Aspects of Marine Environment Protection (GESAMP). Available at: http://www.gesamp.org/publications/high-level-review-of-a-wide-range-of-proposed-marine-geoengineering-techniques.

A systematic review of negative emissions technologies in three parts

Minx, J. C. et al. (2018) 'Negative emissions—Part 1: Research landscape and synthesis', Environmental Research Letters. IOP Publishing, 13(6), p. 63001. doi: 10.1088/1748-9326/aabf9b.

Fuss, S. et al. (2018) 'Negative emissions—Part 2: Costs, potentials and side effects', Environmental Research Letters. IOP Publishing, 13(6), p. 63002. doi: 10.1088/1748-9326/aabf9f.

Nemet, G. F. et al. (2018) 'Negative emissions—Part 3: Innovation and upscaling', Environmental Research Letters. IOP Publishing, 13(6), p. 63003. doi: 10.1088/1748-9326/aabff4.

Solar Radiation Modification

Stavins R, R. S. (2019) Governance of the Deployment of Solar Geoengineering. Harvard, Project on Climate Agreements. Cambridge, USA: University of Harvard. Available at: https://geoengineering.environment.harvard.edu/files/sgrp/files/harvard_project_sg_governance_briefs_volume_feb_2019.pdf.

National Research Council (2015) Climate Intervention: Reflecting Sunlight to Cool Earth. Washington, USA: The National Academies Press. doi: https://doi.org/10.17226/18988.

Reynolds, J. (2019) 'Solar Geoengineering To Reduce Climate Change: A Review Of Governance Proposals', Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences. Royal Society, 475(2229), p. 20190255. doi: 10.1098/rspa.2019.0255.

Climate altering-techniques governance

C2G (2020) Carnegie Climate Governance Initiative Evidence and Policy Briefs, infographics and Reports 2019 – 2020 URL: https://www.c2g2.net/publications/

Chapter 2 | International Legal and Institutional Arrangements relevant to the Governance of Climate Engineering Technologies

Anna-Maria Hubert[1]

Abstract

This chapter surveys the current and potential application of international law related to environmental protection and sustainability to climate engineering. Specifically, it provides an overview of key general norms of international law (including the duty to prevent transboundary environmental harm, the precautionary principle and the duty of international cooperation), treaty instruments (including United Nations Framework Convention on Climate Change and Paris Agreement, Vienna Convention and Montreal Protocol, Convention on Biological Diversity, London Protocol and amendments), international institutions, and soft law relevant to the governance of CDR and SRM.

The chapter highlights that the international legal and institutional landscape relevant to climate engineering presents a complex 'patchwork' of overlapping norms and institutional mandates, and points to how existing instruments and institutions, that have expressly addressed geoengineering regulation and governance to date, reflect a "limited" approach in line with their specific objectives, scope and mandate, which leads to a one-dimensional perspective on climate engineering rather than a comprehensive and integrated approach to its governance. The chapter suggests the need for further international cooperation, and some degree of international governance of various forms.

[1] University of Calgary

2.1. Introduction

Given its potential for far-reaching consequences, climate engineering has the potential to intersect with many different subject areas of international law, including international human rights, international development, peace and security, intellectual property, and food security.[1] Since a comprehensive analysis of the legal implications of climate engineering in respect of all of these areas is beyond the scope of this chapter, this contribution focuses on the potential application of international law related to environmental protection and sustainability. Specifically, it provides an overview of key general norms of international law, treaty instruments, soft law, and international institutions relevant to the governance of proposed climate engineering technologies.

2.2. General Norms of International Environmental Law relevant to the Governance of Climate Engineering

There are a number of general principles and norms of customary international law in the area of international environmental law that bear upon the international governance of climate engineering. These are noteworthy in that they broadly apply to all human activities, including prospective climate engineering measures and their development. This section identifies and describes the legal status, scope and content of several key general principles and customary rules including the duty to prevent transboundary harm, the precautionary principle, and duties of international cooperation, to conduct a transboundary impact assessment, to notify and consult.

2.2.1. Duty of International Cooperation

One of the debated topics related to climate engineering and its governance is the extent to which conditions call for international cooperation. Over the course of this century, the sovereign independence of individual states is increasingly giving way to a world order premised on the idea of mutual interdependence and the recognition of common interests shared by a group of states or the international community as a whole. Enhanced scientific and technological progress creates interdependences from trade and economic integration, but has also caused serious environmental damage globally. Moreover, environmental processes and components are all interconnected, as are the human societies that they support. In his dissenting opinion in the ICJ's Advisory Opinion on the *Legality of the Threat or Use of Nuclear Weapons*, Judge Weeramantry noted that the mutual interdependencies of states are a product of '[a] world order in which every sovereign state depends on the same global environment'.[2] The expansion and deepening of states' commitments to protect the environment means that as new issues arise 'theoretically important areas for decisions are much restricted and hemmed in by treaties, by customary international law and by the consequences [...] of the sheer interdependence of all sovereign states of today.'[3] As the body of international rules becomes denser and state affairs increasingly intertwined, there is a greater likelihood that new issues will be treated as common problems that demand international cooperation in order to be resolved. By the same token, cooperation under international law, including the related right or obligation to cooperate and to create legal norms, may be regarded as a concrete expression of state sovereignty.[4]

The general duty of states to cooperate is reflected in many treaties and other instruments, resolutions, and policy documents. The UN Friendly Relations Declaration underscores that '[a]ll states have the duty to cooperate with one another [...] to maintain international peace and security and to promote international economic stability and progress [...].'[5] Though the obligation may be formulated differently in different instruments, international cooperation is mandated for several matters that are potentially touched upon by climate engineering as common interests of the international community. For example, a duty of cooperation is articulated in international law for the maintenance of international peace and security,[6] the use of commons areas,[7] the protection of the environment[8] and sustainable development,[9] and in the area of science and technology.[10]

In particular, the duty of cooperation permeates most of international law on environmental protection. In his separate opinion in the *Mox Plant Case*, Judge Wolfrum described cooperation as the 'overriding principle of international environmental law,' which ensures that 'community interests are taken into account vis-à-vis individualistic State interests.'[11] The idea of international cooperation on environmental protection as a limit on State sovereignty is explicitly recognised in Principle 24 of the Stockholm Declaration, which reads:

> *Cooperation through multilateral or bilateral arrangements or other appropriate means is essential to effectively control, prevent, reduce and eliminate adverse environmental effects resulting from activities conducted in all spheres, in such a way that due account is taken of the sovereignty and interests of all States.*[12]

This duty was reaffirmed in Principle 7 of the Rio Declaration which predicates the need for states to work together 'in a spirit of global partnership to conserve, protect and restore the health and integrity of the Earth's ecosystem' based upon developed and developing countries' differentiated historical responsibility for environmental degradation and their ability to pay.[13] Importantly, for the discussion of treaty instruments below, the duty of cooperation also functions as the backbone of most, if not all, international agreements on the protection of the environment.[14] The content of this duty may vary in relation to the objectives of the instrument and may have substantive, procedural, and institutional elements.[15] It commonly encompasses requirements to provide technical assistance, to promote scientific research and information exchange, to call for joint action on environmental assessment and monitoring, and to further develop and implement international rules and national laws and measures. For multilateral agreements, cooperation is not only necessary for the effective implementation of existing obligations, but also serves to facilitate the progressive development of treaty regimes, often through international institutions, treaty bodies or other organizational structures. [16] International cooperation can also provide the basis for harmonising domestic laws and policies and coordinating national action,[17] and if sufficiently widespread, could help to alleviate the problem of forum shopping through the formulation and harmonization of international minimum standards.

International cooperation on climate engineering may be mandated for various reasons, not least because it touches upon many subject areas of international law that fall within global common interests, to promote collective learning and responsible governance and regulation, and to address forum shopping and the protection of the global commons.[18] With regard to research and development of climate engineering measures, many international environmental treaties not only call for international cooperation for the promotion of scientific research generally,[19] but also to establish terms for joint participation in the conduct of scientific research and monitoring,[20] and to provide for the exchange of scientific information, including cooperation on scientific programmes, the generation of observations and data,[21] the publication and dissemination of scientific information,[22] and scientific and technical capacity building.[23] Cooperation on scientific and technical matters may take place directly between States or through international institutions.[24]

2.2.2. Duty to Prevent Transboundary Environmental Harm

States have a customary law obligation to ensure that activities within their jurisdiction or control do not cause significant damage to the environment of other States or areas beyond the limits of national jurisdiction.[25] As a corollary of this rule, the principle of prevention requires that a state, in a transboundary context, 'use all the means at its disposal in order to avoid activities which take place in its territory, or in any area under its jurisdiction, causing significant damage to the environment of another state'.[26] This rule entails both an obligation to prevent environmental harm before it actually occurs, and to provide reparations for damage after the fact.[27] The thrust of this obligation is nevertheless forward-looking, in that the prevention of future damage is emphasized as the 'preferred policy' in view of the often irreversible character of damage to the environment and the limitations under international law in providing reparations for environmental damage.[28] The obligation is invoked where the risk of harm is 'significant', meaning 'something more than "detectable" but not necessarily '"serious" or "substantial,"' and is to be assessed based on factual and objective criteria and depending on the particular circumstances of the case.[29] To recover for actual or anticipated damage, there must be proof of a causal link between the activity in question and the risk of significant harm to the environment based on the relevant evidentiary standard.[30]

The customary rule on the prevention of transboundary harm entails both procedural and substantive elements. Procedural obligations include the requirement to conduct an environmental impact assessment, as well as collateral obligations of consultation and negotiation, described below. Substantively, the principle of prevention of transboundary harm constitutes an obligation of due diligence, which generally requires that states avoid, minimize, and reduce the risk of harm by taking its best possible efforts. Due diligence applies to the activities of a state directly, as well as to the activities of private operators within a state's jurisdiction and control. Thus, it 'entails not only the adoption of appropriate rules and measures, but also a certain level of vigilance in their enforcement and the exercise of administrative control applicable to public and private operators, such as the monitoring of activities undertaken by such operators'.[31] This dimension of the due diligence obligation is significant in the context of climate engineering governance given the concern that some climate engineering measures may be carried out by private individuals or corporations, especially in the case where they may be relatively cheap and technically easy to deploy.[32] Due diligence does not amount to a guarantee on the part of a state that the harm would never occur, a so-called 'obligation of result'. Rather, similar to a negligence standard, due diligence constitutes a requirement to take appropriate measures to prevent or minimize harm from human activities in accordance with the capabilities of a state with jurisdiction and control.[33] The standard of care for due diligence is proportional to the degree of risk of transboundary harm from the activity in the circumstances and the vulnerability of harm of affected states. Accordingly, 'activities which may be considered ultra-hazardous require a much higher standard of care in designing policies', and would be correspondingly much more arduous to satisfy.[34] Thus, large-scale deployments of climate engineering measures, such as stratospheric aerosol injection, which are necessarily global in nature, may give rise to a much higher standard of care given the magnitude and scale of the risk of environmental harm.[35] The due diligence obligation to prevent transboundary harm is triggered where the risk of harm of the activity concerned is foreseeable and may give rise to significant adverse effects.[36] The condition of foreseeability or knowledge is closely coupled with the additional requirement of states to carry out an environmental impact assessment, described below.[37] The standard of care in exercising due diligence is that required of a 'good government'.[38] States are required to use the best practicable means at their disposal and in accordance with their capabilities.[39] It is an evolving standard that tracks alongside technological changes and scientific developments.[40] Thus, as held by the Seabed Disputes Chamber of the International Tribunal for the Law of the Sea (ITLOS), 'due diligence is a variable concept' that 'may change over time as measures considered sufficiently diligent at a certain moment may become not diligent enough in light, for instance, of new scientific or technological knowledge'.[41] In summary, for climate engineering measures, several factors are relevant to determining the standard of care of due diligence, including the scale and duration of the intervention, the magnitude of the adverse effects that it is likely to cause, and the current state of scientific and technological knowledge.

Given its universal application to all states with the status of customary international law, the customary international law rule on the prevention of transboundary harm provides a kind of 'floor' for the regulation of climate engineering proposals of all types. In particular, a state is not allowed to engage in, or permit those within its jurisdiction and control to engage in, climate engineering activities, such as stratospheric aerosol injection, marine cloud brightening or ocean fertilization, in an unrestrained and uncontrolled manner where there is a risk of significant environmental harm. Moreover, as discussed further below, the general obligation to prevent significant transboundary harm creates strong obligations to engage in environmental impact assessment, notification, and cooperation, and may even be seen as an indication that States should seek for an international governance framework. On the other hand, it should also be noted that there rule has several limitations with respect to ensuring accountability of different actors for environmental damage arising from such measures.[42] One drawback is that the scope and content of the rule remains abstract and vague.[43] Moreover, it 'requires only that reasonable efforts are made to prevent harm' such that '[i]n the absence of agreed standards, the difficulties that a claimant would face in establishing a lack of diligence on the part of another state exacerbate other evidentiary challenges, such as those related to causation.'[44] In addition, a range of transboundary harm, including that which is unforeseeable or unavoidable by reasonable efforts or caused by the activities of private operators, presents 'a potentially significant accountability gap … when states are held only to a due diligence standard'.[45]

2.2.3. Precautionary Principle

The 'precautionary principle' or 'precautionary approach' offers a more recent addition to the corpus of international environmental law aimed at 'adjusting the insufficiencies of the regimes of prevention' given the widespread growth and intensification of human activities and technologies, a lack of knowledge of the impact of such phenomena on ecosystems, and the need to anticipate serious or irreversible damage.[46] The principles of prevention and precaution may be thought of as existing along a spectrum. Nonetheless, the fundamental distinction between these concepts of international environmental law lies in the extent of evidence of harm of an activity: the preventive principle applies where the risks are known and can be proven scientifically, whereas the precautionary principle 'runs in advance' of prevention by calling for action to protect the environment before sufficient scientific evidence of harm can be fully furnished.[47] As such, the precautionary principle is clearly relevant to the development and use of climate engineering measures, since it generally applies where the potential risk of an activity can be identified, often using traditional risk analysis or scientific assessment, but where scientific information is insufficient to fully demonstrate or quantify the risk or to prove a cause and effect relationship between the activity and possible adverse effects.

The legal status of the precautionary principle as a customary norm of international law continues to be a matter of debate. In its Advisory Opinion on the *Responsibilities and Obligations of States Sponsoring Persons and Entities with Respect to Activities in the Area*, the ITLOS Seabed Disputes Chamber identified precaution as reflected in Principle 15 of the Rio Declaration to be 'an integral part of the general obligation of due diligence of States' even apart from the express regulations that applied in that case.[48] It further noted that the precautionary principle is being incorporated into an increasing number of international instruments, reflecting a 'trend towards making this approach part of customary international law'.[49] Rio Principle 15 declares that '[i]n order to protect the environment, the precautionary approach shall be widely applied by States according to their capabilities. Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation.'[50] More conservative versions as embodied in Rio Principle 15 and incorporated into other multilateral agreements, such as Article 3(3) of the UNFCCC and preamble of the CBD, are considered to be relatively non-controversial. These stipulate that a lack of decisive evidence of harm should not be a ground for refusing to regulate. In other words, the Rio Declaration formulation is generally read to permit precautionary action in the face of serious or irreversible threats but does not compel regulatory action. By contrast, stronger versions are not merely permissive, but instead require States to take precautionary measures in the face of a potential risk to human health or the environment or even to reverse the burden of harm. As discussed below, the precautionary principle is incorporated into many of the environmental treaties relevant to the governance of climate engineering measures, though the legal status, scope and content of the principle varies across these instruments. It should be noted that these different formulations of the precautionary principle in different treaty instruments may have different substantive, procedural, and evidentiary implications. These include the right or duty to take remedial action, as well as requirements to err on the side of environmental protection or to avoid environmental risk, or changes in the burden or standard of proof.[51]

Generally, the application of the precautionary principle is triggered where there is a reasonably foreseeable threat in the absence of conclusive scientific evidence, and where that threat amounts to one of 'serious or irreversible harm'.[52] These criteria also operate to clarify the minimum level of scientific evidence required to justify precautionary measures. The precautionary principle may be criticised on the grounds that it may promote the adoption of measures that may stifle scientific and technological progress.[53] In the context of climate engineering measures, for example, the United Kingdom Science and Technology Committee recommended that the precautionary principle should not be included as a discrete principle to supplement the Oxford Principles, for fear that it would result in a disproportionate ban on climate engineering research and, perhaps, in covert testing.[54] On the other hand, given the uncertainties surrounding climate engineering and climate change, the precautionary principle is clearly relevant by urging prudent decision-making in the face of scientific uncertainty about the possibility of serious or irreversible harm.

Precautionary measures for climate engineering may take on a wide variety of forms and are culturally and politically contingent.[55] The EU Communication on the Precautionary Principle discusses general guiding principles for the adoption of measures taken in reliance upon the precautionary principle.[56] It highlights the need for proportionate, non-discriminatory, consistent, and transparent actions, and further emphasizes the importance of a cost-benefit analysis of action and a lack of action, including the socio-economic and other non-economic considerations associated with different responses, to the extent that such analysis is appropriate and feasible.[57] It is also recommended that precautionary measures should be provisional - that they should be reviewed in light of new scientific information, but maintained as long as scientific knowledge is insufficient and decision-makers consider the risks too high to be imposed on society.[58]

2.2.4. Transboundary Environmental Impact Assessment

An important procedural obligation, which is also rolled into a state's obligation to exercise due diligence to prevent significant transboundary harm, is that a state must ascertain whether there is a risk of significant transboundary harm prior to undertaking an activity that has the potential to adversely to affect the environment of another state or to areas beyond national jurisdiction.[59] In such cases, including in relation to the development and use of climate engineering measures, that state must conduct a prior environmental impact assessment (EIA), in accordance with customary international law.[60] The obligation is triggered where the proposed activity is likely to have a significant adverse impact in a transboundary context.[61] The procedure according to which an EIA is to be conducted under customary international law remains unclear. However, a recent ILC study on the protection of the atmosphere observes that, according to international practice, it should involve the following considerations:

- It should be carried out prior to the decision of the project;
- It must be carried out in such a manner that all relevant environmental impacts can be analysed and evaluated;
- It should allow for public participation in the process at the relevant stages;
- Generally, it should be conducted by State authorities; and
- The result of an assessment must be taken into consideration when the competent authority decides on whether to proceed with the project.[62]

The Special Rapporteur for the ILC study also notes that

> *[w]hile those observations primarily address the requirement of EIA in transboundary contexts, it is uncertain, mainly for the lack of relevant precedents, whether the same applies to EIA for projects intended to have significant effects on the global atmosphere, such as geoengineering activities. It is submitted, however, that those activities are likely to carry a more extensive risk of 'widespread, long-term and severe; damage than even those of transboundary harm and therefore that the same rules should a fortiori be applied to those activities potentially causing global atmospheric degradation.*[63]

2.2.5. Duty to Exchange Information, Notify, and Consult

Originating in the law respecting shared natural resources, the duty to cooperate in international environmental law also entails procedural obligations of information exchange, prior notification and consultation.[64] As expressed in Principle 7 of the UNEP Draft Principles, '[e]xange of information, notification, consultation and other forms of cooperation regarding shared natural resources are carried out on the basis of the principle of good faith and in the spirit of good neighbourliness'.[65] Moreover, as noted above, these requirements also apply to the management of transboundary risks, reflected in Principle 19 of the Rio Declaration and the ILC's Draft Articles on the Prevention of Transboundary Harm,[66] forming part of the corpus of customary international rules where there is a risk of significant adverse transboundary environmental effects.[67] Although largely procedural in nature, these obligations cannot be conducted as a 'mere formality,'[68] but also have substantive content in that they must be carried out in a way that is 'meaningful' and in good faith.[69]

2.3. Environmental Treaties Relevant to the Governance of Climate Engineering

2.3.1. 1992 United Nations Framework Convention on Climate Change

The 1992 United Nations Framework Convention on Climate Change (UNFCCC) was negotiated and adopted in recognition of the need to establish measures to address anthropogenic climate change.[70] It is a framework convention that provides the legal and institutional basis for the further evolution of the international climate regime, most recently with the adoption and coming into force of the 2015 Paris Agreement, described below. The UNFCCC is silent on the topic of climate engineering, but, in view of its direct relevance to the topic, it is likely to provide important background norms and institutional structures for consideration of this topic going forward.

The 'ultimate objective' of the UNFCCC is to achieve the 'stabilization of [GHG] concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system'.[71] This objective is ambiguous as it pertains to climate engineering measures. CDR may fall within the scope of this objective, since removals target the reduction of GHG concentrations in the atmosphere directly. However, SRM measures are more difficult to construe as satisfying this aim, because such measures do not directly affect atmospheric GHG levels, and, moreover, in light of potentially significant environmental risks and uncertainties, may themselves be viewed as a potentially dangerous human interference with the climate system.

The UNFCCC sets forth several general principles to guide the international response to climate change, including the principles of intra- and intergenerational equity and common but differentiated responsibilities and respective capabilities, sustainable development, cost-effectiveness, and the need to apply precaution.[72] These general principles appear broadly relevant to climate engineering, and could even be seen as fundamental elements of an international governance response to this issue in the future. The UNFCCC also requires that States Parties take measures, including environmental impact assessments, to minimize the adverse effects of projects or measures undertaken to mitigate or adapt to climate change.[73] It also stipulates that States Parties 'promote and cooperate in scientific, technological, technical, socio-economic and other research […] intended to further the understanding and to reduce or eliminate the remaining uncertainties regarding […] the economic and social consequences of various response strategies'.[74] Moreover, as noted above, the core substantive obligations in the UNFCCC focus on limiting emissions of GHGs and the protection of sinks, rather than 'on controlling other variables in the climate system'.[75]

One potential contribution of the UNFCCC to climate engineering governance is the institutions that it establishes. The UNFCCC creates an annual Conference of the Parties, which enjoys a broad mandate to elaborate specific obligations on an ongoing basis. It also establishes a Subsidiary Body for Scientific and Technical Advice. This multidisciplinary body is charged with providing the Conference of the Parties and its other subsidiary bodies with timely information and advice on scientific and technological matters relating to the Convention. These institutions are shared with the 2015 Paris Agreement, and, though they primarily have a climate focus, they are likely to serve as a key forum for international deliberations on climate engineering and its governance going forward. At the same time, it should be noted that SRM appears to be currently outside of, or even potentially in conflict with, the objectives of the international climate regime as a whole.

2.3.2. 2015 Paris Agreement

Though the precise relationship between the Paris Agreement and the UNFCCC is not specified, the text of the Paris Agreement indicates that it was adopted with the aim of fulfilling the objectives of the UNFCCC, and is guided by its principles, including the principle of equity and common but differentiated responsibilities and respective capabilities.[76]

Building on the UNFCCC's overarching objective to prevent dangerous anthropogenic climate change, the Paris Agreement sets forth the goal of holding the increase in the global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature to increase 1.5°C above pre-industrial levels.[77] Based on modelled scenarios, it is highly unlikely that these temperature targets can be achieved without substantial implementation of CDR measures,[78] with perhaps SRM being required as well.[79] Against this backdrop, the Paris Agreement outcomes have lent additional momentum and weight to the policy argument that further research and development of climate engineering measures is urgently needed.

However, it is important to underscore that the Paris Agreement does not just speak to end objectives, but also the means by which these objectives are to be achieved. The Paris Agreement lays down a specific scheme for achieving temperature targets by articulating provisions on mitigation, adaption, loss and damage, finance, technology transfer, transparency, and compliance. Progress under these areas is to be guided by overarching principles including sustainable development, poverty eradication, gender equity and human rights, ensuring the integrity of all ecosystems, including oceans, and the protection of biodiversity,[80] as well as equity and CBDRRC, in light of different national circumstances.[81] In addition, the preamble of the Paris Agreement recognises that that 'Parties may be affected not only by climate change but also by the impacts of the measures taken in response to it.'[82] Although this does not lead to the interpretation that climate engineering measures have no place in achieving the ambition of the Paris Agreement, the normative framework laid down in the international climate regime sets out important concepts and principles that may bear upon governance and use of climate engineering measures.

As indicated above in the discussion of the UNCFFC, equity and equitable concepts are central to international climate change law. The Paris Agreement has evolved these concepts, in particular, in relation to burden-sharing between States Parties. The CBDRRC principle is a specific expression of equity that takes into account states' disproportionate contributions to the problem of climate change and their respective capabilities in addressing it.[83] The Paris Agreement states that Parties should implement their commitments to reflect equity and the principle of common but differentiated responsibilities and respective capabilities (CBDRRC), in the light of different national circumstances.[84] Refinements under the Paris Agreement reflect a more dynamic and nuanced formulation of the CBDRRC principle by blurring the bright line between developed and developing countries in past agreements in light of a wide range national circumstances'.[85]

In its influential report on 'Geoengineering the Climate', The Royal Society noted the likelihood that geoengineering will create 'winners and losers associated with the applications of the different methods.'[86] There are several ways in which equitable principles could inform climate engineering governance, spanning from the near-term governance of research and technological development to the longer-term possibility of deployment of climate engineering for future generations.[87] For example, the use of SRM to maintain a business-as-usual scenario without ambitious reductions of GHG emissions may be out of step with the principle of intergenerational equity. This approach may unfairly shift the burden of dealing with the causes of climate change onto future generations, such as by creating a long-term risk of a termination effect, and through continued and unmitigated damage to the environment (e.g., to marine ecosystems from ocean acidification).[88] Regarding intragenerational equity issues, it is difficult to predict which issues could be political sticking points at the intersection of climate engineering and individual states' perceived different national circumstances. However, given the decades-long debate over burden-sharing on mitigation at the international level, there may be significant challenges to be faced in reaching an agreement on the deployment of large-scale climate intervention in a way that accommodates pluralistic notions of differentiation, fairness, and justice.[89] For example, there are implicit arguments in the literature about what would amount to a fair implementation of climate engineering. Based on model evidence, some scientists have argued that an SRM deployment could be optimised to minimise regional inequalities between climate benefits and impacts.[90] As a purely normative question, however, formal equality between regions or individual states is only one, perhaps impoverished, view of how to implement climate engineering equitably.[91] If technologies for approaching a 'designer climate' are in fact possible, the CBDRRC principle may argue in favour of redistributive approaches based on a range of possible rationales.[92] Notions of intragenerational equity are also germane to the near-term governance of scientific research and the development of climate engineering measures, e.g., in relation to technology transfer and capacity-building.[93] For instance, the Paris Agreement adopts a broad view of capacity-building with a view to enhancing the ability of developing country Parties 'to take effective climate change action, including, inter alia, to implement adaptation and mitigation actions, and should facilitate technology development, dissemination and deployment, access to climate finance, relevant aspects of education, training and public awareness, and the transparent, timely and accurate communication of information.'[94] Capacity-building could be defined along similar lines in relation to the governance of climate engineering research, and serve similar functions, including the need to increase trust and confidence between developed and developing countries and to redress any knowledge imbalances between them.[95] The concept may also extend to ensuring that developing countries play a sufficient role in defining the substance of a climate engineering research agenda, participate in the conduct of scientific research, and have access to information about climate engineering measures and their development.[96]

Though the Paris Agreement does not expressly address the topic of climate engineering, a closer reading of the text indicates that CDR and SRM should be assessed differently under this treaty. The pathway for achieving the long-term temperature goal is set out in Article 4(1) of the Paris Agreement. This provision establishes the collective aim that the Parties reach a 'global peaking' of GHG emissions 'as soon as possible', and 'achieve a balance between anthropogenic emissions by sources and removals by sinks of GHGs in the second half of this century.' Emissions are defined in the UNFCCC as the 'release' of greenhouse gases,[97] whereas 'sinks' refers to the 'removal' of greenhouse gas from the atmosphere.[98] As such, emissions reductions remain the priority as a means of achieving long-term temperature goals. CDR measures as a form of 'sink' may also be potentially read in as a means for achieving these aims. On the other hand, the acceptability of SRM as part of the collective global response to climate change remains unclear. The Paris Agreement clearly specifies mitigation as the means for achieving the long-term temperature goal in Article 2(1).[99] SRM is not prohibited, but the focus in the Paris Agreement on mitigation as a means for achieving the long-term temperature goal suggests that States Parties could not rely on SRM as a means to displace their mitigation obligations under the agreement, including domestic policies and actions directed at the reduction emissions and enhancement of removals by sinks.[100]

States Parties are required under Article 4(2) of the Paris Agreement to prepare, communicate, and maintain successive nationally determined contributions (NDCs) that it intends to achieve. In addition, Parties shall 'pursue domestic mitigation measures' with the aim of achieving their NDCs,[101] which creates a binding obligation of conduct on Parties.[102] The NDCs of each Party, regardless of whether they are a developed or developing country, are subject to the principle of non-regression, where each successive NDC is to signify a progression beyond the last, and to represent a Party's 'highest level of ambition, reflecting its common but differentiated responsibilities and respective capabilities, in the light of different national circumstances.'[103] Other references in the Paris Agreement to reducing emissions include the aim to foster 'low greenhouse gas emissions development',[104] 'making finance flows consistent with a pathway towards low greenhouse gas emissions',[105] recommendations relating to the establishment of 'economy-wide absolute emission reduction targets'[106] and 'realising technology development … to reduce greenhouse gas emissions'[107] as well as provisions relating to transparency[108] and accounting.[109] CDR may also be integrated into other Paris Agreement mechanisms such as the global stocktake process which facilitates the requirement for progression in commitments over time.[110] Moreover, though 'the bottom-up structure of the Paris Agreement allows for States to determine for themselves whether they wish to adopt and implement CDR technologies … there still will be considerable demand for cooperation in determining the forms of accounting and reporting for CDR technologies.'[111]

The Paris Agreement strengthens the legal and institutional framework of the Technology Mechanism,[112] which is generally agnostic about which technologies should be developed and used, though it does prioritize reducing GHG emissions and increasing climate resilience.[113] Therefore, though the aim of increasing climate resilience is, in principle, broad enough to perhaps capture CDR, it remains to be seen whether such measures will be incorporated into the Technology Mechanism at some later date. This determination will partly depend upon how States Parties interpret the commitment to transfer and facilitate access to climate technologies under the Paris Agreement's new Technology Framework, which aims at the 'enhancement of enabling environments for and the addressing of barriers to the development and transfer of *socially and environmentally sound* technologies' (emphasis added).[114] The criteria of 'socially and environmentally sound' may have implications for how climate engineering is treated within the Technology Framework. As a broad conclusion, however, if climate engineering methods are researched and developed, governance arrangements should also take into account the different economic and technological capacities of States and aim to alleviate these disparities to ensure fair and effective participation of all.

The Paris Agreement also establishes new institutions, including the Conference of the Parties serving as the meeting of the Parties to the Paris Agreement (CMA) which serves as the central decision-making body for the Parties to implement the Agreement. The CMA has a mandate over the development and integration of rules and processes, which may include any future consideration of climate engineering measures.

2.3.3. 1985 Vienna Convention for the Protection of the Ozone Layer and its 1987 Montreal Protocol on Substances that Deplete the Ozone Layer

The 1987 Montreal Protocol sits under the umbrella of the 1985 Vienna Convention for the Protection of the Ozone Layer (Vienna Convention), a multilateral environmental agreement which provides a framework for the adoption of measures 'to protect human health and the environment against the adverse effects resulting, or likely to result, from human activities which modify or are likely to modify the ozone layer'.[115] Both of these instruments have near-universal participation.[116]

The Montreal Protocol establishes specific legal obligations, including limitations and reductions on the production and consumption of certain controlled ozone-depleting substances.[117] The Protocol was negotiated and adopted in response to emerging scientific evidence that emissions of particular substances were altering the ozone layer, and would have potential climatic effects.[118] The lack of conclusive scientific evidence that ozone depletion was, in fact, occurring prompted States Parties to adopt 'precautionary measures to control equitably total global emissions of substances that deplete it, with the ultimate objective of their elimination on the basis of developments in scientific knowledge'.[119] The Montreal Protocol establishes a regular Meeting of the Parties whose functions include review of the implementation of the Protocol based on new scientific developments, including through the introduction of new controls under various mechanisms in the Protocol.[120] Since 1990, States Parties have agreed to adjust or amend the Protocol several times.

Some commentators have argued that similar adjustments or amendments could be adopted to regulate some forms of climate engineering.[121] Indeed, some climate engineering measures, such as stratospheric aerosol injection, may raise specific issues under these agreements, especially if they involve a substance covered by the Montreal Protocol.[122] For example, research indicates that the injection of stratospheric aerosols may lead to ozone depletion with potentially significant implications for ecosystems and human health due to increases in surface ultraviolet (UV-B) light reaching the surface.[123] As a starting point, the Vienna Convention establishes the general obligation 'to protect human health and the environment against adverse effects resulting or likely to result from human activities which modify or are likely to modify the ozone layer'.[124] States Parties are further required to 'adopt appropriate legislative or administrative measures and cooperate in harmonising appropriate policies to control, limit, reduce or prevent human activities under their jurisdiction or control should it be found that these activities have or are likely to have adverse effects resulting from modification or likely modification of the ozone layer.' 'Adverse effects' broadly encompass 'changes in the physical environment or biota, including changes in climate, which have significant deleterious effects on human health or on the composition, resilience and productivity of natural and managed ecosystems, or on materials useful to mankind'.[125] These provisions are very general and afford States wide discretion in how they are implemented. They arguably fall far short of providing sufficient guidance on the development and deployment of climate engineering. Nonetheless, there is the possibility that these agreements could provide the legal and institutional basis for the regulation of specific climate engineering measures in the future.

At first blush, there also seems to be a precedent for States Parties to extend the scope of the Montreal Protocol to the area of climate change. The most recent amendment to the Montreal Protocol, the Kigali Amendment, seeks to phase-down the production and consumption of hydrofluorocarbons (HFCs). Though HFCs do not deplete the ozone layer, they are powerful GHGs. With the adoption of the Kigali Amendment, States Parties to the Montreal Protocol have extended the scope of their commitments under the agreement to address the problem of climate change more directly,[126] and it is predicted that the recent amendment will avoid up to 0.5 °C increase in global temperature by the end of the century.[127] However, it is important to note that this was done, because the use of HFCs was promoted under the Montreal Protocol as a replacement for ozone-depleting substances, thus, creating a conflict between the objectives of the Protocol and the international climate regime. To address this conflict, States Parties to the Montreal Protocol decided to also regulate HFCs. Against this backdrop, it would be difficult to make a similar argument with respect to the regulation of SRM measures like stratospheric aerosol injection under the Montreal Protocol. However, further developments within the ozone protection regime may be expected. In 2018, the Federated States of Micronesia, Mali, Morocco, and Nigeria submitted a proposal at the meeting of Parties to the Montreal Protocol requesting a report on SRM by the Montreal Protocols Scientific Assessment Panel. However, this was later withdrawn due to time constraints.

2.3.4. 1979 UNECE Convention on Long-Range Transboundary Air Pollution

A regional agreement limited to Europe and North America, the 1979 UNECE Convention on Long-Range Transboundary Air Pollution (LRTAP) was adopted under the auspices of the United Nations Economic Commission for Europe (ECE) in response to significant concerns about acid rain and other dispersed pollutants. 'Long-range transboundary air pollution' is defined in LRTAP as 'air pollution whose physical origin is situated wholly or in part within the area under the national jurisdiction of one state and which has adverse effects in the area under the jurisdiction of another state at such a distance that it is not generally possible to distinguish the contribution of individual emission sources or groups of sources'.[128] This definition builds on the meaning of 'air pollution' in LRTAP, which is defined broadly as 'the introduction by man, directly or indirectly, of substances or energy into the air resulting in deleterious effects of such a nature as to endanger human health, harm living resources and ecosystems and material property, and impair or interfere with amenities and other legitimate uses of the environment'. Some climate engineering methods, such as those that entail the dispersal aerosols in the stratosphere, may satisfy elements of these definitions. However, it should be noted that an evidentiary link between the introduction of the substances and the deleterious effects must be established under the Convention to some evidentiary standard. Furnishing the requisite evidence may be difficult given the experimental nature of climate engineering measures, especially because LRTAP itself does not adopt precaution as a guiding principle, though some of its more recent protocols explicitly do.

As a framework agreement, LRTAP does not itself establish specific limits on atmospheric pollutants. Parties have committed to exercising due diligence to 'endeavour to limit and, as far as possible, gradually reduce and prevent air pollution, including long-range transboundary air pollution'.[129] It also sets forth general obligations to facilitate cooperation and the development of more precise measures to combat air pollution, including the exchange of relevant information and review of policies, scientific activities, and technical measures and cooperation in research.[130]

Since the adoption and coming into force of LRTAP, States Parties have adopted a series of eight separate protocols. Notably, two of these protocols, the 1985 Helsinki Sulphur Protocol[131] and the 1994 Oslo Protocol on further Reduction of Sulphur Emissions,[132] already impose binding limits on sulphur emissions. These Protocols may apply to stratospheric aerosol methods that introduce chemicals such as hydrogen sulphide (H_2S) or sulphur dioxide (SO_2) gases into the stratosphere to limit warming. For example, States Parties to the more recent 1994 Oslo Protocol are required to 'control and reduce their sulphur emissions in order to protect human health and the environment from adverse effects, in particular acidifying effects, and to ensure, as far as possible, without entailing excessive costs'.[133] The Protocols are intended to cover target industrial sulphur emissions and their acidifying effects through the 'critical loads' and 'effects-based' approach. As such, prescribed measures (e.g., the use of low-sulphur fuels) may not be directly relevant for governing SRM.

2.3.5. 1992 United Nations Convention on Biological Diversity

International goals related to the conservation and sustainable use of biological diversity and the avoidance of dangerous climate change are deeply entwined. The recent IPBES Report underscores that climate change is a direct driver that is increasingly exacerbating the impact of other drivers on biodiversity loss. At the same time, it underscores that nature-based solutions will be 'indispensable' to achieving climate targets. For example, it concludes that these may 'provide 37 per cent of climate change mitigation until 2030 needed to meet the goal of keeping climate warming below 2°C, with likely co-benefits for biodiversity'.[134] However, such approaches may also have negative side effects on biodiversity and ecosystem functioning: the deployment of CDR measures such as 'the large-scale deployment of intensive bioenergy plantations, including monocultures, replacing natural forests and subsistence farmlands, will likely have negative impacts on biodiversity and can threaten food and water security as well as local livelihoods, including by intensifying social conflict '.[135]

The 1992 United Nations Convention on Biological Diversity (CBD) establishes the relevant international regime for the conservation of biological diversity, the sustainable use of its components, and the fair and equitable sharing of the benefits arising out of the utilization of genetic resources.[136] The CBD has near-universal participation, with 196 countries having ratified to date, with the notable exception of the US which has only signed. The CBD adopts many modern principles of international environmental law, including a variation of the precautionary principle that 'where there is a threat of significant reduction or loss of biological diversity, lack of full scientific certainty should not be used as a reason for postponing measures to avoid or minimise such a threat'.[137] The CBD also incorporates the 'no harm principle' in its operative part of its text.[138] The geographical scope of the CBD ostensibly covers a wide spectrum of climate engineering activities regardless of where they take place. It regulates 'components' of biological diversity in areas within the limits of its national jurisdiction,[139] and also extends to processes and activities, regardless of where their effects occur, carried out under the jurisdiction or control of a Party, either within the area of its national jurisdiction or beyond the limits of national jurisdiction.[140]

Since 2008, States Parties have adopted a series of COP decisions on 'climate-related geoengineering'. Perhaps the most widely recognised of these is COP decision X/33, which in paragraph 8(w) invites Parties and other governments to ensure:

> *In the absence of science-based, global, transparent and effective control and regulatory mechanisms for geoengineering, and in accordance with the precautionary approach and Article 14 of the Convention, that no climate-related geoengineering activities that may affect biodiversity take place, until there is an adequate scientific basis on which to justify such activities and appropriate consideration of the associated risks for the environment and biodiversity and associated social, economic and cultural impacts, with the exception of small-scale scientific research studies that would be conducted in a controlled setting in accordance with Article 3 of the Convention, and only if they are justified by the need to gather specific scientific data and are subject to a thorough prior assessment of the potential impacts on the environment.*[141]

Though the chapeau of this paragraph adopts highly attenuated language, in essence, Decision X/33 calls upon States to exercise due diligence over climate engineering activities within their jurisdiction and control that may affect biodiversity.[142] Moreover, though not legally binding, the decision sets up what is sometimes referred to in the literature as a *de facto* moratorium on climate engineering activities until there is sufficient scientific evidence to justify such activities and appropriate consideration of environmental risks and other concerns.[143] The justification for this stance in the decision is, in part, the 'the absence of science-based, global, transparent and effective control and regulatory mechanisms for geoengineering', a phrase which could also be read as a call for governance. Decision X/33 carves out an exception for scientific research on climate engineering where such research is scientifically justified and subject to specific conditions. The decision also identifies several general criteria for governance, including science-based decision-making, transparency, environmental impact assessment, and the application of a precautionary approach.

Adding to this guidance, in 2016, the thirteenth meeting of the Conference of the Parties, adopted Decision XIII/14 on 'climate-related geoengineering'. Reaffirming the conclusion of past COP decisions, Decision XIII/14 underscores the relevance of the international climate regime to climate engineering, stating 'that climate change should primarily be addressed by reducing anthropogenic emissions by sources and by increasing removals by sinks of greenhouse gases under the UNFCCC'.[144] It further notes that 'more transdisciplinary research and sharing of knowledge among appropriate institutions are needed in order to better understand the impacts of climate-related climate engineering on biodiversity and ecosystem functions and services, socio-economic, cultural and ethical issues and regulatory options'.[145] This decision is significant in that it emphasizes the need for an approach to additional knowledge generation from all disciplines and stakeholders in relation to climate engineering measures.

2.3.6. 1996 Protocol to the 1972 Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter

In the past decade, the Contracting Parties to the 1972 Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (London Convention; LC)[146] and its 1996 Protocol (London Protocol; LP)[147] have taken major steps to regulate emerging climate technologies with the potential to adversely impact the marine environment. These have resulted in a series of amendments to the more recent London Protocol, which was negotiated and adopted with a view to substantially updating its parent convention and eventually replacing it. The substance of these climate-technology related amendments are in line with the overarching aim of the London Protocol to protect and preserve the marine environment from all sources of pollution, and, in particular, from the dumping of wastes and other at sea.[148] It also reflects the Protocol's strongly precautionary approach to the issue of marine pollution, and especially ocean dumping,[149] and is noteworthy for its science-based legal and institutional framework for the prevention of harm to the marine environment.

2006 and 2009 London Protocol Amendments on Carbon Capture and Sequestration in Sub-Sea Geological Formations

One question that arises is whether states are permitted to capture and store CO_2 in sub-sea geological formations, for example, as the second sequestration phase in BECCS processes. In accordance with its strongly precautionary character, the London Protocol adopts a reverse-listing approach to ocean dumping. All dumping of wastes or other matter is prohibited except for those expressly listed in Annex 1, for which dumping is allowed.[150] The definition of 'dumping' in the London Protocol includes 'any storage of wastes or other matter in the seabed and the subsoil thereof from vessels, aircraft, platforms or other man-made structures at sea'.[151] Previously, then, sub-sea geological storage of CO_2 was generally not permitted, because it was not listed as a permissible waste stream in Annex 1.

In 2006, the Contracting Parties to the London Protocol adopted amendments to Annex 1 of the Protocol to establish a legal basis to regulate carbon capture and storage in sub-seabed geological formations for permanent isolation. Under this amendment, CO_2 may be considered for dumping if (1) the disposal is into a sub-seabed geological formation, (2) the disposal consists overwhelmingly of CO_2, and (3) no wastes or other matter are added for the purpose of disposing of those wastes or other matter.[152] These amendments to Annex 1 entered into force for each Contracting Party no later than 100 days following the adoption of the amendment, except for any Party that makes a declaration to the contrary within that period. As such, the amendment entered into force for all Contracting Parties in 2006. Under the amendment, any Contracting Party to the London Protocol may issue a permit for the sub-seabed disposal of a CO_2 waste stream that meets the above requirements. The Parties to the London Protocol have also adopted two sets of technical guidelines for CO_2 operations: the Risk Assessment and the Management Framework (RAMF) for

CO_2 Sequestration in Sub-seabed Geological Structures,[153] and the Specific Guidelines for the Assessment of Carbon Dioxide for Disposal into Sub-seabed Geological Formations.[154]

In spite of amendments to Annex 1 of the London Protocol, there was one remaining barrier under the London Protocol before carbon capture and storage in sub-seabed geological formations for permanent sequestration would be permitted. Article 6 of the London Protocol prohibits the export of waste 'to other countries for dumping or incineration at sea'.[155] In response, in 2009, the Contracting Parties to the London Protocol adopted an amendment to provide for an exception to Article 6 to allow for the export of CO_2 for geological sequestration.[156] As an amendment to the text of the London Protocol itself (rather than merely an amendment one of the annexes), this change had to follow the more stringent entry into force of requirements set out in Article 21 of the Protocol, which requires two-thirds of the Contracting Parties to have deposited their instrument of acceptance for any amendments to come into force.[157] However, after almost a decade, few parties had indicated their acceptance in accordance with this rule. To address this issue, the Contracting Parties to the Protocol recently agreed to the provisional application of an amendment to Article 6 of the Protocol, which allows for the export of CO_2 for geological sequestration provided that 'an agreement or arrangement' has been entered into by 'the countries concerned', and subject to other requirements and guidance.[158]

2013 London Protocol Amendment on Marine Geoengineering

In 2013, after several years of assessing the legal and scientific issues related to public controversies surrounding ocean fertilization, the Contracting Parties to the London Protocol adopted by consensus a new amendment on the regulation of marine geoengineering.[159] The preamble of the 2013 amendment expresses the Contracting Parties' concern about the potential impacts of ocean fertilization and other marine geoengineering activities on the marine environment, and their 'determination' to put in place 'a science-based, global, transparent, and effective control and regulatory mechanism for such activities'.[160]

'Marine geoengineering' is defined in the amendment as 'a deliberate intervention in the marine environment to manipulate natural processes, including to counteract anthropogenic climate change and/or its impacts, and that have the potential to result in deleterious effects, especially where those effects may be widespread, long-lasting or severe'.[161] As a legal term of art, this definition constitutes one of the first conceptualisations of 'geoengineering' to be enshrined in binding international law. It incorporates central elements of the definition of the term, i.e., the large scale and deliberate nature of the intervention in the environment.[162] In addition, the definition of marine geoengineering includes, but is not limited to, measures intended to counteract anthropogenic climate change. As such, the term applies to other deliberate environmental interventions targeting other kinds of environmental threats (not just climate change). Finally, the amendment does not distinguish between the technical categories of CDR and SRM, covering 'marine geoengineering' measures as a whole, and regulating largely on the basis of potential adverse environmental effects.

The London Protocol amendment on marine geoengineering seeks to establish a stable, legally-binding framework for the regulation of marine geoengineering, while also allowing for regulatory flexibility and adaptability to respond to new scientific and technological proposals that may adversely affect the marine environment in the future based on a precautionary approach. This was achieved with the adoption of a so-called 'positive-listing' approach, which allows for the regulation of new marine geoengineering measures on an ongoing basis. In this sense, the definition of marine geoengineering itself is not determinative of whether a specific marine geoengineering activity falls within the material scope of the regulation. Rather, the definition merely sets out the basic criteria for determining whether a particular marine geoengineering technique will be listed under a new Annex 4.[163] Only those activities listed in Annex 4 are subject to binding regulation, either in the form of a permitting requirement or an outright prohibition. Proposals to list new marine geoengineering techniques are to be reviewed by the Scientific Groups of the LC-LP as well as by 'other experts', as appropriate. The Contracting Parties are encouraged to seek the advice of the international independent experts or an independent international advisory group of experts, especially where the activity has transboundary implications.[164]

At present, the only marine geoengineering technique listed in Annex 4 is ocean fertilization. Tracking previous non-binding resolutions adopted by the LC-LP for this technique,[165] the Annex 4 listing creates a permitting scheme that allows for 'legitimate scientific research' on ocean fertilization to be carried out,[166] but prohibits all other ocean fertilization activities. The London Protocol amendment also provides guidance on the listing of new marine geoengineering activities to be regulated under Annex 4.[167]

A new Annex 5 establishes a 'General Assessment Framework' for evaluating the environmental risks of marine geoengineering activities listed in Annex 4 of the London Protocol. All marine geoengineering activities subject to permitting requirement under Annex 4 must be assessed either under this General Assessment Framework or under specific risk assessments designed in accordance with the General Assessment Framework.[168] The General Assessment Framework sets out several considerations to be taken into account in assessment processes by Contracting Parties including the description of the activity, special criteria in relation to marine scientific research, the location of the activity, the potential for adverse impacts, risk management measures, and environmental monitoring. A Contracting Party may only issue a permit for a listed marine geoengineering activity if it satisfies several requirements, including that 'pollution of the marine environment from the proposed activity is, as far as practicable, prevented or reduced to a minimum' and that 'conditions are in place to ensure that, as far as practicable, environmental disturbance and detriment would be minimised and the benefits maximised'. Currently, all ocean fertilization activities that may be considered for a permit are those that have been assessed as constituting 'legitimate scientific research' in accordance with the 2010 Ocean Fertilisation Assessment Framework which constitutes the relevant Special Assessment Framework under the new amendment.

The London Protocol amendment is not yet in force, with only six Contracting Parties having deposited their instruments of acceptance to date. This situation underscores the limits of reliance on treaty-based approaches for regulating geoengineering internationally going forward.

2.3.7. 1982 United Nations Convention on the Law of the Sea (LOSC)

The 1982 United Nations Convention on the Law of the Sea (LOSC)[169] was negotiated and adopted at a time when climate change was not yet part of the international agenda.[170] However, it is characterised as a 'living treaty' with the capacity to adapt to new challenges relating to the uses of the oceans and their resources.[171] Though the 2013 London Protocol amendment is the more recent and specific instrument, the legal framework laid down in the LOSC remains applicable, and, in some cases, extends beyond the reach of the London Protocol in relation to the regulation of marine geoengineering measures.[172]

State jurisdiction over marine geoengineering varies depending on the maritime zone in which the activity takes place. In general, the jurisdiction and rights of the coastal state diminish by zone moving seaward from the baseline. The coastal state enjoys exclusive sovereign control over climate engineering measures conducted within the 12 nautical miles territorial sea, including its airspace, seafloor, and subsoil.[173] Sovereignty over the territorial sea must be exercised subject to the LOSC, including a right of innocent passage for foreign vessels, and other rules of international law.[174]

The exclusive economic zone (EEZ) is an area beyond 200 nautical miles from the baselines from which the breadth of the territorial sea is measured, and includes the continental shelf below the water column.[175] It is a mixed-use zone that entails balancing the rights and jurisdiction of the coastal State and the rights and freedoms of other States. In the EEZ, the coastal state has sovereign rights for the purposes of exploring and exploiting, conserving and managing the living and non-living natural resources, including 'other activities for the economic exploitation and exploration of the zone'.[176] Growth in carbon pricing, offsets, and emissions trading schemes mean that some climate engineering measures conducted in the marine environment, particularly those that target atmospheric removals or include an energy production element, such as the growth of marine biomass as a feedstock to produce bioenergy for BECCS processes, may qualify as economic exploitation and exploration of the zone. The coastal state also has jurisdiction over key areas related to the development and use of climate engineering measures in the EEZ. These are the establishment and use of artificial islands, installations and structures, marine scientific research, and the protection and preservation of the marine environment.[177] For example, climate engineering measures may entail the use of manned or autonomous vessels or platforms, installations, or other structures at sea, such as those proposed for marine cloud brightening. Another issue is that climate engineering activities conducted in the EEZ may be difficult to characterise legally, and thus could potentially lead to conflict between coastal and third states. Potential user conflicts are governed by the principle that the coastal state's sovereign rights and jurisdiction in the EEZ must be exercised with 'due regard' to the rights and duties of other states and be compatible with the provisions of the LOSC.[178] At the same time, third states have a reciprocal obligation to exercise their rights and freedoms demonstrating due regard for rights and duties of the coastal State and shall comply with the laws and regulations adopted by the coastal state in accordance with the provisions of this Convention and other rules of international law in so far as they are not incompatible with this Part V of the LOSC.[179]

The high seas, those parts of the sea that are beyond national jurisdiction and are not included in the international regime for the Area,[180] are governed by the principle of the freedom of the high seas. According to this principle, the high seas are open to all states,[181] and no state may purport to subject any part of the high seas to its sovereignty.[182] The LOSC incorporates a non-exhaustive list of the freedoms of the high seas, many of which are relevant to climate engineering activities. These include the freedom of navigation, freedom of overflight, freedom to construct artificial islands and other installations, and the freedom of scientific research.[183] High seas freedoms are to be exercised under the conditions laid down in the LOSC, by other rules of international law,[184] as well as with due regard for the interests of other States in their exercise of the freedom of the high seas and activities in the Area.[185] In the majority of cases, climate engineering activities conducted on the high seas would fall within the exclusive jurisdiction of the flag state. The flag state has a due diligence obligation to exercise effective jurisdiction and control over ships flying its flag,[186] including in relation to the protection of the marine environment.[187] It is also worth noting that, at present, states are negotiating a new legally-binding instrument under the auspices of the United Nations General Assembly to address the conservation and sustainable use of marine biodiversity in areas beyond national jurisdiction. If successful, this new treaty could impose additional requirements on climate engineering activities conducted in marine areas beyond national jurisdiction (high seas and the Area), such as a more extensive requirement to conduct an EIA or even to carry out a strategic environmental assessment.[188]

The LOSC also regulates matters functionally.[189] Perhaps the most important provisions in the LOSC relating to the development and use of climate engineering measures are set forth in Part XII of the LOSC on the protection and preservation of the marine environment. The general provisions of Part XII apply to States irrespective of where activities take place.[190] The term 'marine environment' is undefined in the LOSC, raising the question of the extent to which the provisions of Part XII cover the full suite of climate engineering measures, including those that strictly involve the modification of atmospheric conditions. However, the International Seabed Authority's regulations on prospecting and exploration for marine minerals in the deep seabed provide an express definition, which may be considered influential. These regulations define 'marine environment' comprehensively as 'the physical, chemical, geological and biological components, conditions and factors which interact and determine the productivity of, state, condition, and quality of the marine ecosystem, the waters of the seas and oceans and the airspace above those waters, as well as the seabed and ocean floor and subsoil thereof.'[191] However, this definition is not conclusive of the matter, because, though relevant to the interpretation of the LOSC generally, there is a distinction in international law between the international law concepts of 'airspace' and 'atmosphere' which further complicates the legal analysis.[192]

Article 192 of the LOSC sets out the fundamental obligation of states to protect and preserve the marine environment. In the *South China Sea* arbitration, the Arbitral Tribunal (constituted under Annex VII of the LOSC) stated that although phrased in general terms, it was 'well established that Article 192 does impose a duty on States Parties, the content of which is informed by the other provisions of Part XII and other applicable rules of international law.'[193] Article 192 entails 'the positive obligation to take active measures to protect and preserve the marine environment, and by logical implication, entails the negative obligation not to degrade the marine environment.'[194] The interpretation of this general duty is informed by the customary law obligation to prevent transboundary environmental harm,[195] and, thus, states would have a positive duty to prevent, or at least mitigate significant harm to the marine environment when pursuing climate engineering measures regardless of where such measures take place.

The content of Article 192 is further elaborated in Article 194 on measures to prevent, reduce, and control pollution of the marine environment.[196] 'Pollution of the marine environment' is defined in Article 1(1)(4) of the LOSC as the introduction, directly or indirectly, of substances or energy resulting in harm to the marine environment. The phrasing of this definition permits an evolutionary interpretation, allowing for new threats to the marine environment to be read into the LOSC over time.[197] As a result, some climate engineering measures, such as ocean fertilization or ocean alkalinity addition, arguably fall within this definition. It is important to note in this regard that, given its time of negotiation and adoption, the LOSC does not expressly incorporate the precautionary principle into the text, and so the lack of scientific evidence about the harms posed by climate engineering activities may present an issue to ensuring legal accountability for damage to marine ecosystems, though it may be an element of due diligence, as noted above.

Article 194(1) requires that States Parties 'individually or jointly as appropriate, take all measures consistent with this Convention that are necessary to prevent, reduce, and control pollution of the marine environment from any source, using for this purpose the best practicable means at their disposal and in accordance with their capabilities, and they shall endeavour to harmonise their policies in this connection.' This obligation is Janus-faced with respect to its potential application to climate engineering measures conducted in the marine environment. On the one hand, climate engineering may be regarded as 'necessary' measures to control pollution of the marine environment. For example, SRM measures may be used to attempt to reduce the adverse effects of greenhouse warming — a type of marine pollution as an introduction of thermal 'energy' to the oceans — on marine ecosystems.[198] In the same vein, CDR measures, such as ocean alkalinity addition, may also help to counteract the adverse effects of the uptake atmospheric CO_2 emissions in the oceans as a polluting 'substance', causing them to be more acidic. The extent to which climate engineering measures may be justified as a positive measure to address the adverse effects of climate change on the marine environment in accordance with Article 194(1) of the Convention will turn on whether climate engineering measures are interpreted as being 'consistent with this Convention', 'necessary', and constitute 'best practicable means' for addressing the problem of marine pollution. On the other hand, many climate engineering measures may themselves be characterised as a form of marine pollution and have adverse effects on the marine ecosystems. Climate engineering measures are subject to the obligations in Part XII of the LOSC to protect and preserve the marine environment, including under Article 194(1) which imposes a due diligence obligation on States to prevent, reduce and control pollution of the marine environment.[199]

Though it is beyond the scope of this chapter to discuss all implications of Part XII of the LOSC for the development and use of climate engineering measures, several other provisions are relevant, including:

- The duty to measures necessary to protect and preserve rare or fragile ecosystems as well as the habitat of depleted, threatened or endangered species and other forms of marine life[200]
- The duty to take all measures necessary to prevent, reduce, and control pollution of the marine environment resulting from the use of technologies under their jurisdiction or control, or the intentional or accidental introduction of species[201]
- The duty to cooperate in formulating and elaborating international rules, standards, and recommended practices and procedures consistent with this Convention, for the protection and preservation of the marine environment[202]
- The duty to cooperate to promote scientific research and the exchange of information on the pollution of the marine environment, including 'knowledge for the assessment of the nature and extent of pollution, exposure to it, and its pathways, risks, and remedies'[203]
- The duty to provide scientific and technical assistance to developing states for the protection and preservation of the marine environment and the prevention, reduction, and control of marine pollution[204]
- The duty to monitor the risks or effects of pollution[205] and to publish reports on the results obtained from monitoring[206]
- The duty to carry out an environmental assessment of potential effects of activities[207]

- The duty to prevent pollution of the marine environment from or through the atmosphere[208]
- The responsibility and liability of states for the fulfilment of their international obligations concerning the protection and preservation of the marine environment,[209] and the obligation to ensure that recourse is available in accordance with their legal systems for prompt and adequate compensation or other relief in respect of damage caused by pollution of the marine environment by natural or juridical persons under their jurisdiction[210]

Taken as a whole, the LOSC extends the relevant legal framework for climate engineering measures, beyond what is specified in the 2013 amendment to London Protocol on marine geoengineering. At the same time the LOSC has many shortcomings as a specific regime for governing climate engineering measures carried out in the oceans (e.g., state-centric in its approach, lacks many modern principles of good environmental governance etc.).[211]

2.4. International Institutions

In addition to the treaty bodies, described above, several international institutions may play an important role in the governance of climate engineering measures globally. Though a complete assessment of the global institutional landscape is beyond the scope of this overview, key specific international institutions with an existing or potential mandate over climate engineering and its governance include those described below.

2.4.1. United Nations Security Council

The United Nations Security Council has primary responsibility for the maintenance of international peace and security in accordance with the principles and purposes of the UN. The Council is comprised of 15 Members: five permanent members (China, France, the Russian Federation, the United Kingdom, and the United States), and ten non-permanent members elected for two-year terms by the General Assembly.

One strand of the climate engineering governance literature points to the significant security and defence concerns raised by large scale and deliberate climate-modifying technologies, 'with implications as serious as those in wartime'.[212] These include the threat that one state may significantly alter the environmental conditions of another state, or even globally, on a unilateral basis.[213] Though the Security Council has not addressed the topic of climate engineering to date, climate change has been on its agenda for over a decade. Notably, at its 6587th meeting in 2011, under the item 'Maintenance of international peace and security', the Security Council recognised that 'possible adverse effects of climate change may, in the long run, aggravate certain existing threats to international peace and security'.[214] The statement also called on the United Nations Secretary-General to provide 'contextual information' on possible security implications of climate change, as part of his periodic reporting to the Council. Some commentators argue that the Security Council, as the principal standing body charged with international security, could, for example, play a role in establishing the 'rules of engagement' for a deployment of climate engineering with security implications.[215] On the other hand, interactions between the permanent five members of the Security Council, each of which possesses a veto, have not always been functional and may bar meaningful coordinated action on climate engineering.[216] More fundamentally, it may be that the Security Council's concentrated powers and unaccountability to the full membership of the United Nations call into question its political foundation to provide transparent, effective, and legitimate action on climate engineering and its governance.[217]

2.4.2. United Nations General Assembly

The United Nations General Assembly (UNGA) is the central deliberative, policymaking, and representative organ of the United Nations. The Assembly is empowered to make (non-legally binding) recommendations to States on international issues within its competence. Comprised of all 193 Members of the United Nations, it provides a largely political forum for multilateral discussion of international issues within its competence, which has been expanded in recent years to include matters relating to the environment and sustainable development.[218] Notably, in September 2015, the UNGA agreed on a new set of 17 Sustainable Development

Goals (SDGs),[219] set forth in the outcome document of the United Nations summit for the adoption of the post-2015 development agenda.[220] A 2018 report published by the Carnegie Climate Governance Initiative (C2G) examines the potential implications of climate engineering on the achievement of SDGs, concluding, *inter alia*, that 'more transdisciplinary and geographically diverse research is required on the interconnections between [CDR] or [SRM] and delivery of sustainable development' and that the '[g]overnance of research and any potential future deployment of [CDR] or [SRM] will need to be carefully designed to ensure its support for sustainable development and to reduce the risk of negative impacts.[221]

2.4.3. United Nations Environment Programme

The United Nations Environment Programme (UNEP) is the key body dedicated to global environmental matters within the United Nations system. It enjoys the universal membership of all 193 UN Member States. UNEP has a strong scientific function and mandate, while also providing a policy guidance function, [222] extending to key issues including climate change, disasters and conflicts, and environmental governance.[223] It also hosts the secretariats of many key multilateral environmental agreements, including the CBD, which, as noted above, has continued to study and provide guidance on matters of climate engineering and its governance.

UNEP has already directly engaged with the issue of climate engineering through its main governing body, the United Nations Environment Assembly (UNEA). Switzerland, backed by other countries, tabled a resolution on 'Geoengineering and its Governance' for consideration at the fourth annual meeting of UNEA in March 2019. The operative part of the resolution requested that the Executive Director of UNEP 'prepare an assessment of geoengineering technologies, in particular, [CDR] and [SRM]' encompassing: definitional criteria; the current state of the science including research gaps, actors and activities with regard to research and deployment; current knowledge of potential impacts including risks and benefits and uncertainties; challenges related to current and potential governance frameworks for research potential deployment and control for each geoengineering technology; and conclusions on potential global governance frameworks for each geoengineering technology.[224] Over the course of the meeting, the resolution went through several rounds of revision, as is typical. However, the revised resolution was ultimately withdrawn for lack of agreement, including over disagreement about the incorporation of a reference to a precautionary approach.[225]

2.4.4. United Nations Development Programme (UNDP)

Climate engineering raises important and complex issues surrounding international development and equity.[226] Created by the UNGA in 1965, the United Nations Development Programme (UNDP) is the primary United Nations organ for multilateral technical and investment assistance to developing countries.[227] Its current Strategic Plan addresses a number of cross-cutting development themes including governance for peaceful, just, and inclusive societies; crisis prevention and increased resilience; clean, affordable energy, and environmental; and nature-based solutions for development.[228] This expertise and experience could be brought to bear to help to address development issues related to the governance of climate engineering. More recently, it has sought to advance the implementation of the SDGs and their integration by providing support countries in their efforts to design policy and programmes, to access and generate finance, to source and analyse data, and to drive innovation and learning.[229]

2.4.5. International Law Commission (ILC)

The International Law Commission (ILC) was established by the UNGA in 1947 to 'initiate studies and make recommendations for the purpose of ... encouraging the progressive development of international law and its codification'.[230] The ILC has made several important contributions relevant to the intersection of international law and climate engineering. For example, international law scholars have analysed the implications of the general rules on state responsibility, including as reflected in the ILC's work on this topic,[231] in relation to large-scale atmospheric interventions in the climate system.[232] In addition to general international law, the ILC has also addressed the development of the corpus of international rules relating to the protection of the environment specifically. For example, the literature on the governance of climate engineering includes significant discussion of the customary international law rules relating to the prevention of transboundary harm, including as interpreted through the work of the ILC,[233] to climate engineering activities.[234]

The ILC provided a more direct contribution to this topic through its recent programme of work on the protection of the atmosphere.[235] Importantly, for the purposes of this report, it also examined international law issues related to 'geoengineering' and the 'legal limits on intentional modification of the atmosphere'.[236] Presently at the stage of integrating comments by governments, Draft Guideline 7 on the 'Intentional large-scale modification of the atmosphere' currently recommends that '[a]ctivities aimed at intentional large-scale modification of the atmosphere should be conducted with prudence and caution, subject to any applicable rules of international law.'[237] The reference to the need to act with 'prudence and caution' draws upon language first employed by the International Tribunal for the Law of the Sea (ITLOS) in its *Southern Bluefin Tuna* Order[238] – language which indicated in that instance that the Tribunal was 'plainly taking a precautionary approach'.[239] Moreover, though the ILC did not expressly refer to the precautionary principle in its draft Guidelines on the protection of the atmosphere, since 'international courts and tribunals have thus far never recognised the precautionary principle as customary international law', it did note that 'the law relating to degradation of the atmosphere is based on the idea of precaution and the relevant conventions incorporate the precautionary approaches/measures, either explicitly or implicitly, as essential elements for the obligation of States to minimise the risk of atmospheric degradation.'

According to draft Guideline 3 of the ILC's draft guidelines on the protection of the atmosphere, 'states have an obligation to protect the atmosphere by exercising due diligence in taking appropriate measures, in accordance with applicable rules of international law, to prevent, reduce, or control atmospheric pollution and atmospheric degradation.'[240] This draft guideline denotes the conceptual distinction in international law between 'atmospheric pollution' and 'atmospheric degradation', where the former is understood more narrowly to refer to the introduction of substances or energy into the atmosphere with more direct deleterious effects, and the latter to more indirect cases of alteration of the composition of the atmosphere such as stratospheric ozone depletion and climate change.[241]

The international law literature on climate engineering analyses the application of treaty regimes on transboundary air pollution and those addressing global atmospheric degradation, as described above. This conceptual distinction is worth noting for down the road, because it may bear upon the question of which treaty regimes are more appropriate for addressing various climate engineering measures. For example, the international climate regime recognises that climate change is a 'common concern of humankind', a legal concept which may have different jurisdictional and normative implications for climate engineering under international law as compared with transboundary pollution.[242]

2.4.6. United Nations High-level Political Forum on Sustainable Development

The United Nations High-level Political Forum on Sustainable Development (HLPF) was established in 2012 by the outcome document of the United Nations Conference on Sustainable Development, 'The Future We Want'.[243] The HLPF is a subsidiary body of the UNGA and United Nations Economic and Social Council. It is the main United Nations platform on sustainable development, and it has a central role in the follow-up and review of the 2030 Agenda for Sustainable Development and the SDGs at the global level. Its mandate, which includes strengthening the science-policy interface, could thus potentially extend to examining the implications of climate engineering measures for sustainable development in a holistic and cross-sectoral manner. Though the HLPF is intergovernmental in nature, the forum seeks to promote transparency and implementation by encouraging participation of major groups, other relevant stakeholders, and entities having received a standing invitation to participate as observers in the UNGA.[244] This is consistent with the need identified in the climate engineering governance literature to encourage broad participation in the research and governance processes.[245]

2.4.7. United Nations Educational, Scientific and Cultural Organisation

The United Nations Educational, Scientific and Cultural Organisation (UNESCO) is charged with advancing cooperation in education, the sciences, culture, communication, and information. Increasingly, its mandate and strategic aims have extended to the promotion of international scientific cooperation on critical challenges related to climate change.[246] The example of the international regulation of ocean fertilization under the London Convention and London Protocol shows that there is a need to develop guidance on the responsible conduct of research and innovation practices in the field of climate engineering. Given its mandate in this area, UNESCO is well-positioned to contribute guidance that respects and promotes human rights and is informed by ethical principles.[247] In 2017, it published its Declaration of Ethical Principles in relation to Climate Change, which includes several norms relevant to research, development, and deployment of climate engineering measures.[248] For example, Article 8 on 'Science, Technologies and Innovations' calls upon states to 'use the best available scientific knowledge and evidence in decision-making that relates to climate change issues', to 'develop and scale up carefully assessed technologies, infrastructure and actions that reduce climate change and its associated risks,' and to 'increase as far as possible the participation of scientists from all developing countries, LDCs, and SIDS in climate-related science.'

2.4.8. Intergovernmental Oceanographic Commission

The Intergovernmental Oceanographic Commission of UNESCO (IOC-UNESCO) is the principal organ within the United Nations system for marine science. The IOC aims to promote international cooperation and to coordinate programmes in research, services, and capacity-building in marine science and to apply that knowledge for the improvement of management, sustainable development, and the protection of the marine environment. In addition, IOC-UNESCO is recognised as the competent international organization in the fields of marine scientific research (LOSC, Part XIII) and transfer of marine technology (LOSC, Part XIV) under the LOSC.[249] In the past, IOC-UNESCO has addressed matters related to scientific research and governance of marine-based climate engineering measures. It has released a number of summary briefs and reports on this topic, including a key summary for policymakers on the science of ocean fertilization.[250] It was also a sponsor of the recent 'High-level review of a wide range of proposed marine geoengineering techniques' as a member of the Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP).[251]

2.4.9. World Meteorological Organization

The World Meteorological Organization (WMO) is a specialised agency of the United Nations charged with facilitating and promoting international cooperation and coordination on the state and behavior of the Earth's atmosphere, its interaction with the land and oceans, the weather and climate it produces, and the resulting distribution of water resources.[252] Given the broad scope of its mandate, there is the potential that the WMO's programme of work could be expanded to include climate engineering. Notably, its Expert Committee on Weather Modification seeks to encourage strategic research on purposeful augmentation of precipitation, reduction of hail damage, dispersion of fog and other types of cloud and storm modifications by cloud seeding, and at providing guidance about best practices for operational projects.[253] Though weather modification is generally considered to be conceptually distinct from climate engineering, the WMO is well-positioned to play a role, for example, in promoting cooperation and coordination of scientific research, building scientific and technical capacity, and reviewing criteria for climate engineering research including the economic, social, ecological, and legal implications, and offering guidelines and infrastructure for the planning and monitoring of in situ experiments on climate engineering.

2.4.10. Intergovernmental Panel on Climate Change

Operating under the auspices of the WMO and UNEP, Intergovernmental Panel on Climate Change (IPCC) serves as the United Nations body for assessing the scientific evidence on climate change, its impacts and future risks, and options for adaptation and mitigation.[254]

The Fifth Assessment Report (AR5, 2014) included a review of climate engineering measures in multiple chapters.[255] The glossary of the report includes express definitions of several key terms. According to the

IPCC, 'geoengineering' is defined as 'a broad set of methods and technologies that aim to deliberately alter the climate system in order to alleviate the impacts of climate change'.[256] This entry goes on to state that criteria of '[s]cale and intent are of central importance' to the meaning of geoengineering and that such measures raise particular concerns, because 'they use or affect the climate system (e.g., atmosphere, land or ocean) globally or regionally' and may have 'substantive unintended effects that cross national boundaries.'[257] The umbrella term of geoengineering in this report includes the two categories of CDR and SRM. The glossary defines CDR as 'a set of techniques that aim to remove CO_2 directly from the atmosphere by either […] increasing natural sinks for carbon, or […] using chemical engineering to remove the CO_2, with the intent of reducing the atmospheric CO_2 concentration.' The report draws the distinction that, while some CDR methods may fall under the umbrella of geoengineering, others may not, depending on the magnitude, scale, and impact of the particular CDR activities. The reference in the IPCC's definition of CDR to 'sinks' potentially links into the definition of 'mitigation' in the UNFCCC. However, the entry for this definition also states that the boundary between CDR and mitigation may be unclear and could entail overlap. SRM is defined in the glossary as 'intentional modification of the Earth's shortwave radiative budget with the aim to reduce climate change according to a given metric (e.g., surface temperature, precipitation, regional impacts, etc.)'. The commentary to this entry goes on to declare that 'SRM techniques do not fall within the usual definitions of mitigation and adaptation'.

In 2019, the IPCC released its Special Report on the impacts of global warming above of 1.5°C above pre-industrial levels and related global GHG emission reduction pathways which was initiated in the Decision of the 21st Conference of Parties of the UNFCCC to adopt the Paris Agreement.[258] CDR is included as a 'core concept' of the Special Report — defined as 'anthropogenic activities removing CO_2 from the atmosphere and durably storing it in geological, terrestrial, or ocean reservoirs, or in products which 'includes existing and potential anthropogenic enhancement of biological or geochemical sinks and direct air capture and storage, but excludes natural CO_2 uptake not directly caused by human activities.'[259] A key finding of the Special Report in relation to climate engineering is the acknowledgement that limiting warming to 1.5°C will require substantial adoption of CDR measures.

All pathways that limit global warming to 1.5°C with limited or no overshoot project the use of carbon dioxide removal (CDR) on the order of 100–1000 $GtCO_2$ over the 21st century. CDR would be used to compensate for residual emissions and, in most cases, achieve net negative emissions to return global warming to 1.5°C following a peak (high confidence). CDR deployment of several hundreds of $GtCO_2$ is subject to multiple feasibilities and sustainability constraints (high confidence). Significant near-term emissions reductions and measures to lower energy and land demand can limit CDR deployment to a few hundred $GtCO_2$ without reliance on bioenergy with carbon capture and storage (BECCS) (high confidence).[260]

The amount of CDR necessary would depend on the pace and extent of cuts to GHG emissions. Moreover, even under the most optimistic pathways which assume rapid reductions in GHG emissions after 2020, and a relatively small amount of CDR, land use is expected to be significant. The report states with 'high confidence' that 'most current and potential CDR measures could have significant impacts on land, energy, water, or nutrients if deployed at large scale'.[261] Moreover, implementation of measures such as afforestation and BECCS 'may compete with other land uses and may have significant impacts on agricultural and food systems, biodiversity and other ecosystem functions and services.'[262] By contrast, so-called 'solar radiation modification' measures were not included in any of the assessed pathways of the 1.5°C Special Report. It concluded with 'medium confidence' that, although some SRM measures may be 'theoretically effective in reducing overshoot, they face large uncertainties and knowledge gaps as well as substantial risks and institutional and social constraints to deployment related to governance, ethics, and impacts on sustainable development. They also do not mitigate ocean acidification.'[263]

Consideration of climate engineering, both for CDR and SRM, will be extended to the IPCC's Sixth Assessment Report. It should be noted at this stage that IPCC experts have already played a significant role in framing climate measures in 'constructing CE as an object of governance through demarcating and categorising this emerging field of inquiry' and may be considered itself a form of de facto governance.[264] This observation raises important questions about the need to incorporate broader stakeholder views and the lay public in normalising and institutionalising climate engineering to provide for democratically legitimate and transparent governance.

2.4.11. International Organization for Standardization

Established in 1946, the International Organization for Standardization (ISO) is an independent, non-governmental organization comprised of 164 national standards bodies. The ISO develops industry-driven standards for products, services and systems that are developed through by industry experts, governments, representatives from consumer associations, academia, and NGOs. ISO/TC 207/ SC7/ WG13 (Greenhouse gas management and related activities) and future standard ISO 14082 expand upon the ISO's existing standards on GHG emissions in ISO 14064 by providing guidance on quantifying the climate impacts of substances that have an impact on radiative forcing and up until now have not been easily quantifiable. These substances include black carbon and other particulates, which were not previously covered by existing standards and are not physically and chemically gases. Currently, at the preparatory stage, draft ISO 14082 on Radiative Forcing Management focuses on measuring and quantifying the impact of a substance on radiative forcing.

In principle, the draft standard could include consideration of some SRM measures, by providing recommendations for how different actors could alter radiative forcing or their impact on climate change. Though contained in an earlier draft, the Technical Committee later issued a statement that 'geoengineering techniques such as [SRM] and Earth Radiation Management [ERM] are out of the scope of the document.'[265] This scenario raises important questions about the extent to which it is appropriate for non-state actors, and commercial bodies, in particular, to play a leading role in the development of governance of SRM specifically. Such entities may be less accountable and transparent than other governmental and intergovernmental organizations.

2.4.12. The Development of Soft-law Principles and Instruments

Academics and other experts have proposed various soft-law principles and instruments for the governance of climate engineering measures. These include the Oxford Principles, which are five high-level principles to provide guidance to decision-makers on climate engineering research and possible deployment.[266] The authors point to the possibility of elaborating upon the Oxford Principles through the 'development of technology-specific research protocols as the first step of the bottom-up process of building a flexible governance architecture'.[267] The Oxford Principles also formed the basis for the 'Asilomar Conference Recommendations on Principles for Research into Climate Engineering Techniques' agreed at a meeting of climate researchers in Asilomar, California in March 2010.[268] Other academics have examined the possibility of expanding on these efforts to develop a 'Code of Conduct for Geoengineering Research' which, drawing upon existing norms of international and domestic law, could serve as a near-term governance instrument to guide the responsible conduct of geoengineering research in various fora.[269]

2.5. Conclusion

With few exceptions, international law remains largely silent on the regulation of climate engineering measures and their development. Though dependant on the overarching aims and objectives of governance, this chapter has pointed to potentially significant gaps in existing legal regimes, suggesting the need for further cooperation at the international level to promote effective, legitimate and fair governance of these emerging technologies. In addition, the analysis in this chapter also points to how existing instruments and institutions that have expressly addressed geoengineering regulation and governance to date, also reflect a "limited" approach in line with their specific objectives, scope and mandate. This leads to a one-dimensional perspective on climate engineering rather than a comprehensive and integrated approach to the governance.

At the same time, this survey of the existing international legal landscape shows that there are a number of general norms of international environmental law, treaties and soft-law instruments and international institutions with relevance to geoengineering. Large-scale environmental interventions to address the causes and effects of climate change raise a host of environmental concerns, such as ozone depletion, biodiversity loss, and the protection of the marine environment. Moreover, as noted at the beginning of this chapter, such measures may also affect other areas of international law and cooperation, such as human rights, international trade, peace and security, intellectual property, food security, and the law of the sea. The international legal and institutional landscape relevant to climate engineering thus presents a complex 'patchwork' of overlapping norms and institutional mandates. Taken together, these underscore the need for some degree of international governance for climate engineering measures, and provide a framework of norms and mechanisms for addressing environmental and other concerns. Elements include international cooperation, prevention of environmental harm, precaution, environmental impact assessment, prior notification and consultation, cooperation, information sharing and capacity building on scientific research, prior notification and mutual information. Top-down intergovernmental processes may also be complimented by bottom-up soft-law governance initiatives by academics, scientific bodies, NGOs and corporate actors within a polycentric governance framework.[270]

As such, no treaty or institutional organization is likely to provide a 'one-size-fits-all approach' for climate engineering measures as a group.[271] Though issues of climate engineering governance are only now breaking onto the international agenda, it is already apparent that fragmentation is a concern. Regime conflicts are generally to be avoided, since a 'doubling of efforts' can erode the effectiveness of international law, waste scarce resources, give rise to concerns about forum shopping, risks of conflicts between actors, legal uncertainty, and issues of overlapping or conflicting legal obligations.[272] The principle of systemic integration of international law stands for the proposition that 'when several norms bear on a single issue they should, to the extent possible, be interpreted so as to give rise to a single set of compatible obligations.'[273] In the context of achieving environmental sustainability, it recognises the interdependence of social, economic, financial, environmental, and human rights aspects of principles and rules of international law.[274] Given that regulation of climate engineering is only now unfolding, an important aspect of the principle of systemic integration highlights the need to develop governance for climate engineering across different legal and institutional settings in a way that promotes greater coordination, coherence and efficiency.

Chapter 3 | Addressing risks and trade-offs in governance

by Matthias Honegger[1][2]

Abstract

Climate change and climate-altering technologies pose an emerging risk governance challenge involving risk-risk trade-offs both regarding potential outcomes as well as governance choices. Trade-offs characterize not only various emergent governance and policy design choices but also how research is conducted and communicated. This chapter identifies numerous risks and trade-offs and offers several steps that could be pursued in the near- to medium-term to gradually overcome trade-offs and strengthen opportunities for governance strategies that attenuate multiple risks. Many of these steps aim at strengthening capacities for anticipation, cooperation, and joint decision-making, which would appear essential qualities for addressing the risk-risk trade-offs posed by climate change and countervailing risks associated with potential CDR and SRM applications. Suggested measures in the context of governance processes include: strengthening capacities for international inter-agency collaboration, coordination, and learning; proactively exploring how specific governance challenges match particular international agencies' mandates; conducting policy impact assessments in the context of national mitigation policy planning. Suggested measures in the realm of research, research funding, and research governance include: enabling more diverse, transdisciplinary research; supporting the international exchange of expertise; enabling continuous science-policy conversations; conducting research to generate insights on potential interlinkages in the context of the Sustainable Development Goals.

[1] IASS Potsdam, Perspectives Climate Research and Utrecht University

[2] This chapter benefited from various inputs including particularly by Jonathan Wiener, Mark Lawrence, Ortwin Renn, and other chapter authors.

3.1. Introduction

Climate change has characteristics of emerging risks, which are complex, uncertain, and often ambiguous as they evolve. Climate change can impact via direct physical pathways, as well as via other non-physical pathways on a wide range of societal objectives such as the 17 Sustainable Development Goals (SDGs) (Nerini et al., 2019)[3]. These characteristics of climate change also shape the decision-making context in which present and potential future actions dedicated to limiting impacts from climate change (including emissions reductions, CDR, adaptation, and potentially SRM) are embedded. A particularity for climate change is that the default – inaction – causes the destabilization of the climate system and associated risks of severe impacts on human lives and natural environments. Climate action is thus overall characterized by risk-risk trade-offs where the target-risk (climate change impacts) is juxtaposed by countervailing risks caused by climate action/interventions.

Risk trade-off analysis (Graham and Wiener, 1995) suggests a three-step approach to governing risk-risk trade-offs: First, trade-offs need to be recognized. Second, target-risks and countervailing risks need to be weighed. Third, 'risk-superior moves' are to be identified, allowing overall risk reductions. Emerging risk governance furthermore posits a necessity for anticipating various future scenarios to develop risk management options that are robust against a range of possible emerging risk landscapes (IRGC, 2015; Grieger et al., 2019).

This chapter identifies and unpacks several risk trade-offs about decisions on research and policies for CDR or the emerging governance of SRM. To do so, the following sections elaborate on risks and trade-offs already described in the literature with an interwoven physical, governance, and research dimension. For example, trade-offs around land-use (for producing biomass for mitigation, food or energy production or safeguarding biodiversity), will require governance to balance activities' potential for climate change mitigation, harm, and co-benefits[4] through appropriate processes and institutions that enable or restrict the activities based on a sound scientific understanding of multiple causal relations. The necessity for anticipating various scenarios is particularly evident for SRM governance, as the target-risk (climate change) and countervailing risks from potential SRM intervention are expected to evolve significantly in the coming decades.

Identifying risks and trade-offs and better understanding their interconnected physical, governance, and research dimensions is a prerequisite to designing measures and processes for approaching governance and situating these in the most appropriate institutional contexts. However, critical causal relations are poorly understood to date, and assessments have only started attempting evaluation and weighing of target-risk and countervailing risk associated with various CDR or SRM applications. Advancing collaborative research and international deliberation might at this stage thus represent a 'risk-superior move' as such efforts will in the long-term allow reducing multiple risks and strengthen future decision-making capacities. This chapter offers several process recommendations to lay the foundation for gradually strengthening both formal and informal governance in line with emerging risk governance.

The first section of this chapter (3.2) focusses on the physical domain to explore the physical aspects of target-risk and countervailing risk of CDR or SRM application. The second section (3.3) explores how policy design and governance measures are subject to risk-risk trade-offs while they also shape risks and trade-offs, and suggests measures for addressing governance-related risks and trade-offs. The third section (3.4) discusses risks and trade-offs involved in research and suggests measures in the realm of research, research

---

[3] The SDGs form the core of the 2030 Agenda for Sustainable Development adopted in 2015 by all UN Member States as a shared blueprint for peace and prosperity for people and the planet, now and into the future. While not legally binding, the SDGs offer a highly diverse (environmental, social, institutional and political) set of shared objectives, and an urgent call for action by all countries - developed and developing - in a global partnership.

[4] 'Co-benefits' is a term commonly used in the context of climate change mitigation to describe any benefits that would not pertain to mitigation (spanning various outcomes pertaining to health, energy access, living conditions, ecosystem services, individual productivity, and macro-economic benefits; Ürge-Vorsatz et al., 2014).

funding and research governance. The chapter concludes (in section 3.5) with a brief summary of the observations and suggestions.

3.2. Physical aspects of risks, co-benefits, and trade-offs

As seen in Chapter 1, the physical implications of CDR and SRM approaches are very different. In the case of CDR, target-risk and countervailing risks are asymmetrical: target-risk mitigation (i.e. climate change mitigation) is inherently global as it is for all mitigation efforts, whereas the countervailing risks and co-benefits tend to be local or regional. In contrast, for SRM, both target-risk and countervailing risk tend to be global[5]. However, neither CDR nor SRM has immutable characteristics concerning their physical performance: Outcomes fundamentally depend on the design of interventions, namely on the amount, scale, and pace of application as well as their interaction with local geographical factors. Given their importance in determining physical risks, co-benefits, and trade-offs, the following section examines the relationship between these factors.

3.2.1. Physical implications of various CDR approaches

The target-risk that CDR seeks to attenuate are growing global GHG concentrations and their long-term consequences. Costs and countervailing risks associated with CDR tend to occur locally and immediately (although larger-scale and delayed effects may also be possible in some cases including large-scale ocean interventions). The incentives to pursue CDR are therefore severely misaligned. As is the case for emissions reductions, a significant aggregate risk related to CDR, therefore, pertains to the risk of mitigation underprovision[6]. However, the countervailing risk due to physical effects from large-scale applications at local levels is often raised as of more immediate governance concern. Physical effects can cause both adverse outcomes (risk) as well as positive (co-benefits) as described below.

In the context of CDR, mitigation underprovision can arise via two pathways: First, overreliance on an expected future contribution of CDR to mitigation – advancing an agenda of delaying emissions reductions – might be followed by a late realization that CDR potentials cannot or will not be mobilized at such scales (corresponding to the 'moral hazard' concern; see section 3.4.2). Second, the absence of near-term political effort to mobilizing CDR as part of nationally determined mitigation contributions would cause a self-fulfilling prophecy that CDR does not contribute to mitigation.

Potential physical effects of CDRs pertain primarily to their specific resource needs when implemented at large scale. The most critical trade-offs[7] regard demands for land, water, and soil nutrients (for biomass-reliant approaches including afforestation and bioenergy with carbon capture and storage -BECCS); demand for electricity and heat (for Direct Air Capture and Storage -DACS); availability of various materials in large quantities (for enhanced weathering and ocean fertilization); and the availability of geological storage of CO_2 (for both DACS and BECCS). Biodiversity and agricultural production trade-offs depend on specific choices when implementing afforestation, reforestation, biomass harvesting, as well as ocean-based approaches[8]. Trade-offs, as well as synergies, could arise around any land-use change due to a potential to either constrain food production or biodiversity-rich ecosystems. However, the same measures, if designed appropriately, could offer synergies in contributing to several objectives (e.g. food security, strong soil ecosystems, access to clean water, health and well-being, agricultural productivity and climate protection (Smith et al., 2019)). Detailed knowledge of local conditions thus appears to be essential to mobilize co-benefits and prevent harm (Honegger et al., 2018). Preparation and dispersal of powdered materials for accelerated weathering on land or water surfaces as well as for ocean fertilization could furthermore cause adverse health effects, yet such

[5] Except for small-scale local albedo modification seeking e.g. to counteract urban heat islands for adaptation purposes.

[6] Underprovision is the fundamental challenge that has plagued climate change mitigation from its beginning due to the public-good nature of protecting the climate (Keohane and Victor, 2016).

[7] For a detailed list, see Honegger et al. (2018).

[8] Uncertainties around ocean ecosystem implications remain particularly high.

activities could potentially also counteract acidification of soils and water bodies. All land-use intensive approaches (a-/ reforestation, BECCS, and soil-carbon approaches) could cause significant local albedo changes and changes in water evaporation. These can – if the land-surface is large enough – cause regional changes in weather through temperature, cloud formation, and precipitation. Depending on the local conditions, these can be positive or negative (e.g. if they limit precipitation elsewhere or deplete local water resources). Transboundary weather changes are also possible in case of particularly large applications near country borders.

3.2.2. Physical implications of various SRM approaches

As outlined in chapter 1, there are two types of physical implications from potential SRM application: first, effects on climate variables[9]; second, the side-effects of materials and deployment vehicles used.

Modeling studies consistently suggest that SRM application (particularly SAI, see chapter 1) could be pursued in ways that revert several key physical climate parameters closer to their pre-industrial state across geographies (thus offering significant potential for target-risk attenuation)[10]. However, the details depend on two factors: (a) the atmospheric GHG-concentration trajectory[11]; (b) the design, scale, and pace of application. Questions of design include where albedo modifications take place and what materials are used. Scale and pace refer to the degree of warming that is to be counteracted by the intervention and over which time horizons. All of these factors point to significant trade-offs that any decisions on potential global SRM deployment would need to navigate with significant distributional effects similar to the distributional effects caused by inadvertent climate change.

The design process for SAI12 would furthermore have to navigate trade-offs in the choice of the types of aerosol particles used, the geographical location of injection, and the vehicles of transport. Sulfate-based aerosols could cause problems to health and impact ecosystems13, while other materials might avoid some of these problems or in part even counteract them (e.g., acidification). Model- and observation-based studies highlight that targeting an even application via a multiplicity of injection points in both hemispheres would likely be a precondition for a geographically even reduction in temperatures and other key climate parameters across geographies14. Many studies furthermore suggest that SRM would only meaningfully attenuate climate impacts across physical variables (notably precipitation) if it only sought to partially counteract warming (see Textbox 2).

---

[9] Climate variables include temperature and precipitation across local, regional, and global scales over short (days) to long (centuries) time horizons as well as various knock-on effects from these two variables (e.g. on snow or ice-coverage, wind patterns, ocean temperatures, sea levels, and extreme weather, etc.).

[10] Irvine et al., 2019; Jones et al., 2018; MacMartin, Ricke and Keith (2018); Muri et al. (2018); Kravitz et al. (2014); Irvine, Ridgwell and Lunt (2010), Ricke, Morgan, and Allen (2010).

[11] This includes humanities' aggregate emissions path including any ramp-up in CDR activity as well as the response of Earth systems including secondary GHG emissions feedbacks.

[12] While SRM includes approaches as diverse as enhancing the reflectivity of land- or water surfaces, altering clouds or installing sun-shades in space, this chapter focuses on Stratospheric Aerosol Injection (SAI), which presents features that would have global implications.

[13] Such effects (as described in chapter 1) could include slowing the recovery of the ozone layer, contributions to air pollution, and acidification of land and aquatic ecosystems.

[14] See e.g. Haywood et al., 2013; Jones et al., 2017, Tilmes et al., 2013.

Textbox 2 – SRM application could seek different forms of climate risk attenuation

Two main scenarios have been considered regarding scale and pace of deployment[15], in response to a net-emissions pathway that eventually reaches net-zero (or temporary net-negative) global GHG emissions (Long and Shepherd, 2014; MacMartin, Caldeira, and Keith, 2014). The first one dubbed 'peak-shaving' (Figure 4, left) would seek to halt warming at a specific global temperature level (e.g., 1.5°C or 2°C), while GHG concentrations follow an overshoot-and-return pathway. Accordingly, application volumes of SAI would first increase until global emissions reach net-zero. As global net-negative GHG emissions would start reversing to lower GHG concentrations, SRM volumes could gradually phase out again as GHG concentrations approached the level matching the intended warming level.

The second scenario dubbed 'limit the rate of change' (Figure 4, right) follows a different logic. It does not rely on overshoot-and-return of GHG concentrations[16], but instead seeks to extend the period over which global temperatures rise to stabilize at a higher level (whereby CDR is 'merely' needed for achieving net-zero global GHG emissions to stabilize GHG concentrations at a higher level). As such, the level of SAI could remain lower compared to 'peak-shaving' and solely seek to limit the harm associated with the most rapid change in climatic conditions.

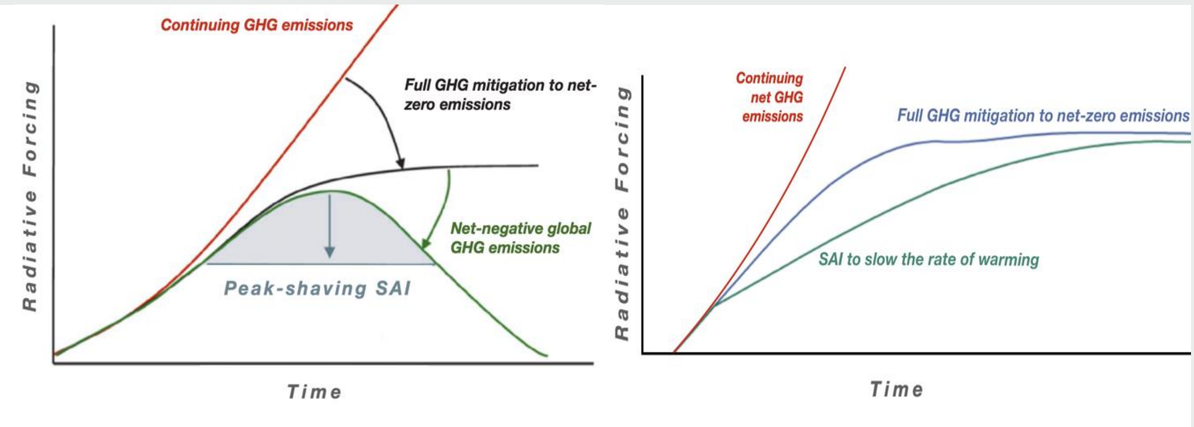


Figure 4 – Two different conceivable scenarios of SRM application with different implications for the pursuit of sustainable development: 'peak-shaving' (left, adapted from Long and Shepherd, 2014) or 'limit the rate of change' (right, based on Keith and MacMartin, 2015).

3.2.3. The meaning of physical implications of CDR and SRM

While there is a large and perhaps growing number of potential physical effects that could variously be associated with specific forms of CDR or SRM applications, it is essential to bear in mind that what ultimately matters are not the physical effects per se, but how these shape human- and environmental realities (Ki-Moon, 2019)[17]. The physical implications of CDR and SRM (changes in physical parameters of, e.g., temperatures, precipitation, and their respective variations that affect environmental, economic, and social realities through various highly complex pathways) are insufficiently understood to date, as seen in chapter 1.

---

[15] See Sugiyama et al. (2016) for a discussion of a range of SRM application scenarios.

[16] Overshoot-and-return scenarios are doubtful, as they require very large, long-sustained application of CDR to achieve net-negative global GHG emissions. Yet they are already built into numerous scenarios limiting warming to 1.5°C, including those summarized by the IPCC (Rogelj et al., 2018).

[17] One measure for this could be whether their use would, for example, align with or challenge the pursuit of sustainable development locally and globally.

While impact pathways stemming from 'conventional' climate change have increasingly been studied over the last two decades for example in *adaptation studies*[18] (IPCC, 2014), the novel ways in which alternative climate pathways can be produced require further dedicated study. This includes – but is not limited to – adaptation needs in case of GHG concentration overshoot-and-return, adaptation benefits from SRM (if either slowing or halting warming), local inadvertent climatic impacts from various CDR applications or local forms of deliberate land- or water surface-albedo or cloud modifications.

More model-based research can help evaluate and weigh target-risk attenuation and countervailing risks and co-benefits of CDR and SRM techniques under various application scenarios. However, this type of research ought to increasingly be conducted and communicated mindfully of the limitations of abstract modeling for identifying real-world risks and trade-offs. Modeling alone falls short in part due to the intricate relationship of the physical dimension and the governance dimension (as discussed in the following section).

The birds-eye perspective that modeling can offer does by itself not seem to provide a sufficient basis for the type of assessments needed for designing CDR policies. To balance the (aggregate-scale) target-risks (including the risk of missing mitigation targets) with local countervailing risks, it seems essential to systematically start exploring region-specific CDR implications via small-scale real-world pilot activities of those CDR approaches deemed to fit national circumstances and local conditions best. Only upon carefully piloting such activities in real-world conditions can a more substantial understanding of highly diverse geography-dependent implications emerge. Some CDR approaches could offer significant benefits (e.g. for agricultural productivity, soil, and ecosystem resilience), which, if identified, may be readily mobilized. However, many risks or trade-offs are region-dependent or only arise out of particular social or political circumstances. Planning for CDR application thus has to take place in national or subnational policy contexts, such as those taking place in the preparation of Nationally Determined mitigation Contributions (NDCs)[19][20] (Beuttler et al., 2019).

For SRM, it would be beneficial to pursue more interdisciplinary research that explores how physical and political dimensions of target and countervailing risks compare in various future scenarios, thereby contributing to the knowledge basis needed to eventually identify risk reduction opportunities that are robust against multiple future developments (see section 3.4).

3.3. Risks and trade-offs related to policy design and governance

Risks and trade-offs in physical outcomes are highly dependent not only on scenarios but also on the dedicated governance (including decision-making processes, resulting policies, as well as accompanying measures). This is true not only for material outcomes in environmental or economic terms but also for non-material values and cultural norms that may be affected by applications of CDR and SRM. Choices in the design of policy and governance are themselves characterized by risk-risk trade-offs.

[18] IPCC Assessment Report 5 Working Group II synthesizes present scientific understanding of how changes in climate variables affect human and environmental realities.

[19] NDCs were introduced in the section 2.3.2 on the Paris Agreement.

[20] Switzerland has recognized the need for applying CDR to achieve its climate neutrality target following expert deliberation (Beuttler et al., 2018), but planning processes are still at an early stage (see the communication of the Swiss Federal Council: https://www.bafu.admin.ch/bafu/en/home/topics/climate/news-releases.msg-id-76206.html)

3.3.1. Inclusive governance versus Governance efficiency at the global level

Ensuring inclusive governance and appropriate participation in decision-making and governance processes is a key challenge. Some lessons relevant to SRM can be drawn from over 20 years of climate change governance via a multi-layered governance system from local action to global coordination via the UNFCCC. The present governance structure for climate change mitigation and adaptation, particularly under the Paris Agreement allocates different obligations to different layers. Some central decisions (e.g., long-term temperature targets) and coordination functions (rules for transparency of national action) are taken at the highest aggregation level (the UN), while the most implementation-related decisions take place at national or sub-national levels. Friction and imperfect interaction of these governance layers have caused problems in the past, including gaps between formal targets at the global level (1.5°C or 2°C temperature increase by 2100) and national targets, gaps between national targets, policy planning and implementation, lacking accountability of state[21], policy instruments not being suitable for local implementation[22], and a lack of representation of populations, including indigenous communities.

While core functions of global cooperation for both CDR and SRM will likely have to be fulfilled by government representation in multilateral and intergovernmental organizations (including institutions mentioned in chapter 2), it seems important that various opportunities for inclusive governance are pursued early on, particularly in regards to SRM (including at early deliberation and assessment stages in various countries' contexts, see also section 3.4). Several CDR-related governance challenges are largely an extension of well-known governance challenges of mitigation via emissions reductions. In contrast, SRM requires addressing a set of novel decisions, including on the permissiveness of deliberately altering a major planetary system. Such decisions might require a greater degree of inclusiveness than decisions on a global temperature target and associated economic transformation as taken in the context of the Paris Agreement.

If there is a continued lack of dedicated efforts to strengthen inclusive governance, decisions at both global and national levels might increasingly be seen in conflict with values and cultural norms around democratic rights and, therefore, to lack legitimacy (Stephens and Surprise, 2020). Inclusive governance processes take more time than decisions taken in highly specialized expert-driven contexts. To allow for inclusive governance of CDR and SRM**,** participatory engagement processes need to be set in motion as early as possible – whether it is in the context of deliberating on the use of CDR in a countries' NDC or whether it is in the context of deliberating on research or governance of SRM.

3.3.2. Sovereignty of domestic policies versus Transboundary effects of CDR approaches

Where large-scale CDR strategies would cause a risk of significant adverse transboundary effects (such as on weather, resource conflicts from increased upstream water consumption, or food price fluctuations), there is a risk of international tensions, which may need to be addressed by governance. Although to date such tensions have not manifested in a serious manner (from mitigation activities including CDR via afforestation or reforestation), they could become more significant, should parties – potentially aided by dedicated international support – start pursuing CDR at increasing scales. On the other hand, it is the sovereign right of states to plan and execute their mitigation activities without interference (and to communicate them as their NDC). Similarly, states enjoy significant liberties in prioritizing, working toward, and assessing progress made with regard to the Sustainable Development Goals. There are well-known limitations to the degree to which

---

[21] This includes key parties reneging on prior obligations as soon as missed obligations became apparent (including Canada in the Kyoto Protocol and the United States under the Paris Agreement).

[22] For example, overly complex MRV systems have initially rendered market mechanisms barely accessible to least-developed country participants, which was later remedied by actively facilitating the participation of least developed countries; in other instances, forestry projects have caused perverse incentive structures and 'leakage' (relocation of deforestation activity elsewhere).

international governance can offer stringent rules or guidance for national governments to follow as they are asked to work toward sustainable development in the context of mitigation activities (regarding such experience under the Clean Development Mechanism, see Dransfeld et al., 2017). Institutions[23] seeking to limit harm of such kind, could collaborate in the preparation of detailed (yet likely voluntary) guidance and potentially develop a system of third-party verification. Climate finance institutions seeking to support the implementation of high-quality CDR activities could adopt such systems as part of their selection process, particularly regarding potential transboundary impacts. To not infringe on sovereignty, to avoid disadvantaging countries with limited governance capacities, and to avoid rendering small-scale activities unattractive (due to large transaction costs) these should be operationalized in ways that do not impose excessive burdens on small-scale activities. Experience has shown that such transaction costs can hold back the pursuit of mitigation, including CDR, particularly in least-developed countries.

3.3.3. Maximizing mitigation versus Ensuring sustainable development

Experience with mitigation policies shows how domestic policy instrument design choices shape the occurrence of sustainable development harm or co-benefits. Outcomes are fundamentally dependent on whether domestic policies are designed in a nationally appropriate manner – suited for the specific environmental conditions and social, economic, and political structures. To mobilize the synergies between maximizing mitigation and ensuring sustainable development (rather than having to choose one over the other), it is crucial to take experience into account and to ensure that countries can learn from one another as they continue to devise and revise mitigation policies including for CDR.

Textbox 3 – Policy design shapes sustainable development implications of mitigation activities, including CDR

For some CDR approaches there are important lessons that can already today be drawn from experience in conventional mitigation efforts with afforestation, reforestation, and ecosystem preservation (vast land requirements, social structures -e.g. enforced ownership by indigenous communities determining success, accompanying measures in the broader economy alleviating pressure to otherwise use the lands), biomass plantations (water demands, monoculture and soil erosion problems), and many more. Policy instrument design is known to determine whether incentives are suited to generate sustainable results, particularly for nature-based approaches (appropriate species choices avoiding monocultures, social participation, etc.). International governance can play an important role by providing guidance or requiring procedures for assessing, communicating on, and accounting for implications for sustainable development coupled to international support for mitigation activities including for CDR (e.g. under the Sustainable Development Mechanism of the Paris Agreement).

Experience with Carbon Capture and Storage (CCS) also offers useful learnings for DACCS, regarding trade-offs and risks associated with low social acceptance and high-risk perception among populations, particularly where evaluation and decision-making are not approached in an inclusive and participatory manner.

Crucially, planning for beneficial mitigation policies requires long lead times, and a continuous effort that allows situating measures within already existing structures and processes, yet with the high-level political backing that ensures follow-through (rather than single-intervention, top-down policy setting that lacks the political will for implementation).

[23] This could include international organizations variously focused on environmental, social, and economic issues including but not limited to biodiversity, desertification, food and agriculture, trade, and other.

3.3.4. Centralized governance versus Polycentric governance - Effectiveness versus Diversity

Polycentric governance denotes a complex form of governance with multiple centers of decision-making, each of which operates with some degree of autonomy (Ostrom, 2005, 2010). One challenge of polycentric governance is coordination. The absence of effective coordination would cause institutional fragmentation and governance would lack effectiveness, thereby exacerbating governance-related risks, including mitigation underprovision or uncoordinated SRM applications. Some central governance functions may need to be assigned very clearly, for example for the choice of a unique venue for CO_2-accounting of CDR under the UNFCCC and its Paris Agreement. Other functions may be best addressed via multiple centers of governance, with effective coordination.

CDR is currently addressed under several governance frameworks, many of which pursue the stated purpose of limiting permissible CDR action (as elaborated in chapter 2). Unless provisions are operationalized in such ways as to provide the necessary clarity and conducive business environment, these can end up being prohibitive to, e.g. private sector engagement via international market mechanisms (see Textbox 4) or domestic mitigation policies. Underprovision of climate change mitigation is even more pronounced for CDR than it is for emission reduction, given that emission cuts are often achieved for reasons other than climate protection[24], whereas many CDR approaches presently do not seem to come with such 'co-benefits'. This apparent lack of (at least visible) co-benefits points to a severe risk of missing mitigation objectives of the Paris Agreement, with potentially grave consequences. Mitigation underprovision due to institutional fragmentation and ineffective governance is especially pertinent since a continuous rise in GHG concentrations exacerbates the probability of (uncoordinated) SRM application (as SRM might increasingly seem an attractive quick fix for rising climate impacts).

Textbox 4 – International CDR pilot activities

There is very limited experience with policies targeting the implementation of various types of CDR, including in countries which, based on resource availability, could pursue CDR at a meaningful scale as part of their mitigation contribution (NDC). International policy instruments such as carbon markets or results-based climate finance could help mobilize CDR where necessary natural resources (e.g. land available for sustainable biomass production, geological storage or excess energy) are most substantial. Countries with less domestic CDR capacities could fund CDR abroad (Honegger and Reiner, 2018). Most models that portray mitigation for 2°C or 1.5°C assume cost-efficiency at the global level, which requires international cooperation on emissions reductions and CDR. Implementing such international cooperation – as foreseen under the Paris Agreement (specifically its Article 6) – would require building up an ecosystem of experienced market participants, experts, and third-party verifiers to ensure consistent monitoring, reporting and verification of mitigation outcomes, as well as robust processes to prevent harmful side-effects. Pilot activities with stringent quality control could enable the pursuit of small-scale CDR activities as part of an ensemble of mitigation projects and thereby offer crucial lessons for appropriate CDR policy design all over the world[25]. As countries increasingly adopt net-zero mitigation targets, governments will be expected to lead by example and to help generate the necessary practical experience via bilateral pilot activities. Such activities should take place in highly controlled settings, to allow for correcting measures and learning to take place and enable the development of best-practice examples.

There is a relevant scholarly interest in polycentric governance of climate change (Jordan et al., 2018) and SRM specifically (Nicholson, Jinnah and Gillespie, 2018). However, without greater coordination, there is a risk of fragmentation causing conflicting obligations (as seen in chapter 2), and exacerbating probability of

[24] Co-benefits, which drive many emissions reductions actions include notably economic efficiency, lower reliance on imported fuels, health benefits, and other; (Urge-Vorsatz et al., 2014).

[25] In the Swiss context, such activities could be implemented by the KLIK foundation in cooperation with FOEN.

premature or uncoordinated application of SRM. More coordination may, therefore, be needed between various UN agency secretariats, which are understood to be central players in shaping coherent starting points for decision-making by the respective Convention parties as well as between other Intergovernmental Organizations.

3.3.5. Preventing uncoordinated or premature application of SRM

In light of significant uncertainties as well as large potential adverse effects, especially in case of uncoordinated application, there is a need for governance to (a) ensure that SRM is not deployed as long as the understanding of impacts remains insufficient and (b) prevent uncoordinated SRM application in the long-run. Achieving both requires building a shared understanding of the potential effects of SRM applications and establishing a robust foundation of international cooperation.

As seen in chapter 1, knowledge of potential local and global effects of SRM application is extremely limited, and SRM deployment in such a state of ignorance would pose a grave risk primarily due to these uncertainties. In line with a precautionary approach and the obligation to cooperate in case of a possibility of transboundary harm, institutional governance on SRM (including its research) thus has to prevent deployment in the foreseeable future, as long as understanding about potential and impact is clearly insufficient (chapter 4 explores some ways in which this could be pursued).

Effective prevention of uncoordinated deployment in the long term poses a different governance problem: While SRM experts and an increasing number of governments understand that uncertainties associated with transboundary effects of SRM, certainly for now, forbid considering deployment by any actor, this understanding may not be sufficiently robust at a global scale to underpin preventative measures such as moratoria or bans, to prevent uncoordinated SRM application by all global actors effectively. In the long term (see chapter 4), a ban or moratorium would only be effective to the extent that it would deter countries from not abiding by it (Victor, 2011). As mounting climate change impacts to some actors become an existential threat, the deterrence would need to be increased accordingly[26]. Without a very compelling shared understanding of the stakes of potential unilateral application or application by a small coalition of countries, it would seem less and less likely that an institutional moratorium or ban would be executed upon with the necessary political will to enforce it in the long-run. Analysis of trade-offs strongly suggests that scientific research should be conducted to explore the risk landscape, including risks associated with less-than-optimal application scenarios. Pursuing such research in a cooperative manner could in and of itself be crucial to strengthening the case for preventing uncoordinated SRM application in the long term.

The preferred approach to avoid uncoordinated deployment, in the long term, is undoubtedly to mitigate climate change sufficiently so that the deployment of SRM never appeals to any actor (group). As previously described (section 3.2.1), this cannot be taken for granted as it requires much more decisive action and institutional cooperation than what is currently done at domestic and global levels to reduce GHG emissions and complement with CDR approaches to reach global net-zero emissions within two to three decades. A second-best approach would seem to create a norm that prevents various actors from considering uncoordinated deployment, but the effectiveness of such an approach in the long term is also questionable. Therefore, the non-ideal theory would suggest a third-best approach may also be needed (in addition to the first and second-best) as part of a precautionary approach to avoiding uncoordinated deployment in the long-term (Morrow and Svoboda, 2016). This would mean to establish a dedicated process of global governance in which the international community could transparently deliberate on the governance requirements for a potentially desirable form of coordinated SRM application and the conditions under which globally coordinated SRM application might enter into formal decision-making processes. Such a body would also

[26] Bunn (2019) and Philippe (2019) identify lessons from the governance of nuclear technologies for the governance of SRM. They identify a need for capabilities to a) monitor, b) detect and attribute and c) to deter undesirable application. They note that the deterrent in the case of nuclear weapons nonproliferation is extremely large (given that it includes the threat of military intervention by nuclear powers) and that deterrents to SRM would be unlikely to be this large and credible.

have to grapple with the risk associated with abrupt cessation of significant SRM application, known as "termination shock" (perhaps including by designing redundancies and appropriate institutional arrangements; Parker and Irvine, 2018). The existence of a dedicated legitimate multilateral body with a mandate to decide over any potential application of SRM could contribute to the discouragement of uncoordinated deployment.

All the above strategies to prevent premature or uncoordinated SRM applications require a willingness to invest serious political engagement on preventative measures. Therefore, systematically strengthening decision-making capacities by pursuing collaborative research and engaging both academia as well as decision-makers would seem a prerequisite to pursuing any robust governance of SRM (Morrow, 2019). Inappropriate decision-making capacities across governments and international institutions are presently an important source of concern. Strengthening capacities is a necessary condition to avoid premature or uncoordinated SRM application. Research, expert deliberation and public engagement on the subject of SRM have been taking place only in a handful of countries to date[27]. These countries are by consequence benefiting from an increasingly sophisticated basic understanding among experts, which is often shared with decision-makers and occasionally with the public, of the governance problems posed by SRM and the possibilities for action. While there are some ongoing efforts to strengthen the capacity and involvement in other countries, in part catalyzed by non-governmental organizations[28], current efforts appear insufficient. Efforts to address this problem should also take the concern into account that substantial investments into SRM research could result in researchers lobbying for the deployment of SRM (see section 3.4.5). Differences in domestic decision-making capacity is also a concern in the context of equity: countries with fewer resources, expertise and research capacity will be disadvantaged in critical decisions to actively shape the global governance of SRM.

Textbox 5 – Theoretical considerations on dealing with the problem of SRM overprovision[29]

Weitzman (2015) suggested what he referred to as a 'naïve' proposal to governing SRM in a dedicated permanent governance body, in which decisions to increase the level of SRM application require a larger majority of votes (e.g. 75%) than a decision to decrease the level of SRM (e.g. 25%). Recent papers furthermore explore whether the threat of so-called counter-geoengineering (deliberate interventions to counteract SRM-induced cooling) could deter countries from engaging in unilateral or excessive application of SRM and whether cooperation might be stronger as a result of such a deterrent (Parker et al., 2018 and Heyen et al., 2019).

3.3.6. Suggestions for addressing risks and trade-offs shaped by governance

The suggestions, elaborated below, include to (a) Strengthen capacities for international inter-agency collaboration, coordination and learning; (b) **Explore how specific governance challenges match particular international agencies' mandates**, and (c) Conducting policy impact assessments in the context of national mitigation policy planning.

[27] Countries with some research efforts to date are Germany, the UK, the US, China, Japan, and Switzerland.

[28] These include most prominently the Solar Radiation Management Governance Initiative hosted under the umbrella of UNESCO and the Carnegie Climate Governance Initiative hosted by the Carnegie Foundation.

[29] In contrast to *mitigation* (which is plagued by underprovision), SRM appears to be plagued by the reverse problem, whereby actors might individually be incentivized to overprovide SRM compared to a social optimum.

Strengthen capacities for international inter-agency collaboration, coordination and learning

The first suggestion for dealing with governance-related risks and trade-offs is to encourage and enable relevant international institutions to coordinate their work. For that purpose, human resources should be dedicated (including by creating new secretariat positions[30]) with expertise in CDR and/or SRM, which would act as de-facto focal points for coordination on matters relating to CDR and/or SRM within each institution. Such staff could ensure the internal institutional capacity to explore how CDR and/or SRM issues relate to various parts of the institutions' general mandate, offer member states or other participating entities (informal or formal) capacity building on such issues (particularly benefiting states with limited domestic capacity to do so on their own), and coordination with counterparts in other institutions. If most of the potentially relevant organizations for a polycentric governance approach to CDR and SRM had staff positions dedicated to these issues, the resulting capability for cross-institutional coordination and learning could help with two of the identified challenges: the risk of inappropriate decision-making capacity across governments and international institutions as well as the risks of fragmentation and uncoordinated action by multilateral and other international institutions.

Explore how specific governance challenges match particular international agencies' mandates

The second suggestion is for secretariats of international organizations to proactively engage in a systematic exploration of governance problems posed by CDR and SRM, to identify how such issues may fall, or not, into the mandate of each organization, and to describe what would be needed by each organization to effectively address the issue identified.[31] This would allow these organizations to be more responsive when demand for decisions rises. Furthermore, such activities can be pursued in continuous coordination between organizations – particularly if combined with the above-suggested personnel capacities positioned across organizations – which can enable crucial cross-institutional learning. Such information flows may ultimately allow avoiding conflicting or otherwise overlapping interpretations of mandates and decisions regarding the governance of CDR or SRM.

Conduct policy impact assessments in the context of national mitigation policy planning

In regards to CDR as a particular class of climate action affecting multiple policy fields, the third recommendation is to leverage expertise in the various relevant policy fields to conduct policy impact assessments in the context of national mitigation policy planning. This would require bringing together expertise from various environmental policy fields where CDR policies could be deployed, such as forestry and land-use change policies, ecosystem preservation policies, landowner- and indigenous peoples' rights, energy and biofuels policies, carbon taxes, carbon markets, environmental standards, various policy fields associated with geologic activity including notably policies regarding CCS, and many more. Interdisciplinary policy impact assessments can provide valuable learning for policies that would aim to incentivize CDR implementation. In addition, useful recommendations can help better inform decisions on implementation of CDR in nationally appropriate mitigation actions and long-term strategy development for a 2050 horizon, and provide relevant guidance and best-practice examples for countries that lack resources for conducting impact assessments from the ground up.

---

[30] There may be cases where additional financial support by member states (or an additional mandate, see also the following footnote) would be needed to enable secretariats to implement such a step.

[31] Organizations might have varying leeway to conduct such internal exploration within existing mandates given by member states. Where an additional mandate would seem appropriate to conduct such internal exploration, member states could start deliberating on tasking the organization with such an exercise.

3.4. Risks and trade-offs related to research

While following a different set of rules than public policy, scientific research and the communication of scientific findings are not entirely free of values and the political entanglements that come with them. Many have pointed out the problematic relationship between climate change politics and the integrated assessment models of various economic impact and transformation scenarios on climate change. For instance, in recent years many have found the inclusion of large amounts of 'negative emissions' or CDR in most model runs aiming for 2°C or 1.5°C of warming by end-of-century to be politically problematic (for obscuring the scale of the mitigation challenge ahead, or for falsely permitting the models to attain ambitious temperature targets when they seem increasingly out of reach). An abundance of value judgments has also been identified in various SRM research endeavors (both in natural and social science). Figure 5 illustrates SRM features that are all related to design choices and uncertainties, layered to form a pyramid. The corresponding value-judgments often go unmentioned in studies or assessments, even though they underpin assessments and governance.

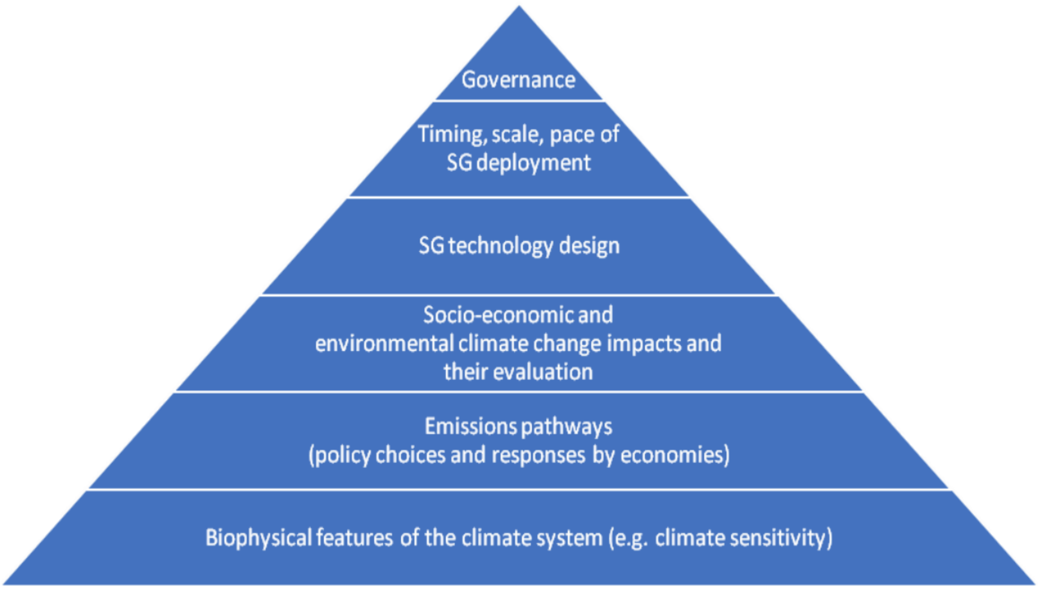


Figure 5 – A pyramid of value-laden assumptions underpinning assessments of SRM (named here SG, solar geoengineering), which represents uncertainties for governance considerations (Honegger, 2019)

3.4.1. Focused authoritative knowledge generation versus a Diversity of assessment approaches

Observation of ubiquitous value judgments in research and assessment of CDR and SRM highlights the importance of the institutional context in which knowledge on both series of techniques is generated, consolidated, and communicated. Debates on whether a primary science-policy interface on 'climate engineering' should be situated with the IPCC or whether other organizations (including, e.g. UNEP) should also conduct assessments on the matter have revealed the political emphasis given to the choice of an institution to gather and present (scientific) knowledge. Although arguably there does not have to be a decision in favor of, e.g. IPCC, UNEP or others to synthesize research on CDR or SRM, the lack of clarity on which scientific body is better suited to assess particular issues associated with CDR and SRM can result in some confusion precipitating into governance. There may be benefits to having one particular science-policy institution be the primary focus for assessments pertaining to climate change. However, much like in the context of (polycentric) governance, a diversity of scientific assessments could be beneficial, particularly at an early deliberation stage. Given that there will likely always remain some level of friction between institutions when it comes to delineating respective areas of expertise (and political influence), a trade-off might be to favor a more decisive allocation of the climate dimensions of assessments of CDR and SRM to the IPCC, while other institutions conduct assessments within the scope of their mandates (also see chapters 2 and 4). Institutions such as the IPBES, which explicitly combine assessments regarding effects on biodiversity with capacity building, could also play an essential role in advancing a shared and increasingly refined understanding of the science and associated governance challenges. Independently from where assessments take place, they must be done transparently and inclusively and with clearly-stated sets of criteria.

3.4.2. CDR research 'moral hazard' versus Mitigation underprovision

Fear of what is frequently referred to as 'moral hazard'[32] (Lin, 2013) or 'mitigation deterrence' pertains to research on CDR and its development as some are concerned that researching CDR would temper policy efforts to cut GHG emissions (Campbell-Arvai, 2017). Should this be true (there is inconclusive evidence, but it is a serious possibility; see Markusson, McLaren and Tyfield, 2018) this would pose a problematic trade-off: given that some form of CDR is required to achieve ambitious climate change mitigation targets, it would be counterproductive to respond by slowing research and development: Delays in CDR application would effectively worsen the mitigation gap between 1.5 or 2°C mitigation pathways and real-world implementation (Smith et al., 2017) and global net-zero emissions appear unachievable without CDR (IPCC, 2018).

Efforts to advance research to implement CDR, therefore, need to be conducted and communicated in a way that avoids fueling mitigation deterrence by not creating the false impression that CDR might ever displace deep and fast emissions reductions. When considering the actions needed to achieve ambitious national targets such as net-zero national emissions, it may be easy to see how only a vast ensemble of mitigation activities can ultimately deliver (Campbell-Arvai, 2017). As laid out in chapter 1, several governance actions will be needed to pursue CDR in such a way. However, such activities will likely also reveal significant challenges that CDR implementation will be facing, including unresolved research, environmental and policy challenges as well as uncertain social acceptability.

Textbox 6 – Researching CDR in national contexts, including for planning national mitigation action in NDCs, or long-term low carbon development strategies (LEDS)

To date, research has addressed CDR almost exclusively in the global context (whereby the claims of 'feasibility' of various approaches have sharply diverged, depending on research rationale and assumptions). Bottom-up research on the political feasibility of specific applications, with specific policy designs, and in specific national contexts, is almost entirely missing. Insights from global modeling for national policymaking are limited, given that such studies' findings apply to global average conditions and technology generalizations rather than any single countries' conditions (resource availabilities), specific technology designs, and stakeholder constellations. Dedicated applied studies on national CDR mitigation potentials, adverse effects, and co-benefits (drawing on quantitative and qualitative methods) – as conducted extensively for emissions reductions options in the context of countries' NDC or LEDS preparations – would be a prerequisite to inform the inclusion of CDR in national mitigation policy planning. Formulating specific and separate targets for emissions reductions and for CDR activities respectively could allow critical civil society voices to scrutinize mitigation efforts and thereby help prevent 'mitigation deterrence' (McLaren et al., 2019).

[32] The term 'moral hazard' was first applied to 'geoengineering' by Keith (2000) and caught on widely in the literature. Other terms such as risk compensation (Lin, 2013) or mitigation deterrence; (McLaren, 2016) were later found to more accurately describe the concern that emissions reductions or adaptation efforts might unduly be postponed or weakened upon considering the possibility of SRM or CDR.

3.4.3. SRM research 'moral hazard' versus Risk of ignorance

For SRM, the concern that research would cause emissions reductions efforts to falter has been voiced frequently (McLaren, 2016). Experience with *adaptation,* which was initially considered somewhat of a taboo due to similar concerns and the later recognition of its importance, might offer some lessons potentially applicable to SRM. One such lesson might be that it is crucial not to mistake one to be a substitute for the other by very clearly communicating their very different capabilities and limitations: Mitigation addresses the root problem of elevated GHG concentrations and adaptation or SRM respectively seek to attenuate the consequences for human lives and ecosystems. Levying the fear of mitigation deterrence to argue against proactively advancing research on SRM would also cause long-term risks (Reynolds, 2014). As discussed, not doing research does not per se appear a valid strategy to prevent future SRM application (Morrow, 2019). It could even undermine efforts to prevent uncoordinated deployment, and it would ensure that any consideration of SRM applications would be based on widespread ignorance of potential designs, expected performance, risks, and side-effects, which would then offer ample grounds for speculation and dangerous experimentation. Effectively it might end up unfairly yielding power to a few actors that did pursue research early on or have continued to disregard others' wish not to undertake research. Any decisions on SRM of global reach – if or when they arise in the future – would then effectively be shaped by the relatively narrow understanding of those few actors.

There is mixed evidence suggesting that public conversations on SRM research could result both in stronger or weaker support for rapid climate change mitigation action – depending to a large extent on the narratives and framings used (Raimi et al., 2019). The suggestion, therefore, may be to proactively advance SRM research in interdisciplinary settings (Burns et al., 2016) wherein particular attention is given to contextualizing ongoing work within the risk-risk trade-offs that characterize climate action overall, thus advancing a holistic perspective in which a precautionary approach to climate change and a precautionary approach to SRM is balanced, as both are marked by scientific uncertainty and potential for irreversible damage.

Textbox 7 – 'Precaution' applied to problems of risk-risk trade-offs

The precautionary principle as the most formal characterization of precaution has been formulated in numerous ways. Sandin (1999) found nineteen and Sunstein (2005, p. 18) found twenty different and partly conflicting formulations. Its operationalization is often ambiguous and does not simply carry over from one governance problem to another (Wiener, 2002). In the context of research and deliberation on SRM, precaution could mean that uncertainty associated with future climate impacts justifies action (Reynolds and Fleurke, 2013). Whereas in the context of SRM application, precaution could suggest shifting the burden of proof such that a proponent of deployment would need to prove that deployment would pose acceptable levels of risk. Operationalization of precaution tends to apply only to the governance of a single risk. In contrast, operationalization of precaution (when applied to problems characterized by risk-risk trade-offs) may introduce a severe countervailing risk (Wiener, 2002). Precaution thus can only be a useful guiding principle for governance contexts in which it can be operationalized without introducing additional ambiguity and without causing severe countervailing risks. As soon as the scope of the governance context is too broad, precaution would have to be expected to offer more confusion rather than clarity due to its different interpretations and mode of operationalization, in various governance contexts and different cultures. Identifying and implementing risk-superior moves, which attenuate multiple risks at once, therefore seems a more appropriate governance strategy including in regards to SRM research. This could suggest pursuing SRM research in ways that advances rather than undermines the case for deep and rapid emissions cuts, while also strengthening international cooperation (thus lowering the risks of unilateral action).

3.4.4. Risk of transboundary impacts from SRM research

Many SRM interventions would, by their very nature, be regionally or even globally effective. Some types of large-scale outdoor research would be hard to distinguish from the actual application. Consequently, impacts from large-scale research – both positive and negative – could have transboundary effects. This implies that in instances where research endeavors hold potential for transboundary effects, research governance would need to be international. Various potentially useful SRM research activities could, however, be conducted without significant physical transboundary impacts, while more substantial atmospheric research activities seeking to mirror actual deployment could potentially have some transboundary effects associated with particulate dispersal[33]. In order to prevent any tensions between countries due to suspected transboundary impacts from larger-scale research activities, there may thus be a need for specific domestic or international governance steps to assess the potential for such impacts and to prevent them with a substantial margin of safety. To achieve the objective of preventing transboundary effects, any credible governance effort would first have to define thresholds for when outdoor research would need to undergo additional scrutiny to demonstrate no physical transboundary effects. Some countries might perhaps even want to call for governance measures targeting SRM research even when it does not threaten physical transboundary harm, (e.g. on the grounds that such research represents an issue for which the duty of international cooperation applies (see chapter 2). Chapter 2 discussed institutional and legal contexts in which large-scale research with significant transboundary effects or uncoordinated SRM deployment could be fought, but their effectiveness and applicability to various scenarios seem uncertain.

It is unclear to which extent restrictions alone would effectively prevent the pursuit of outdoor SRM research altogether. When accountable and transparent channels of research are discouraged from engaging in this space, there is a risk that it would then be relegated to the secrecy of military research given that countries would likely want to know what they are giving up (Victor, 2011). There are general limitations to the effectiveness of a moratorium or other formal acts seeking to prevent various activities, as previously detailed in regards to uncoordinated deployment and in chapter 4 (section 4.4.8 on moratoria), which might also apply to large-scale research.

3.4.5. Insufficient interdisciplinary and international research causing a risk to governance cooperation versus risk of ‘slippery slope’

Early research integrating transdisciplinary knowledge regarding potential implications of CDR and SRM across societal objectives has shown that the inclusion of a diversity of perspectives, in terms of geography, gender, academic disciplines and non-academic expertise is necessary[34]. Political institutions and funding agencies should dedicate specific resources to interdisciplinary and international research programmes. Academics recognize the value of integrating various types of knowledge, which can help identify blind spots in our understanding and produce feedback into the process of scientific inquiry. However, academia needs support to develop such programmes. There is currently a risk that, in the absence of serious efforts to conduct transdisciplinary research, a shared understanding across scientific disciplines, as well as ethical,

---

[33] The Stratospheric Controlled Perturbation Experiment (SCoPEx) planned by Prof. Keutsch’s research group at Harvard is dedicated to studying the interaction of various particles with one another, with the background stratospheric air, and with solar and infrared radiation, which per the project website involves dispersal of ice, calcium carbonate (less than 2kg) and at later stages potentially sulfates. The physical properties of the planned experiments suggest no significant transboundary effects. Due to the heightened public interest in any physical research into potential SRM schemes, the research team sought external advice and guidance, which has resulted in an independent advisory committee the members and terms of which can be found on the project website: https://projects.iq.harvard.edu/keutschgroup/scopex-governance.

[34] The 17 Sustainable Development Goals are an example for an encompassing set of societal goals, which can help structure work that seeks to assess CDR or SRM in a manner that fully integrates diverse physical and social aspects (see Honegger et al., 2018).

cultural, and political dimensions will be missing. This has implications for governance, as outlined in section 3.3.

Insufficient capacity to synthesize scientific insights across disciplines can also result in further entrenchment of pre-existing judgments and viewpoints (Thiele, 2019). A dominance of divisive discourses would give further fuel to divisive politics. Confrontational politics fueled by an absence of a shared scientific understanding would furthermore risk being dominated by attention-grabbing sensationalist media portrayals as well as divisive communication strategies. Such communication strategies frequently sidestep nuanced and careful discussion. Without acknowledging scientific uncertainty and the interconnected nature of issues associated with CDR and SRM, broad-based deliberation is rendered much harder, if not impossible. In such a divisive scenario, overly narrow technocratic perspectives of western elites might end up clashing with other perspectives – rather than allowing detail-oriented technical expertise and more holistic perspectives to complement one another in an integrative manner.

In contrast, there is a fear that dedicating any resources to studying CDR or SRM would result in what has been termed a 'slippery slope' to their application. In the case of CDR the considerations described in sections 3.2.1 and 3.4.2 regarding the desirability of further research and policy attention toward CDR apply. For SRM the concern hinges on the two assumptions that 1. Research will lead to deployment independent of research findings; 2. That deployment of SRM would never be democratically desired (Callies, 2018). Any transdisciplinary research efforts seeking to reduce ignorance and strengthen international cooperation should be mindful of the 'slippery slope' concern and ensure findings are not presented in policy-prescriptive terms.

3.4.6. Risk of uneven research capacities fueling unfair power differentials

As long as research on CDR and/or SRM only advances in a small number of countries, the risk that some countries lag behind, lack appropriate expertise, and, therefore, might not be able to make informed decisions, should be given due consideration. Scientific expertise influences the decision-making capacity of a country, and a deficit in locally rooted research into geography-specific or culturally-specific implications of CDR or SRM in various countries or regions can also cause decision-makers to overlook crucial implications of specific designs of policy instruments and governance. This may result in sub-optimal outcomes for such regions that lack appropriate expertise. Where research can be seen as an act of upstream governance leading to important decisions with global implications – as is the case for most of the research into SRM as well as for some research on CDR with cross-boundary implications – it is crucial to strengthen research capacities of countries in the global south. Global governance will require a more equitable global ecosystem of research and expertise to be robust in the long term (Rahman et al., 2018).

There is an additional risk that countries with limited resources for research and development of CDR (thus lacking an ecosystem of experts and practitioners) miss out on opportunities for funding CDR activities if and when international climate finance or carbon market mechanisms include such project types. The Clean Development Mechanism revealed that policy instrument design needed to be mindful of the challenges accessing such support structures. Already at the stage of research and development, as well as at later stages, dedicated projects and mechanisms could seek to strengthen the capacities of institutions in developing countries to pursue CDR in ways that are desirable and appropriate to the local circumstances.

Textbox 8 – Small collaborative North-South research projects could trigger knock-on capacity-building effects

Even at a small scale, North-South research collaboration could be an important first step toward ensuring that all countries have a voice in scientific research and assessments of CDR and SRM (thus strengthening plurality of value-systems, voices and experiences co-shaping a shared understanding of the governance challenges posed by CDR and SRM). Presently, many countries might not have the resources to conduct research into these emerging issues, and by consequence, are not building up expertise to adequately address these emerging topics in the context of assessments or governance. A stepwise approach to strengthening voices of the global south could first involve small research grants for consortia in which two research groups partner up – one in the funding country and another in a country of the global south – to conduct research into region-specific implications of CDR or SRM. Such partnerships would prove successful if they result in mutual learning, strengthening expertise in both countries and enabling (young) researchers particularly from countries in the global south to have an increasingly important voice in the international academic realm – by publishing research and attending international conferences[35]. Other countries could follow-suit upon seeing such bottom-up initiatives successfully strengthening the global academic conversation on CDR and SRM. The resulting expertise rooted in various cultural and geographical contexts could then also increasingly offer opportunities for funding and conducting regional assessments by various national academies of science (or regional umbrella organizations). Such efforts would allow that the global conversation on governance – based on the best available science – can rely on a diverse set of expertise and regionally-rooted assessments (rather than being merely based on the judgments of western academic elites).

3.4.7. Suggested measures in the realm of research, research funding, and research governance

To address the risks mentioned above and trade-offs in the context of research into CDR and SRM, a few concrete steps could be pursued simultaneously with a long-term perspective, including encouraging more diverse, transdisciplinary research, supporting the international exchange of expertise, enabling continuous science-policy conversations, and conducting research to provide insights relevant to the full set of objectives covered by the SDGs[36].

Encouraging more transdisciplinary research efforts to systematically explore interdependent benefits and risks of CDR and SRM under specific scenarios of application. Involving individuals spanning greater diversity of perspectives – across geographies, gender, academic disciplines and applied expertise, would allow broadening, in addition to deepening – the basis of understanding on which political choices may ultimately be founded.

Encouraging the international exchange of scientific and policy expertise and knowledge by, for example, funding contributions from experts from the global south in other countries, funding research projects coordinated by experts from the global south, or supporting other ways that can help strengthen mutual learning across cultural and geography-dependent contexts. This could matter in particular for the design and assessment of various CDR or SRM interventions, and their respective social, cultural, environmental, economic, and political implications.

Enabling continuous science-policy conversations, both domestically and abroad. For example, working under the auspices of relevant UN agencies can help researchers better understand decision-making processes and thereby identify how their work can help strengthen governance. On the other hand, policy-makers can better explore multi-faceted trade-offs, intricacies, and uncertainties associated with potential applications of CDR or SRM when they are in direct interaction with experts. Such exchanges would appear most important when novel categories of action overlap with novel governance contexts, as would be the case for large-scale applications of CDR or SRM applications with potentially global implications.

---

[35] The DECIMALS fund, co-hosted by the World Academy of Sciences (under the umbrella of UNESCO) and the Solar Radiation Management Governance Initiative has funded researchers in Argentina, Bangladesh, Benin, Indonesia, Iran, Ivory Coast, Jamaica, and South Africa.

[36] Some early attempts to map out potential implications of CDR and SRM for the pursuit of the SDGs have revealed further research questions and significant potential to further deepen and widen assessments via broad-based, international, inter- or transdisciplinary research projects and assessment initiatives (Honegger et al., 2018; Smith et al., 2019)

Conducting research to provide insights relevant to the full set of objectives covered by the SDGs would allow identifying, studying, and communicating multi-faceted interdependencies in potential applications of CDR or SRM, in a way that focuses on a set of objectives which the international community has agreed to prioritize. The nature of the 17 SDGs furthermore broadens analysis to explore not only physical implications, but also cultural, moral, institutional, and legal aspects as well as issues regarding global cooperation and partnerships.

3.5. Conclusion on addressing risks and trade-offs

CDR or SRM applications, as well as potential measures to advance their governance, are characterized by risks and trade-offs across material and non-material dimensions.

CDR as a category of climate action is associated with the global (target) risk of climate change and insufficient mitigation, but the implementation of CDR is at the same time burdened with countervailing local costs and risks. The latter stem from potential local or regional resource conflicts, which could arise should CDR be pursued at large scales. Their occurrence strongly depends on the interaction of policy design, application scale, and local governance capacities. Adverse outcomes can variously be minimized through robust national policy planning processes, international best-practice exchanges, guidance, and institutional funding criteria, while co-benefits can be fostered through the same means. In the case of very large applications, there might be a possibility of future transboundary effects, which might require further cooperation to avoid conflicts. The governance challenges posed by CDR resemble the challenges posed by GHG emissions reductions, insofar that both are characterized by misalignment of incentives (local costs and global benefits) and the resulting problem of underprovision.

SRM might in the long term pose the contrary governance challenge (overprovision) insofar both the target-risk and countervailing risks tend to be global as most SRM interventions are globally effective by design and the costs to deployment are low relative to the potential gains once climate change becomes an extreme or even existential threat to some. The physical attenuation of climate change across most climate parameters as well as the occurrence of any unwanted effects fundamentally depend on intervention design. Understanding of effectiveness and risks is to date, however, grossly insufficient for considering SRM application an appropriate policy option in the short term. Uncoordinated application needs to be prevented in the long term also, due to its potential for harm and political conflict. However, reliably preventing uncoordinated SRM application likely requires reaching a globally shared understanding of the high stakes involved in decisions targeting SRM. Global governance of SRM is thus characterized by a need to prevent premature and uncoordinated deployment while ensuring that learning takes place on both the potential of SRM to reduce climate risks as well as on the associated countervailing risks.

Attempts to strengthen cooperative global governance need to account for and variously anticipate growing target-risk (climate change) and various possibilities to address countervailing risks. A shared understanding of interdependent risks and trade-offs associated with CDR and SRM may be fostered by supporting dedicated transdisciplinary efforts involving and supporting diverse sets of individuals with diversity in geography, gender, academic disciplines as well as political expertise in various related policy areas. Such efforts could be oriented towards the full set of objectives included in the SDGs in order to generate insights of relevance to agreed-upon societal objectives and to ensure that analysis integrates material (physical) and non-material dimensions.

Chapter 4 | Elements and steps for global governance

by Jesse Reynolds[1]

Abstract

This chapter evaluates options and approaches for future regimes on the international governance of climate engineering, that is, carbon dioxide removal (CDR) and solar radiation modification (SRM). Based on the previous chapters, it offers explicit criteria for the assessment of governance options. Possible governance sites – including but not limited to intergovernmental institutions – are then considered. The chapter then reviews a wide range of potential substantive options for governance. The author offers six specific recommendations: to distinguish between CDR and SRM as well as among the diverse CDR techniques; to undertake authoritative, comprehensive, and international scientific assessment; to encourage the research, development, and responsible use of some CDR techniques; to help build capacity for evaluating CDR and SRM in countries that lack the resources; to facilitate the elaboration and implementation of non-state governance; and to begin international processes that explore potential governance of SRM while remaining agnostic concerning its ultimate use.

[1] Emmett / Frankel Fellow in Environmental Law and Policy, Emmett Institute on Climate Change and the Environment, School of Law, University of California Los Angeles, USA

4.1. Introduction

There is a widespread consensus that decision-making regarding climate engineering – that is, carbon dioxide removal (CDR) and solar radiation modification (SRM) – would benefit from additional, dedicated governance. This chapter evaluates possible options and approaches for potential future regimes for the international governance of climate engineering. It focuses on steps that national governments can take in this direction.

What should such governance do? A few general objectives can be suggested. First, it should lessen the risks and negative impacts of climate change and the responses to it. Second, governance should be consistent with widely shared values. In particular, those who are affected by decisions should have the opportunity to appropriately participate in making them. Third, if and when CDR or SRM are used, governance should ensure that they complement greenhouse gas (GHG) emissions reductions and other responses to climate change and that they do not increase international tensions. The suggestions in the previous chapter offer somewhat more detailed prescriptions.

Any further international governance of CDR and SRM will arise in the existing international legal and political order. The absence of a centralized global lawmaker means that international governance is only weakly coordinated, with overlaps and gaps among mechanisms' objectives and institutions' scopes. In order to provide relevant knowledge, science-based guidance, and venues for effective and legitimate decision-making, new governance must consequently leverage positive aspects and attenuate negative ones of the multi-layered, polycentric global order. Moreover, the absence of a centralized global enforcer of international law means that it is (for the most part) binding only through states' consent. Any proposal must offer apparent net gains for those states that are expected to participate.

Climate change and the responses to it are intergenerational phenomena, and developing international governance of CDR and SRM – especially their large-scale use – will be a multidecadal and uncertain process. Nevertheless, meaningful steps can be taken soon to lay a foundation for this. Furthermore, some shorter-term actions with respect to international governance – including of CDR's and SRM's research – could be directly beneficial. This chapter considers options and approaches that could be pursued in a few years, while bearing longer-term governance objectives and processes in mind.

The next section offers some explicit criteria to assess governance options and approaches. The two thereafter lay out options along two dimensions: where in the international policy landscape such governance could arise, and what its substantive content could be. The final section recommends specific shorter-term actions that states should take to help develop international governance of CDR and SRM.

4.2. Assessment criteria of governance options

In order to structure the discussion on options and approaches for potential future international governance for CDR and SRM, explicit criteria are helpful. Building on the previous chapters, six functional criteria are offered here with the caveat that they do not constitute a definitive list. All but the final one are guided by agreements and statements which many countries have endorsed. Importantly, multiple criteria imply that trade-offs among them will be necessary (see chapter 3). Furthermore, the criteria must be considered in long, intergenerational timescales, even when assessing shorter-term governance. This is because certain governance arrangements could satisfy the criteria at one point in time while later working contrary to them.

4.2.1. Reducing climate change and its impacts

The prevention and lessening of climate change have been a widely shared international goal for almost thirty years. The objective of the 1992 UN Framework Convention on Climate Change (UNFCCC) is, in part, the 'stabilization of greenhouse gas concentrations in the atmosphere at a level that would *prevent dangerous anthropogenic interference with the climate system*' (Article 2, emphasis added). Likewise, one of the Paris Agreement's goals is to limit warming to 2°C and to pursue efforts to limit it to 1.5°C, implicitly to 'reduce the risks and impacts of climate change' (Article 2.1(a)). And among the Sustainable Development Goals (SDGs) is to 'Take urgent action to combat climate change and its impacts' (United Nations General Assembly, 2015, goal 13), while limiting climate change is a central element in the pursuit of the other SDGs (Nerini et al., 2019).

Consequently, and as noted elsewhere in this report, one criterion for the international governance of CDR and SRM is the potential of the various technologies to reduce climate change and its impacts. Both CDR and SRM could help achieve this goal (chapter 1). This is clearer with the former (IPCC, 2018, p. 17), as safe, reliable, and affordable removal of carbon dioxide (CO_2) would have essentially the same net effects as carbon dioxide emissions reduction on the gas's atmospheric concentration and on climate change. Moreover, CDR is necessary to stay within the Paris Agreement's temperature-based global warming goal. Some SRM technologies appear able to lower climate change impacts (e.g., IPCC, 2018, p. 350; Irvine & Keith, 2020) but this would be imperfect and the evidence for it is less certain. Furthermore, SRM would not address the underlying causes of climate change but instead only its physical manifestations, although the extent to which policy must tackle the former – possibly at the expense of the latter – is unresolved.

The various responses to climate change have distinct characteristics. Emissions reductions are required to lessen climate change in the long term, but can only slow the increase in atmospheric GHG concentrations, not lower them. CDR can reduce net emissions, even making them net negative and thus lowering the concentrations. If atmospheric GHG concentrations become high enough to cause dangerous climate change – as probable future scenarios suggest – then SRM may be able to lower the rate and/or peak of climate change. We must also adapt our societies and, to the limited degree to which it is possible, the planet's ecosystems to a changing climate. What remains will be climate change impacts. In this way, and as already indicated in chapter 3, these various responses can be complementary and, ideally, would constitute a coherent portfolio (see Figure 6).

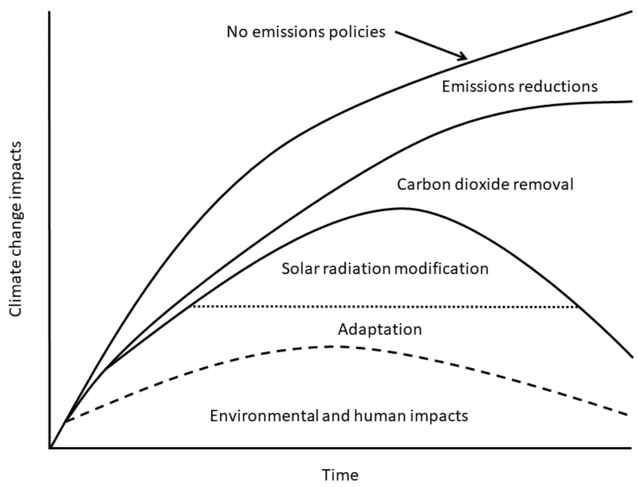


Figure 6 – Concept of an idealized portfolio of complementary responses to climate change. Originally developed by John Shepherd (Long and Shepherd, 2014, p. 765).

Furthermore, these responses to climate change also help manage uncertain risks. That is, climate change impacts might be more or less severe than expected, and the responses to it might be more or less effective or acceptable. In this context, a given response option could fill an unexpected but important 'gap' in the others' reductions of risk.

4.2.2. Contributing to sustainable development

Currently, the relevant overarching normative framework for international cooperation with respect to the environment and related issues is sustainable development. In the UN's 2030 Agenda for Sustainable Development, among the SDGs are ending poverty and hunger, expanding good health and well-being, sustainably using the oceans, and protecting terrestrial ecosystems (UN General Assembly, 2015, goals 1, 2, 3, 14, and 15).

On the one hand, CDR and SRM appear able to decrease climate change and its impacts, consequently helping enable sustainable development. On the other hand, they pose diverse physical risks and social challenges of their own, and their relationship with the SDGs is complicated and nuanced (Honegger et al., 2018). This is evident in chapter 3's assessment of physical trade-offs, synergies, and risks. Therefore, the international governance of CDR and SRM should not only strive to reduce climate change impacts, but be able to balance this with other environmental, economic, and social objectives, captured in the SDGs and elsewhere. This will require the capacity to generate and synthesize useful knowledge, to identify and bring together affected interests and other stakeholders, to enable CDR and SRM as appropriate, and to regulate and limit their potential negative physical and social impacts.

4.2.3. Supporting greenhouse gas emissions reductions

Many countries have committed to reducing GHG emissions as part of a long-term objective of achieving net-zero emissions. Not only are such reductions the leading means to combat climate change, but they also arguably constitute an independent objective. For example, in the Paris Agreement, parties aim to reach global peaking of GHG emissions as soon as possible (Article 4.1), while adaption and finance flows are to foster low emissions development (Article 2.1(b-c)).

Yet a widespread concern is that the consideration, research, and development of CDR and SRM would displace emissions reductions (as discussed in section 3.4.2 and 3.4.3). Although emissions reductions and CDR would have the same net effects on atmospheric GHG concentrations and climate change, the former remains essential, whereas the latter's various technologies are still somewhat uncertain.

The international governance of CDR and SRM should thus be able to support continued and strengthened GHG emissions reduction. Furthermore, developed countries should continue to take the lead in reducing emissions (Paris Agreement, Article 4.4) in line with the principles of equity, and of common but differentiated responsibilities and respective capabilities (Paris Agreement, Article 2.2).

4.2.4. Establishing and maintaining legitimacy

The expectation that governance be legitimate is almost universal. As such, the international governance of CDR and SRM should be perceived as legitimate, broadly conceived. Central to this is the fact that many states could be affected, especially in the case of SRM. At the least, this means that governance should be consistent with international law and other widely shared norms, including respect for human rights and democracy (e.g. Swiss Constitution of 1999, Article 54(2)). Along these lines, the UN Commission on Human Rights 'Calls upon States to provide transparent, responsible, accountable and participatory government, responsive to the needs and aspirations of the people' (United Nations Commission on Human Rights, 2000, paragraph 1). Legitimacy also requires trust, particularly among those whom the governance does or could affect. Establishing, building, and maintaining trust is commonly a resource-intensive process in which inclusion, communication, and assurance are key.

A long-standing challenge – notably for global governance – is that legitimacy's characteristics, sources and standards are unclear and not universally agreed upon. At a general level, one way to conceive of it is having three primary forms (Schmidt, 2013). *Input legitimacy* requires that the governed have the opportunity to participate meaningfully in decision-making (that is, legitimacy through inclusiveness)[2]. In turn, governance should be responsive to the concerns of the governed and other stakeholders. This points toward the inclusion of the many potentially affected interests, appropriate assurances, and trust. Given that especially SRM could affect the entire globe, input legitimacy implies that diverse global representatives of many states – if not all of them – should be able to participate in decision-making. *Output legitimacy* is, more or less, dependent on governance's effectiveness, which calls for efficiency as well as bringing together and building expertise. And *throughput legitimacy* depends on whether procedures are fair, accessible, and open.

4.2.5. Fostering peaceful and stable international relations

International governance of CDR and SRM will be developed in an existing landscape of states, intergovernmental institutions, and important non-state actors. It could consequently have impacts on multiple political dynamics and objectives – such as the peaceful coexistence of nations (Charter of the United Nations, Article 1) – that precede and extend beyond sustainable development. As seen in chapters 1 and 3, many CDR and SRM technologies could have transboundary impacts, both positive and negative. Furthermore, SRM could, at least in theory, be implemented by one or a few states or maybe even non-state actors, affecting many countries and perhaps independently of any international consensus. As a first approximation, positive impacts would facilitate peaceful international relations while negative ones could create or amplify tensions. Even in the absence of negative impacts, some states might perceive themselves to have been harmed or to have been excluded from important decision-making. A particularly important dimension in the context of climate change and of CDR and SRM specifically is the relationships between developed and developing countries.

The international governance of CDR and SRM should not exacerbate international tensions that could arise, for example, from some states acting in ways that (are perceived to) harm others. Moreover, if possible, it should aim to improve international relations among them through transboundary capacity building, collaboration, and cooperation.

4.2.6. Reflecting current knowledge and adapting to changing conditions

To a large degree, SRM and CDR are technically complex, with relevant knowledge unevenly distributed and often difficult to synthesize. Yet decisions, including regarding governance, must be made. What's more, governance, especially that which is legal in character and international in scale, is generally slow to change whereas emerging technologies often develop rapidly. This presents a challenge in keeping it aligned with fast-evolving issues. Moreover, emerging technologies can be characterized by uncertainty or ambiguity. Governance that can anticipate, adapt, and keep 'connected' to the target phenomena is important when conditions change and new knowledge is generated (Marchant et al., 2011). In such cases, governance should learn from experience and update over time (IRGC, 2016).

This is particularly important for CDR and SRM, for which significant uncertainty persists, including concerning their capacities, their opportunities, their risks, associated social preferences, and future climate change. The international governance of these technologies should be able to integrate useful knowledge, monitor relevant consequences, respond to feedback, anticipate change, and adapt to evolving conditions and new information.

[22] More suggestions relative to inclusive governance were given in section 3.3.1, as well as in section 3.4.5 on knowledge generation that would serves as a basis for legitimate governance.

4.3. Options for sites of international governance

This section considers possible sites of the development and/or implementation of international governance of CDR and SRM. It builds on chapter 2, which reviews existing international legal and institutional arrangements. The analysis is based on aspects such as core competence, expertise, function, how 'political' or 'scientific' the institution is, and the decision-making process. Because most – but not all – new international governance develops from an existing international institution that is associated with a multilateral agreement, these offer the primary way of organizing this section.

4.3.1. UN Framework Convention on Climate Change

CDR and SRM are matters first of climate change, as their intended and primary effects would be climatic. The central vehicle for international governance of climate change is the climate change regime, whose three treaties – UNFCCC, the Kyoto Protocol, and the Paris Agreement – are furthered by a Secretariat, Subsidiary Bodies for Implementation (SBI) and for Scientific and Technological Advice (SBSTA), and annual Conferences of Parties (COPs).

Numerous scholars and other observers have suggested the climate change regime as a site for the international governance of CDR and SRM (e.g. Rickels et al., 2011; Zürn and Schäfer, 2013). It has substantial widespread participation, legitimacy, and expertise. Furthermore, the regime's institutions are already aimed toward proactively reducing climate change and its impacts in the context of sustainable development. Governing CDR and SRM there could integrate the technologies with other responses to climate change, which could help keep decreasing GHG emissions as the top priority. Finally, the consideration and governance of international efforts to reduce climate change within a single site could be more effective (although this might also run risks of institutional capture). Ultimately, it is difficult to imagine the international governance of CDR and SRM without the climate change regime having a central role.

The UNFCCC already has a mandate to govern CDR, or at least some technologies thereof. It falls within the foundational agreement's objective of stabilizing atmospheric GHG concentrations (UNFCCC Article 2) and parties' obligations to enhance sinks and reservoirs of GHGs (UNFCCC Article 4.1(d); Paris Agreement 5.1; see Honegger et al., 2019) as part of mitigating climate change (UNFCCC Article 4.2(a)). As such, the UNFCCC agreements' obligations and incentives to reduce net emissions; its methods for measuring, reporting, verifying, and communicating emissions; and its provisions regarding technology transfer, capacity building, and climate finance could all encompass CDR. In addition, the COPs, SBSTA, and other bodies have helped clarify how to incorporate some CDR techniques, particularly nature-based approaches, into the regime's regulatory architecture through mechanisms such as those for land use, land-use change, and forestry (LULUCF).

Despite the climate change regime's emphasis on emissions reductions, it could also contribute to the governance of SRM. Although the UNFCCC's objective of stabilizing atmospheric GHG concentrations (UNFCCC Article 2) does not clearly include SRM, it could be interpreted as doing so. First, the objective offers characteristics of the stabilized concentrations' level and speed of its stabilization. If effective, SRM could increase both the acceptable GHG concentrations that would not dangerously interfere with the climate system and the amount of time available for this stabilization. Second, models indicate that SRM would indirectly reduce atmospheric GHG concentrations through preventing some carbon releases (greater ecosystem respiration, lower primary productivity, and lower oceanic uptake) that warming would cause (Keith et al., 2017). Third, the UNFCCC's scope could be interpreted liberally, focusing on its calls to protect the climate system (UNFCCC Articles 3.1, 3.4). Fourth, SRM could help keep global warming within the Paris Agreement's temperature goals. Finally, an amendment or protocol could broaden the UNFCCC's objective.

However, a serious challenge to governing SRM through the UNFCCC is political. Negotiations there, such as those at the COPs, are often polarized and protracted. This may be due to the important issues that climate change implicates, such as economic growth and development; to insufficient international trust; and to the issues' complexity. Regardless, adding SRM into this environment may be disruptive and divisive, especially in the near term with significant scientific and normative uncertainty. Broaching the topic in the UNFCCC system might do more harm than good, at least in the short term.

4.3.2. Intergovernmental Panel on Climate Change

The Intergovernmental Panel on Climate Change (IPCC) has the mandate to comprehensively assess

> *The state of knowledge of the science of climate and climatic change; … Possible response strategies to delay, limit or mitigate the impact of adverse climate change; The identification and possible strengthening of relevant existing international legal instruments having a bearing on climate… (UN General Assembly, 1988; see also IPCC, 2013).*

Governed by representatives of its 195 member countries, its leading vehicles have been major Assessment Reports produced by international teams of hundreds of experts and occasional, more focused Special Reports, both of which have considered CDR and SRM. These are widely considered to be authoritative, informing international and national decision-making concerning climate change, sustainability, and more. The contributing scientists clearly have relevant expertise to assess CDR – such as how to report for removals in emissions inventories – and SRM – such as through modeling and understanding interactions among Earth systems. In fact, the IPCC held an 'expert meeting on geoengineering' in 2012. And as with the climate change regime, having the scientific assessment of CDR and SRM would likely be more effective within the IPCC, as doing so would capitalize on existing knowledge and relationships in the relevant epistemic communities. On the other hand, the organization's scope is limited to climate change and could thus fall short in assessing other salient aspects of CDR and SRM, such as effects on biodiversity and agriculture. Also, because it aims to be neutral with respect to policy, the IPCC can contribute to but not take the lead in governance.

4.3.3. Convention on Biological Diversity

Among the risks of climate change, those to biodiversity are among the most severe, and adapting ecosystems and threatened species to climate change is difficult. Furthermore, SRM and some CDR techniques could have significant impacts on biodiversity of their own. The Convention on Biological Diversity (CBD) is the leading international legal site for the conservation of biodiversity. Like the UNFCCC, the central framework treaty enjoys widespread ratification, with the notable exception of the US, and a Secretariat, annual COPs, and other supportive bodies, and its objectives and commitments are in the context of economic and social development and poverty eradication (CBD Preamble recital 19; Article 20.4). The CBD COP is the only forum where representatives of (nearly) all countries negotiated and approved decisions concerning CDR and SRM (see chapter 2). As such, the biodiversity regime is well-positioned to legitimately contribute to the international governance of CDR and SRM (Bodle *et al.,* 2014, p.22).

However, the biodiversity regime is limited as a site for developing the international governance of CDR and SRM. For one thing, the agreements do not focus on climate change, and its governance would largely be limited to impacts on biodiversity. Of course, biodiversity will be substantially affected by climate change and the CBD bodies regularly address it through, for example, COP decisions. In addition, the US – which is presently a leading location of the research and development of CDR and SRM – is not a party to the CBD.

4.3.4. Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services

Modelled on the IPCC, the relatively new Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) aims to 'strengthen the science-policy interface for biodiversity and ecosystem services for the conservation and sustainable use of biodiversity, long-term human well-being and sustainable development' (IPBES, 2020). That is, it is an assessment body, not a regulating one. And like the CBD, one limitation is the IPBES's focus on biodiversity, not on climate change. Nonetheless, it could complement the IPCC in exploring issues of the conservation of biodiversity related to CDR and SRM impacts.

4.3.5. United Nations Environment Programme

The UN Environment Programme (UNEP, recently rebranded as UN Environment) is 'the leading global environmental authority that sets the global environmental agenda, promotes the coherent implementation of the environmental dimension of sustainable development within the United Nations system and serves as an authoritative advocate for the global environment' (United Nations General Assembly, 2012). Its original mandate includes promoting international cooperation, providing policy guidance for the UN system, reviewing the impact and implementation of policies and programs, monitoring environmental conditions in order to ensure that salient issues are considered, and promoting relevant scientific knowledge and information (United Nations General Assembly, 1972). Among international organizations, UNEP is able to consider the full range of environmental issues and relevant sectors. It also plays an important role in the identification of emerging issues and in the development and implementation of multilateral environmental agreements and institutions, including the UNFCCC, IPCC, CBD, and IPBES. In its work, scientific knowledge is essential for evidence-based guidance for policy. Besides having the capacity to identify issues through scientific review, promote and catalyze the development of policy, and provide a foundation for action, UNEP is arguably less politicized than other forums such as the UNFCCC and CBD institutions. It also has ongoing activities that are pertinent to international governance of CDR and SRM, such as the regular publication of pertinent reports, among which are the *Emissions Gap*, the *Global Environment Outlook*, and *Frontiers* (emerging issues of environmental concern).

In 2019, the UN Environment Assembly (UNEA) discussed (but did not submit to vote) a Swiss-submitted resolution that, substantively, would have created an expert committee to assess proposed technologies and existing governance of 'geoengineering'. The primary reasons that the resolution failed to gather sufficiently wide support appear to be (1) its joint consideration of CDR and SRM, particularly regarding CDR's implied potential global risks and adverse impacts; (2) its inclusion of the current state of the science and knowledge of potential impacts, which some perceived as conflicting with the IPCC's mandate; (3) its possible reference to precaution; and (4) its consideration of potential global governance frameworks.

4.3.6. World Meteorological Organization

The World Meteorological Organization (WMO) is the UN body that provides leadership and expertise in international cooperation concerning weather, climate and related sciences. It has long been involved in climate change, such as helping establish and formally hosting the IPCC. Furthermore, for decades it has worked on weather modification, which is related to SRM. Its Expert Team on Weather Modification Research provides a hub for encouraging research and promoting best practices. Its Commission for Atmospheric Sciences has investigated 'geoengineering' (WMO, 2016), and some WMO members have expressed interest in 'developing a science-based assessment on climate engineering, specify [*sic*] the gaps in scientific understanding and promote specific research activities to fill such gaps' (WMO, 2015). Together, this suggests that the WMO holds relevant expertise and capacity to contribute to the international research of, monitoring of, and guidelines for SRM.

4.3.7. International maritime law and institutions

State and non-state actors' actions on, in, above, and affecting the seas are governed through several international bodies and multilateral agreements. Supported by various expert bodies, these have the capacity and legitimacy to govern marine-related CDR and SRM.

The International Maritime Organization (IMO) is the UN agency responsible for facilitating international cooperation concerning states' 'regulation and practices relating to technical matters of all kinds affecting shipping engaged in international trade [and the] maritime safety, efficiency of navigation and prevention and control of marine pollution' (Convention on the IMO, Article 1). The IMO supports the implementation of several multilateral agreements.

One of these is the UN Convention on the Law of the Sea (UNCLOS), which provides for states' rights and obligations in and regarding the seas. As described in chapter 2, several of its provisions would apply to CDR and SRM activities. In fact, because its definition of 'pollution' could encompass GHGs, climate change, and some forms of CDR and SRM, and because UNCLOS parties are to prevent, reduce, and control pollution of the marine environment from all sources, the treaty could apply to a wide range of CDR and SRM practices – not only those that occur at sea.

The London Convention and London Protocol are a pair of multilateral agreements that regulate pollution caused by dumping or incineration at sea. In 2013, the parties to the London Protocol – whose broader objective covers the protection and preservation of the marine environment from all sources of pollution – approved an amendment to govern 'marine geoengineering' in general (see chapter 2). However, because few states have ratified it, the amendment has not come into force. More generally, these agreements' modest degree of participation and relatively narrow scope would make them poor sites of governance of CDR and SRM other than those techniques that involve placement of matter into the seas.

4.3.8. United Nations

The United Nations (UN) is the central site of global cooperation. Its General Assembly (UNGA) consists of representatives of all widely recognized countries and can address almost any matter of international relations, implicitly including international governance of CDR and SRM. Although UNGA's decisions are not binding under international law, they are influential given the body's widely perceived legitimacy. Yet it is arguably among the most politicized of international forums and may be inappropriate for scientific and technical matters such as the governance of SRM and CDR, at least beyond general statements.

The UN Secretariat is the UN's executive branch. It is dedicating attention to, among other things, emerging technologies. Its head, the Secretary-General, recently developed a Strategy on New Technologies to help them contribute to fulfilling the SDGs and the UN mission more generally (UN Secretary-General, 2018). This includes commitments to increase the UN's engagement with the intersection of technologies and sustainable development. The Secretariat's Department of Economic and Social Affairs followed up with a project on frontier technologies for sustainable development (Department of Economic and Social Affairs, 2018). Both of these endeavors could address CDR and/or SRM.

Outside of the secretariat, the Environment Management Group (EMG) coordinates activities regarding the environment and human settlements across the many UN bodies. This role could be important in the governance of CDR and SRM, which implicates multiple international agreements and bodies. The EMG considered placing 'climate-altering technologies and measures' on the agenda of its most recent Senior Officials Meeting, but ultimately did not do so.

4.3.9. Other intergovernmental institutions

Several other specialized intergovernmental organizations will be relevant to the international governance of CDR and SRM. Among these are the UN Commission for Sustainable Development, the UN Educational, Scientific and Cultural Organization, the Food and Agricultural Organization (FAO), the International Civil Aviation Organization, the Executive Body of the Convention on Long-Range Transboundary Air Pollution, the regime for the protection of the ozone layer, the UN Commission on the Peaceful Uses of Outer Space, and the International Organization for Standardization. Although they may eventually have important roles to play, they offer neither initial nor central sites for the international governance of CDR or SRM.

4.3.10. De novo international process

As somewhat novel phenomena, CDR and SRM could be governed through a new mechanism or institution. Forums or bodies are sometimes created, often by one or more existing ones, to govern actors and actions across an emerging issue, especially if extant arrangements lack a clear institutional site with sufficient scope, expertise, and legitimacy to do so. For example, among the institutions discussed here, the newest is IPBES. It grew out of UNEP discussions, which were in turn endorsed by the UNGA.

A new forum or institution can include many states as well as other intergovernmental bodies, or only those states that are willing and able to act in a contested domain. The latter path may be pursued if consensus is not attainable, perhaps because a small number of recalcitrant states are impeding action. A potential barrier with this approach can be insufficient legitimacy and the associated international political consequences. On the other hand, a body with fewer members can be more dynamic and adaptive.

4.3.11. Decentralized governance

Finally, international governance can be decentralized. For example, a report of Germany's Federal Environment Agency (*Umweltbundesamt*) states that 'It is not self-evident that a governance framework for all geoengineering technologies is needed at the *international* level. For instance, there are land-based geoengineering concepts that are unlikely to have a transboundary impact, and that could be addressed at national (or EU) level with no or minimal international guidance' (Bodle et al., 2014, p. 126, emphasis in original). One means of decentralized, international (in one sense of the word) governance would be the coordination of national policies through less formal channels and horizontal peer networks.

Another means would be for states to encourage the development, elaboration, and operationalization of non-state governance. Although a handful of general principles have been developed for CDR and SRM, the most prominent of which have been the Oxford Principles (Rayner et al., 2013), these have been only weakly operationalized. Such decentralized international governance can be advantageous when states are reluctant to act, lay the groundwork for future national and international processes, and offer greater adaptiveness in the face of changing circumstances, growing knowledge, and emerging risks and challenges (Reynolds and Parson, 2020). It has been relatively successful in contested environmental domains, as evident in the Forest Stewardship Council and Marine Stewardship Council. Sometimes, non-state governance is later assumed, in diverse ways, by state actors. For example, human reproductive and genetic technologies are strongly contested. In this case, governance began with professional society's guidelines and some national regulation, expanded to joint statements by leading national academies of science, and has now been taken up by the World Health Organization. However, non-state governance may be less effective and perceived as less legitimate. Despite its non-state nature, authoritative action may be necessary to elaborate norms, catalyze bottom-up implementation, and offer focal points.

4.4. Range of potential substantive options for international governance

This section considers the substance of options for international governance of CDR and SRM. The intention here is to consider a wide range of possibilities. These incorporate the suggestions from chapter 3, as appropriate.

4.4.1. Facilitate research

CDR at substantial scales will be necessary to keep global warming within the Paris Agreement's goals, and SRM may later also be justified to limit climate change impacts. But much uncertainty remains, some of which could be resolved through research. Consistent with the objective of reducing climate change and its impacts, international governance could facilitate the effective and responsible research and development of CDR and SRM. Specifically, it could ensure that the technologies' capabilities, limitations, requirements, secondary effects, physical risks, and social challenges are understood well enough to support informed decision-making (see Grieger et al., 2019). Along these lines, the Swiss Academies of Arts and Sciences concludes, 'More research on CDR and SRM is therefore indispensable so that the corresponding costs, risks and side effects are known in the case of specific application projects' (Swiss Academies of Arts and Sciences, 2018, p. 4).

Research should align with policy goals and constraints. To do so, it should not be limited to the natural sciences and engineering but instead be multi-, inter-, and transdisciplinary. In this regard, the most recent decision on 'climate-related geoengineering' by the CBD COP (see above) calls for 'more transdisciplinary research and sharing of knowledge among appropriate institutions' (CBD/COP/DEC/XIII/14.5). In particular, research should encompass continued modeling of climatic and other physical processes, potential negative secondary effects, responsible outdoor experiments, delivery means and equipment testing, trade-offs with the SDGs and other goals, public opinion assessments and stakeholder engagement, and social challenges. Scientific research of the various CDR techniques – although diverse – can generally orient toward their capacity to scale up and safely sequester carbon, whereas that of SRM must focus for now on questions of efficacy, technical feasibility and risks.

Although most research is enabled through national and private funding, some international processes could help this be more effective, efficient, responsible, and equitable. For example, international governance could 'encourage national spending, develop cost-sharing arrangements, and incentivize private investment' (Bodansky, 2013, p.546).

For one thing, statements by authoritative international bodies would indicate the importance of further research and proactively catalyze action. This is arguably more important for SRM, where research remains modest due to weaker linkage with existing climate change policy, potentially severe physical risks and social challenges, the lack of profit motive for private research, and ongoing contestation. As noted, the CBD COP has already made such a decision; others such as the UNFCCC COP, UNEP, WMO, IMO, and even UNGA could follow.

Second, international governance could make research more effective through several means. It could identify existing institutional and personal expertise to leverage as well as establish channels of knowledge exchange. Some coordination could prevent duplication of efforts. An international body could emphasize priorities, such as knowledge from diverse disciplines and backgrounds, exploration of multiple CDR and SRM technologies, ongoing monitoring and impact assessment, and investigations of the technologies' limitations, risks, and challenges. The latter priority is important so that the research does not unduly bias future decision-making in favor of the technologies' use. These tasks seem better fit for the international institutions that have substantial scientific expertise, such as UNFCCC SBSTA, UNEP, WMO, and IMO. Given the benefits of coordination and prioritization, a single site – or one for each of CDR and SRM – would be more preferable. Existing international research collaborations, including Future Earth and the Belmont Forum, could have important roles here.

Third, research could be improved through independent assessment, synthesis, and knowledge transfer. The IPCC and IPBES are well positioned for this.

Finally, international governance could help research be more equitable. It could encourage developed countries that have the means to do so to help build research capacity in developing ones, discussed more in chapter 3 (Textbox 8) and below.

4.4.2. Encourage the responsible use of CDR

CDR resembles GHG emissions reductions in that it lowers net emissions. It is necessary to meet internationally agreed-upon climate change goals, and parties to the Paris Agreement are obligated to 'take action to conserve and enhance, as appropriate, sinks and reservoirs of greenhouse gases' (Article 5.1). Whoever undertakes CDR bears local financial and nonfinancial costs, while the entire world benefits from reduced atmospheric GHG concentrations. It is thus a global public good, which will be underprovided. Moreover, many CDR techniques face significant political and institutional headwinds. Some appropriate promotion of CDR is needed to overcome this collective action problem.

Encouraging and expanding the responsible use of CDR will require clarifying policy, including at the international level. For example, if states' leaders knew that they could meet their international mitigation obligations in part through specific techniques, then they would have the incentive to encourage CDR's research, development, and use. This suggests a need to integrate CDR into current standards of national emissions inventories (Paris Agreement, Articles 4.13, 13.7(a)). For the various CDR techniques, this would require both detailed provisions and clarity. The former would be for monitoring, reporting, verification of permanent removals and life cycle assessments. Clarity would regard parties' use of CDR in their Nationally Determined Contributions, long-term low emission development strategies, and use of the Article 6 cooperative mechanism. This should be done by the UNFCCC institutions – which have experience with LULUCF and reducing emissions from deforestation and forest degradation – in cooperation with the IPCC Task Force on National Greenhouse Gas Inventories. The UNFCCC institutions and IPCC could also, as part of the global stock-takes under the Paris Agreement, assess states' capacity to use CDR and progress in doing so.

4.4.3. Regulate risks for sustainable development

In order to help fulfil the SDGs, international governance should lessen negative secondary effects of CDR and SRM, from both their research and use (see IRGC, 2015). There is not a regulatory vacuum in this regard (see chapter 2). Instead, most of their risks, especially those of CDR, will be local and controlled primarily by national, subnational, and European regulation. Transboundary environmental risks, such as those from larger-scale CDR and SRM activities, are to some degree governed through existing international law, including the customary international law of transboundary harm. And risks to the marine environment – the most significant area beyond national jurisdiction – are subject to the widely-ratified and comprehensive UNCLOS.

Nevertheless, international governance could offer further guidance on how the SDGs, on the one hand, and the research, development, and potential use of CDR and SRM, on the other, can be pursued synergistically rather than in conflict. For one thing, governance could support the development, elaboration, and application of non-state principles, codes, and best practices. For another, international bodies could develop guidance for national regulation and the implementation of international law. Finally, it may be appropriate to develop international governance of SRM's significant transboundary risks. Either way, it should address more than only physical and environmental risks, but also other salient aspects such as transparency and public participation in decision-making. The amendment to the London Protocol that regulates 'marine geoengineering' could serve as a model in some ways (see section 2.3.6).

It is unclear at which site(s) such international governance concerning the physical risks and social challenges of CDR and SRM could be crafted. To the extent that this is limited to stimulating and coordinating national and non-state governance, then the UNFCCC, CBD, UNEP, WMO (for SRM only), and IMO, or a decentralized process, may be appropriate. International governance of large-scale SRM activities could be promulgated as a nonbinding decision by these institutions or might eventually warrant a new international instrument or body. In reality, governance will likely be developed and implemented in multiple international forums and institutions. This points toward a need for inter-institutional coordination and integration.

4.4.4. Further integrate with existing governance

CDR and SRM could be, to some extent, integrated with extant governance in order to make it more effective and legitimate and to work toward multiple objectives. Incorporation with climate change policy – described above in the context of encouraging the responsible use of CDR – is particularly important to manage the diverse responses and keep reducing GHG emissions as the top priority. Again, although much of this can occur in national policy, international governance could strengthen this by sending signals of priorities and coordination.

Relevant international institutions could assign the responsibility for interfacing with CDR and SRM to one or a small number of offices or, where appropriate, subsidiary bodies. They could then identify how the issues fit within the institutions' mandates, inventory and assess capacity, foster knowledge creation, strengthen engagement, and locate and describe challenges. Externally, these responsible offices and bodies could establish channels to strengthen inter-institutional communication and mutual learning. In this, the SGDs could serve as an integrative framework. These processes could possibly be catalyzed and arranged by the UN Environment Management Group or an independent multi-stakeholder forum.

4.4.5. Build governance capacity

Governance requires the capacity to, at multiple levels, effectively develop, monitor, and enforce as appropriate. However, states and other relevant actors may not yet have this capacity to govern novel emerging issues such as those of CDR and SRM. Some states could start building the requisite capacity for international governance domestically. Their relevant public departments could set aside resources, including dedicated staff, to take these matters on. Inter-agency coordination would also be beneficial. This will require substantial investment in learning about the technologies; their capacities, limitations, and risks; governance opportunities and challenges; and the associated politics.

Other states lack sufficient resources to build capacity domestically. Climate change research in general – of which CDR and SRM constitute only a small fraction -- is poorly funded in many parts of the globe. However, for multiple reasons including legitimacy and effectiveness, developing countries should participate in crafting and implementing international governance (Rahman et al., 2018). Efforts by developed countries to help build capacity in developing ones are consequently important. (The Solar Radiation Management Governance Initiative offers an example of effective non-state building of capacity in developing countries.) This would require investing both financial and intellectual resources, which could be done on a state-by-state basis or facilitated by international bodies, such as the UNFCCC SBSTA.

4.4.6. Strengthen international cooperation

Some observers are concerned that CDR and especially SRM could worsen international relations. Both sets of technologies could cause negative transboundary impacts and be perceived in an unwelcome light. Establishing and maintaining international trust could help prevent such an outcome or even strengthen international cooperation (Davies 2010, p. 279). Four means could advance this. The first was described above: building capacity in countries that lack it, such as through mutual learning, financial support, and knowledge transfer. Second is international research collaboration, including joint research projects and the exchange of expertise and experts. Third, research and development activities should be transparent. Here, SRM should arguably satisfy higher standards than those of routine scientific research. Fourth, militaries could be discouraged from involvement in SRM research and development. The first two of these – capacity building and international research collaboration – could be accomplished through diverse bi- and multilateral mechanisms, both formal and informal as well as existing and new. Together with transparency, they are relatively technical matters and could thus be handled by international institutions such as UNFCCC COP and SBSTA, UNEP, and WMO. The final issue of military involvement in SRM is more political and better suited to the UNGA or, if possible, through the parties of the Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques (ENMOD; see chapter 2).

4.4.7. Leverage the private sector

Most innovation occurs in the private sector, and one of the leading governance mechanisms to encourage it is intellectual property (IP) rights, mainly patents. CDR and SRM may warrant dedicated IP policies. The former might benefit from patent pools for the various CDR techniques, public-private partnerships, and alternatives to patents, such as prizes. In contrast, because SRM offers distinct incentives – especially the lack of a clear profit model – and is more contested, novel dedicated governance of IP may be particularly beneficial. In addition, there may be areas of research and development, particularly in SRM, where states wish to limit the private sector's role. But in other cases, an SRM research commons could, for example, maintain the motivation to profit from legitimate SRM activities, such as providing services to public agencies via procurement; facilitate transparency through open-source standards and more; and prevent patent thickets (Reynolds et al., 2017). Although IP law is a national responsibility, international governance catalyzes, coordinates, and harmonizes it. This would call for the involvement of international institutions with IP expertise, such as the World Trade Organization and World Intellectual Property Organization.

4.4.8. Implement breakpoints, stage gates and moratoria

There is some worry that early research and development of CDR and SRM will cause future decision-making regarding their use to be unduly favorable. International governance could establish criteria under which CDR and SRM work would or would not proceed. A *breakpoint* is a commitment to stop under certain circumstances, while otherwise defaulting positively to proceeding. A *stage-gate* is an agreement to go forward for now, coupled with an explicit later decision concerning whether to continue. And a *moratorium* is a temporary ban that could be ended under certain conditions – that is, a negative default (Parson and Herzog, 2016).

On the one hand, these mechanisms are, in a general sense, appropriate and presumably widely supported for the higher stakes, less certain CDR and SRM technologies. Furthermore, they may be wise for individual projects and institutions. For example, a funding agency could, as it begins supporting CDR and SRM, make explicit conditions under which it would stop doing so. Indeed, the UK's Natural Environment and Engineering and Physical Sciences Research Councils used such a stage-gate when they funded CDR and SRM (Engineering and Physical Sciences Research Council, 2012). However, a challenge arises when a body would attempt to implement a breakpoint, stage gate, or moratorium that governs other actors. In effect, it would be claiming authority over others, which might or might not be perceived as legitimate. Moreover, the implementation of a moratorium is an implicit claim of the authority to lift it and consequently open the door to the contested activity at hand. Another limitation is that these policies may not be sufficiently adaptative, as those who develop the breakpoint, stage gate, or moratorium may not foresee the ways in which circumstances may change in the intervening time. This is particularly the case as the policies become temporally longer.

4.4.9. Establish a foundation for future decision-making

Some decisions in the international governance of CDR and SRM could have significant impact but are not yet ready to be made due to scientific and normative uncertainty as well as lack of trust. This is especially the case with the full range of environmental, social, and political issues associated with whether to use SRM. Fortunately, these future difficult decisions need not be made soon. However, they often cast a shadow over and can impede the development of governance in the near term. It could thus be helpful to take steps to lay a foundation for such future decision-making.

There are at least four mutually nonexclusive possible means to begin this process. First is so-called 'track II diplomacy,' in which authoritative individuals who are not formally bound to a state – retired officials, academics, religious and nongovernmental organization leaders – participate in closed-door workshops and other low-profile dialogues in order to make progress with contentious international issues (Jones, 2015). Despite its unofficial nature, track II diplomacy could be catalyzed by a state that is perceived as neutral in the issue area.

The second possible means would be to catalyze the formation of an esteemed body of diverse experts in an independent and multi-stakeholder roundtable, such as a 'World Commission on Climate Engineering' (Parson 2017; Chhetri *et al.*, 2018). Like track II diplomacy, its members should not be state officials, but its activities would be more visible.

Third, international governance institutions could dedicate resources to identify their capacities to contribute to governance, explore related future needs and challenges, and to conduct an impact assessment of considered policies.

Finally, states could initiate international dialogues over these longer-term decisions. These could occur in an existing intergovernmental institution such as UNEP or the WMO. (The political atmosphere in the UNFCCC could be strained by doing so there.) Broad participation would be important given SRM's likely global effects.

4.5. Recommendations

This section offers recommended steps toward international governance of CDR and SRM. Unlike the previous sections, which sought to capture a wide range of possibilities, these reflect the author's assessment of what one or a few states could feasibly and effectively initiate. These are based on the various technologies' capabilities, limitations, and risks (chapter 1); the current international legal and institutional arrangements (chapter 2); the critical trade-offs regarding physical and environmental impacts, governance, and research (chapter 3); and the assessment criteria (above). These six recommendations are not mutually exclusive and are, in some ways, complementary. Finally, most of them call for action in international organizations and institutions, which due to their member-driven characters, would require initiative from one or more states.

The first recommendation is a general one that underlies the other four: **to distinguish between CDR and SRM as well as among the diverse CDR techniques in their additional dedicated governance.** A functional approach implies that the technologies should be governed by the same mechanisms to the extent that their characteristics, opportunities, and risks are in common and by distinct mechanisms to the extent that they differ. Chapter 3 concludes that CDR's most salient aspects, including its risks, are largely local and vary among the diverse technologies, whereas those of SRM are primarily international and global. The heterogeneity of CDR techniques is evident in the review of their means of operations, risks, and challenges in chapter 1 (see also Cox and Edwards, 2019). Along these lines, a recent report on CDR by the *Stiftung Risiko-Dialog* (Risk Dialogue Foundation) commissioned by the Swiss Federal Office for the Environment concludes: 'Discussions of CDR under generic terms such as geoengineering should be avoided because they combine [with SRM] two fundamentally different approaches and risk profiles and are thus not effective. The discussion of risks, opportunities, potentials etc. requires a clear definition of each of the approaches' (Beuttler *et al.*, 2019, p.21). This is consistent also with the separation of CDR and SRM and rejection of the term 'geoengineering' in the IPCC Special Report on 1.5°C warming (IPCC, 2018, p. 550) and the US National Academies reports (National Research Council, 2015a and 2015b).

Second is **to accelerate authoritative, comprehensive, and international scientific assessment.** There is still no such assessment of the capabilities, limitations, impacts, risks, and governance needs of CDR and SRM. These assessments should be neutral with regard to which CDR and SRM technologies, if any, should be used. The preferred lead site for this is the IPCC, given its mandate, wide participation, and perceived legitimacy. It should dedicate substantial effort toward SRM, for which the knowledge base remains relatively limited and the need for outdoor testing and experimentation seems to be an obstacle. If the IPCC does not do so in its Sixth Assessment Report, then its Plenary Panel should thereafter devote special reports to CDR and to SRM. This could arise internally or be externally instigated, as the UNFCCC COP invited the IPCC to provide a special report on global warming of 1.5°C. Otherwise, assessment by UNEP and/or the WMO (for SRM only) may be justified. Because the scopes of the IPCC and WMO are limited, any assessment there should be complemented by work at IPBES and the Food and Agriculture Organization for effects on biodiversity, ecosystem services, and agriculture.

The **third** recommendation for the future governance of CDR and SRM is that the international policy-making community should **encourage the research, development, and responsible use of some CDR techniques**. This should be geared toward meeting the Paris Agreement's global warming goals and the SDGs. Specifically, the UNFCCC institutions should elevate CDR's visibility in the climate change regime's processes and activities; push for greater systematic consideration of parties' obligations to pursue CDR, under the rubric of enhancements of sinks and reservoirs; and work toward realistic and viable financial incentive systems. Any actions should be based on the best available scientific evidence and, as stated above, differentiate among the various CDR techniques. A COP decision should call for more transdisciplinary research, for parties and other intergovernmental institutions to establish a point of contact for CDR matters, for international information sharing and cooperation, and for GHG emissions reduction to remain the top priority. It could also establish an Ad Hoc Technical Expert Group on the enhancements of sinks and reservoirs that could, for example, regularly assess the potentials, risks, and social challenges of the techniques and 'scan the horizon' for new developments. As part of a COP decision, the UNFCCC's SBSTA should be directed to develop standards for the monitoring, reporting, and verifying of all permanent removals, as well to help build capacity in developing countries. At a later date, the 'Paris Rulebook' could be modified to clarify the extent to which parties may and should use CDR techniques in their Nationally Determined Contributions, their long-term low GHG emission development strategies, and the Article 6 cooperative mechanisms. Any COP decision should be in the context of the UNFCCC's principles including common but differentiated responsibilities and respective capabilities, full consideration of developing countries' specific needs and special circumstances, precaution, effectiveness and efficiency, and sustainable development.

Fourth, states should **help build capacity for evaluating CDR and SRM in some of those countries that lack the resources to do so**. A broad, diverse set of states will need to engage in order for any international governance to be effective and perceived as legitimate. Specifically, developed countries interested in CDR's and SRM's international governance should launch programs to partner with developing and climate-vulnerable ones, providing funding and academic partnerships that allow developing countries to address their own research priorities and build their own expertise. This would also constitute important 'science diplomacy,' creating peer-to-peer networks of experts, providing an intellectual foundation for subsequent governance work. Although one or a few developed countries' ability to help internationally build such capacity may seem limited, the resources required are modest, and initial steps by some states could catalyze action by others and by international institutions.

Fifth, states and intergovernmental institutions should **facilitate the elaboration and implementation of non-state governance**. In the absence of state action – often due to contestation and steep learning curves – non-state actors can further the international governance of CDR and SRM, which can help prepare for state governance at a later stage. This relatively bottom-up process would complement the other top-down ones. It should have an inclusive and deliberative approach and strive to advance widely shared norms of governance such as transparency, engagement with potentially affected stakeholders, and prior assessment of impacts. An ad hoc coalition of a few states and funders – both public and private – of climate change research could undertake this. They could begin by convening discussions of respected scientists in related fields, research institutions, and professional societies.

The **final** recommendation is for international processes that **explore potential further governance of SRM while remaining agnostic concerning its ultimate use**. This should be unrushed, stepwise, and open so that trust and knowledge can be established and assessments can be produced. The primary purposes of the process would be to engage more numerous and diverse states, allow them and the relevant international institutions to learn about and develop the capacity to address SRM, establish common understandings, and to build trust. A diverse international expert committee should be created. The output should include a report that lays out the current status, needs, opportunities, challenges, and options for the international governance of SRM, with specific reference to intergovernmental institutions' capacities to contribute. Although its substance would not be new – and not entirely unlike this current document – its origin would give it greater authority and visibility.

One path for this would be through an international institution. UNEP is the preferred site for such a process. Its mandate and capabilities include identifying emerging issues, conducting scientific reviews, and catalyzing international governance across issue areas and sectors. Moreover, it has a reputation for expertise and relatively low politicization. Independent of this processes' home, it should coordinate as appropriate with other relevant international institutions such as the UNFCCC and CBD.

Any action at UNEP would need to address the reasons that the 2019 resolution there was insufficiently supported. Four explanations are identified above (section 4.3.5 on UNEP). The proposed resolution jointly considered CDR and SRM and called for assessing the state of the science and knowledge of potential impacts. In contrast, the recommendation here is to begin an international dialogue on only SRM's governance. This leaves two remaining issues. Regarding precaution, its legal status and precise substantive content are not settled (German Research Foundation (DFG) Foundation's Priority Programme 1689, 2019, pp. 64-65; Bodle et al., 2014, p. 129), and precaution may be a poor guide in the context of high-stakes risk-

risk trade-offs. States' divergent preferences in this regard could be managed through a perambulatory passage in the resolution that recognizes well-established principles in international environmental law, including those in the UNFCCC, without explicit reference to precaution. Finally, concerning the objective of considering global governance frameworks, this could likewise remain implicit in order to garner sufficiently broad support. After all, the suggested process's primary purposes would be engagement, learning, and trust, not establishing international governance per se, even though these purposes are necessary for eventual governance.

Chapter 5 | Concluding remarks

This report has reviewed the state of international governance of climate engineering and various options going forward, intending to provide information relevant to international policymaking. This conclusion briefly summarizes some of the arguments from the four chapters, then provides a list of four key cross-cutting themes that the chapters point towards, and finally suggests a roadmap for specific aspects on which more research and political engagement would be needed.

As seen in **chapter 1**, the breadth of uncertainties and ambiguities involved in CDR and SRM technologies give rise to create a complex agenda for the policy debate.

Currently, no CDR technique is comprehensively understood or acceptable to be developed at a large scale, nor is a policy environment yet available to underpin climate-relevant CDR deployment, whether BECCS, DACS or other technologies. While some techniques, such as forestation, can be deployed today, the full extent of consequences of large scale tree planting would require further study to understand all environmental, climate, sustainability, economic and social impacts. How we might achieve robust reporting, monitoring of environmental effects –to avoid damages to biodiversity and ecosystems– and verification, will require a global accounting system and a centrally coordinated mechanism or body, that includes financial capability. The social acceptability of each CDR technique cannot be assumed. Policy and financial support, in the form of appropriate incentives and contribution to basic, strategic and applied research is required, alongside focused efforts to guarantee the permanency of carbon storage, given the needs for CDR to complement GHG emission reduction quickly, despite some risk of displacement of CO_2 emission reduction.

Some SRM methods such as SAI or MCB appear able in theory to effectively, rapidly, and inexpensively reduce temperature increase and, to a lesser degree, changes in precipitation patterns. However, modeling suggests that they would imperfectly compensate for climate change and there are significant uncertainties and knowledge gaps, substantial environmental risks (some of which causing potentially irreversible damage), and important institutional, social and political constraints and challenges. Besides, the risk that SRM is perceived as a substitute for emission reductions must be addressed up front, as well as the risk of termination shock (if it is stopped too soon or too abruptly) and the risk of unilateral deployment.

Further research across disciplines is required before any decisions about techniques can be made. Also, science alone cannot provide all answers. Social deliberation must be organized to balance expert analysis and help better understand and guide policy choices. Many facets of climate-altering technologies are uncertain and subject to ambiguity, which affects the perspectives on the tolerability of risks.

Chapter 2 has pointed to potentially significant gaps in existing regimes (depending on the overarching aims and objectives of governance), suggesting the need for further cooperation at the international level to promote effective, legitimate and fair governance of these emerging technologies.

At the same time, there are several general norms of international environmental law, treaties and soft-law instruments and international institutions with relevance to climate engineering. The international legal and institutional landscape relevant to climate engineering thus presents a complex 'patchwork' of overlapping norms and institutional mandates, including those of (but by far not limited to) the UNFCCC, IPCC, CBD or London Protocol. Taken together, this fragmented 'patchwork' underscores the need for some degree of international governance for climate engineering measures, and provides a framework of norms and mechanisms for addressing environmental and other concerns. Elements include international cooperation, prevention of environmental harm, precaution, environmental impact assessment, prior notification and consultation, cooperation, information sharing and capacity building on scientific research, prior notification and mutual information. To avoid regime conflicts, there is a need to develop governance for climate engineering across different legal and institutional settings in a way that promotes greater coordination, coherence and efficiency.

Elaborating from chapters 1 and 2, **chapter 3** has identified several risk-risk trade-offs and offered several steps that could be pursued in the near- to medium-term to gradually resolve the trade-offs and strengthen opportunities for governance strategies that attenuate multiple risks.

Trade-offs characterize first various emergent governance and policy design choices. Policy is frequently confronted with several challenges, including the balancing of inclusive or participatory governance with efficiency and effectiveness; the sovereignty of domestic policies contrasted to the need to address potential transboundary effects; and centralized governance versus polycentric governance (harmonization versus diversity). Regarding SRM, risk of premature or uncoordinated deployment is a topic of much concern, particularly in the absence of a globally shared understanding of the far-reaching implications. Suggested measures toward overcoming these trade-offs and achieving robust risk reduction across multiple risks include strengthening capacities for international inter-agency collaboration, coordination, and learning; proactively exploring how specific governance challenges match particular international agencies' mandates; and conducting policy impact assessments for CDR in the context of national mitigation policy planning.

The chapter has then reviewed trade-offs faced in research. For example, scientific research too often remains within disciplinary boundaries and produces authoritative technical knowledge that does not includes the consideration of the variety of normative contexts and cultures. More inclusive research on SRM is needed. Lack of collaborative international research and uneven decision-making capacity may lead to the capture of the governance process by a small number of countries.

Finally, **chapter 4** has suggested and evaluated options and approaches for future international governance of CDR and SRM. Noting the relative lack of appetite in the international diplomatic community, as well as in national governments, a step-by-step approach is recommended. First, explicit criteria for the assessment of governance options have been identified, relying on widely agreed upon objectives of international policy such as the priority to reduce climate change and contribute to the SDGs, to establish and maintain trust and legitimacy, and foster global peace and stability.

The various options for legal or institutional sites for international governance have been reviewed, considering intergovernmental institutions and their respective core competencies and expertise; type, extent and consequences of decisions; and level of politicization. The chapter has also considered the possibility of decentralized governance or governance by non-state actors.

Options for the substance of the governance arrangements have been proposed, including the ability to leverage the private sector and implement breakpoints, stage gates and moratoria to help manage the endeavor's trajectory in line with policy and social priorities.

Final recommendations include (1) to distinguish between CDR and SRM as well as among the diverse CDR techniques in additional dedicated governance; (2) to accelerate authoritative, comprehensive, and international scientific assessment of these technologies; (3) to encourage the research, development and responsible use of some CDR techniques; (4) to help build capacity for evaluating CDR and SRM in some of those countries that lack the resources to do so; (5) to facilitate the elaboration and implementation of non-state governance, in complement to governance by governments; and (6) to explore the potential further governance of SRM while remaining agnostic concerning its ultimate use.

5.1. Four cross-cutting themes emerge from this report

1) Noting the pervasive uncertainty that characterizes both CDR and SRM and their governance, develop adaptive approaches to reducing uncertainty and deploying the most appropriate technologies. Be very prudent and cautious, and avoid lock-ins.

In addition to GHG emission reduction, the deployment at a large scale of some climate engineering would be needed to contribute significantly to reducing the causes and consequences of climate change.

However, the risks involved present complex features and non-linear processes that often produce unintended consequences, with potentially large-scale impact. Furthermore, the consequences of using a technique must be balanced by the consequences of not using it. Besides, the resolution of the trade-offs and the elaboration of any policy options require addressing matters of justice, equity and fairness.

Policy decisions must rely on risk-based assessment, prudence and caution. A way forward could be to adopt a step-by-step approach and plan for flexibility and adaptability of the governance. This would require continuing research to reduce the knowledge gaps, monitoring implementation, integrating feedback in the possible adjustment and revisiting of the governance arrangements, and preventing any institutional and legal lock-in.

2) Separate CDR and SRM in policy discussions

It is often confusing to address CDR and SRM in the same policy discussion. Furthermore, one needs to be clear about what technologies we talk about within each group of distinct techniques such as BECCS and DACS for CDR, or SAI and MCB for SRM. Objectives, techniques, risks and expected benefits are different and distinct governance arrangements are needed. The objective of CDR is to address the cause of climate change while SRM could address some of the symptoms. Both have or could have adverse effects. While those from CDR would be more local or regional, those from SRM would be global. But both present particularly difficult assessment and governance challenges. CDR is in the mandate of the UNFCCC. At more, SRM is only indirectly linked to the objective of the UNFCCC. The CBD does not differentiate.

Also, overarching coordination that articulates the complementarity of technologies in a portfolio of approaches to climate change reduction could help the discussion going forward.

Finally, differentiating governance of research and governance of deployment could help address fundamental concerns about the idea of deliberate intervention in the climate system.

3) Acknowledge that existing international arrangements lean toward –or even in some cases create an obligation– to engage in further research and cooperation

A need for authoritative, comprehensive, and international scientific assessment has been emphasized in international law, customary and treaty law, in various fora and by numerous scholars, as well as the need to collaborate towards developing some kind of an international governance framework. Open questions remain regarding ‘assigning’ the respective technologies to one or several of the existing international institutions or conventions concerned, directly or indirectly, with actions to combat climate change and its consequences. Acknowledging institutional diversity and complementarity of the various mandates, there is no obvious ‘siting’. Instead, collaboration among institutions is highly recommended. The challenge is to integrate and articulate overarching principles and specific approaches, and research and management, as tentatively illustrated in Figure 7 below. A transnational (i.e. not necessarily intergovernmental) venue for assessing the risks and benefits could feed its output into various venues for managing them.

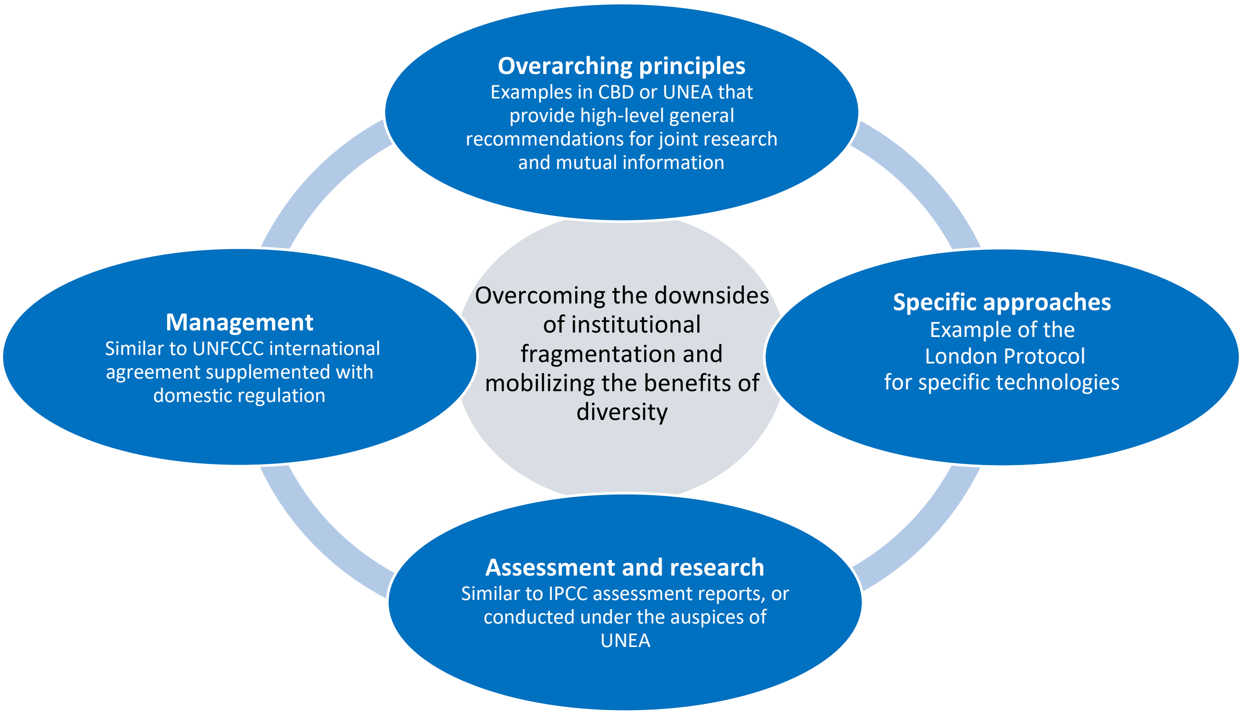


Figure 7 – How we could overcome the downsides of institutional fragmentation and mobilize the benefits of diversity: a tentative governance framework for organizing overarching principles and specific approaches, research and management

4) Combine top-down and bottom-up approaches to the national and international governance of CDR and SRM.

Such approaches should be grounded in the principle of inclusiveness. Conversations should happen, both within each of the various stakeholder groups (policy institutions, scientific institutions, civil society, industry), and among these groups, for the emergence of shared and transparent understandings, visions and goals. It should also happen at the national level, where national governments should be involved.

While multifaceted governance with bottom-up and top-down elements and with several institutions focusing on specific aspects of climate engineering seems to be the most promising approach, there is still a need to ensure overall coherence and perspective, resulting in polycentric governance.

5.2. Possible roadmap for broader conversation of CDR and SRM

This report concludes with a suggested roadmap to broader conversation science, policy and society. While such exercise should not aim to any pre-defined normative or prescriptive goal, it would set in motion a movement where issues presented in this report could be discussed, in view of developing long-term climate sustainability and societal responsibility in matters regarding intra-generational and inter-generational equity. Regarding SRM in particular, there is relatively little appetite in the international diplomatic community for taking on these issues in a substantial way, so in light of the challenges ahead, a step-by-step approach would be advisable, with the creation of appropriate context conditions and milestones and where each contribution would importantly be viewed as valuable and useful.

- **Adopt a systemic ('systems') approach to risk and benefits of the various technologies and their governance** noting the need to consider cascading effects, both positive and negative, across countries and generations, the interconnectedness between technology and governance, and feedback effects.
- **Choose a neutral place for dialogue**, with a group of hosts that altogether have a convening power to enhance inclusiveness, organize collaboration, and can coordinate a learning and sharing process between science, policy and other stakeholders, to eventually ensure the legitimacy of advice and recommendations.
- **Organize national conversations with society, including a broad spectrum of actors** to capture and articulate the views of civil society on both a national and global scale, in order to make policymakers more confident that their decisions align with societal goals and expectations. Climate engineering discussions are very focused on scientific assessments, knowledge generation and expert opinion. However, policy decisions result from judgements about these matters as much as aspects of public perception and preferences, which are diverse and often fragmented.
- **Engage national policymakers** on the fact that CDR can help achieve national climate targets. Mechanisms for assessing, accounting and incentivizing CDR should be developed at the national level. Much of the international debate will emerge from national or EU debates.
- **Enhance international and multilateral collaboration** in multi-disciplinary research that involves a broad range of stakeholders from various countries that do or could do research (both technical and policy) and deployment, or that could be negatively affected by deployment. While UN institutional infrastructure must be engaged directly, groundwork should also be done at the national level and in other multilateral fora, which should help frame the issue.
- **Encourage public funding for research** that prioritizes interdisciplinary and international work towards complementing strategies for reducing GHG emissions with actions to reduce GHG concentration and controlled experimentation when needed**.**
- **Improve mechanisms to create ownership, incentives and co-benefits** for investment (including from industry) whenever desirable, especially for CDR.
- **Create mechanisms to adapt institutions and international conventions**, when those are not adapted to challenges related to specific technologies. This concerns, in particular, amending mandates if appropriate, and aligning decisions of respective international conventions that concern CDR or could concern SRM. For that purpose, enhance interagency collaboration.

- **Consider the following six key issues for further research**

1. Moral hazard of mitigation displacement

How to ensure that discussion, research and deployment of CDR and SRM do not hinder reducing GHG emissions?
How to address the moral hazard of not communicating the fact that CDR is necessary to reach global climate goals?

2. Complementarity between and combination of climate engineering technologies

In addition to conventional mitigation and adaptation, what could a portfolio of technologies look like, considering their respective potential to contribute to climate change mitigation, the costs and the risks involved and specific geographic or other conditions?

3. For CDR: assessing the risks and benefits of the various distinct technologies

How to organize and fund collaborative research?
How to account progress in climate goals, to monitor development and fund research and deployment?

4. For SRM: avoiding the risk of unilateral deployment, and assigning objective

What goal might be assigned to SRM?
How to avoid risk of termination shock, mitigation displacement and premature or unilateral action?
How could scientific work be conducted without the risk of unduly legitimizing SRM?

5. Collaboration between international institutions and conventions

How can institutional collaboration be organized for coordinated policy development aligned towards a common goal?
How can we overcome barriers, and develop response options and recommendations for complementarity?
How to take advantage of diversity within an overarching framework?

6. Mechanisms for responsibility and accountability to create trust

What kind of processes and instruments can be used to enhance legitimacy of and trust in those who decide and take action?

Glossary

Terms related to climate engineering

Carbon dioxide removal (CDR) is defined as 'anthropogenic activities removing CO_2 from the atmosphere and durably storing it in geological, terrestrial, or ocean reservoirs, or in products. It includes existing and potential anthropogenic enhancement of biological or geochemical sinks and direct air capture and storage, but excludes natural CO_2 uptake not directly caused by human activities.' (IPCC, 2018a)

Climate-altering technologies are synonymous with climate engineering.

Climate engineering is intentional large-scale human interference in the earth system to combat climate change (C2G, 2020[1]).

Geoengineering

In 2009, the Royal Society defined geoengineering as: 'the deliberate large-scale manipulation of the planetary environment to counteract anthropogenic climate change'.

The Convention on Biological Diversity —decision X/33 defines climate-related geoengineering as 'technologies that deliberately reduce solar insolation or increase carbon sequestration from the atmosphere on a large scale that may affect biodiversity (excluding carbon capture and storage from fossil fuels when it captures carbon dioxide before it is released into the atmosphere). www.cbd.int/climate/doc/cop-10-dec-33-en.pdf

The IPCC's fifth assessment report (IPCC, 2014) defined geoengineering as 'a broad set of methods and technologies that aim to deliberately alter the climate system in order to alleviate the impacts of climate change. Most, but not all, methods seek to either (1) reduce the amount of absorbed solar energy in the climate system (Solar Radiation Management) or (2) increase net carbon sinks from the atmosphere at a scale sufficiently large to alter climate (Carbon Dioxide Removal). Scale and intent are of central importance. Two key characteristics of geoengineering methods of particular concern are that they use or affect the climate system (e.g., atmosphere, land or ocean) globally or regionally and/or could have substantive unintended effects that cross national boundaries. Geoengineering is different from weather modification and ecological engineering, but the boundary can be fuzzy'.

In its later Glossary (2018a), the IPCC states that 'in this report, separate consideration is given to the two main approaches considered as "geoengineering" in some of the literature: solar radiation modification (SRM) and carbon dioxide removal (CDR). Because of this separation, the term "geoengineering" is not used in this report.'

Mitigation refers to 'a human intervention to reduce emissions or enhance the sinks of greenhouse gases'. (IPCC, 2018a)

Sinks are reservoirs (natural or human, in soil, ocean and plants) where a GHG, an aerosol or a precursor of a GHG is stored. The UNFCCC art 1.8 refers to a sink as the process, activity or mechanism to remove them from the atmosphere. (IPCC, 2018a)

Solar radiation modification (SRM) 'refers to the intentional modification of the Earth's shortwave radiative budget with the aim of reducing warming. Artificial injection of stratospheric aerosols, marine cloud brightening and land surface albedo modification are examples of proposed SRM methods. SRM does not fall within the definitions of mitigation and adaptation (IPCC, 2012, p.2).

[1] www.c2g2.net

Note that in the literature SRM is also referred to as solar radiation *management* or albedo enhancement'. (IPCC, 2018a)

In Chapter 1 of this report, SRM 'would aim to reflect sunlight back into space, or allow more heat to escape Earth's atmosphere', thus including cirrus cloud thinning.

Terms related to governance and risk

Governance is often defined as the range of actions, processes, traditions and institutions by which authority is exercised and decisions are taken and implemented (IRGC[2]) in order to direct behavior toward an explicit goal.

IPCC describes governance as a 'comprehensive and inclusive concept of the full range of means for deciding, managing, implementing and monitoring policies and measures. Whereas government is defined strictly in terms of the nation-state, the more inclusive concept of governance recognizes the contributions of various levels of government (global, international, regional, sub-national and local) and the contributing roles of the private sector, of non-governmental actors, and of civil society to addressing the many types of issues facing the global community.' (IPCC, 2018a).

C2G (2020) describes governance as including 'regulation, broad participation in decision-making, transparency and access to information at the international, national, and subnational levels, and needs to apply to research, testing and deployment'.

Adaptive Governance is 'an emerging term in the literature for the evolution of formal and informal institutions of governance that prioritize social learning in planning, implementation and evaluation of policy through iterative social learning to steer the use and protection of natural resources, ecosystem services and common pool natural resources, particularly in situations of complexity and uncertainty'. (IPCC, 2018a)

International governance thus deals with matters of governance that require discussion at the international level, in international institutions or other fora. It relies on political cooperation among transnational actors, aimed at negotiating responses to problems that affect more than one state or region.

Polycentric governance denotes a complex form of *governance* with multiple centers of decision-making, each of which operates with some degree of autonomy. (Ostrom, 2005, 2010).

Moral hazard describes a situation in which people or organizations do not suffer from the results of their bad decisions, so may increase the risks they take. (Cambridge Dictionary)

Risk is the potential for adverse consequences where something of value is at stake, and where the occurrence and degree of an outcome is uncertain. (IPCC, 2018a)

Generic definitions of risk include: 'the uncertain consequences of an activity or event with respect to something that humans value' (IRGC, 2005). According to ISO 31000, risk is the 'effect of uncertainty on objectives', and 'an effect is a positive or negative deviation from what is expected'.

---

[2] https://www.epfl.ch/research/domains/irgc/risk-governance/

Expert workshop: the international governance of climate engineering

A workshop was held during the preparation of the report, on 23 April 2020. Participants from governments, universities, research institutes and non-governmental organizations (listed on page 150) made critical comments and suggestions on the draft, which were taken into account by the authors of the report. The workshop discussed the following questions:

General questions

- What are the most critical objectives, concerning the international governance of carbon dioxide removal and/or solar radiation modification?
- What are in your view the most promising, necessary or useful governance or policy options (already proposed or not yet)? What are the less promising options?
- Benefitting from mutual learning between stakeholders and broader society: What could respective stakeholders seek to learn from each other?

Session 1 – Technology options

- In the light of the uncertainties associated with each technology, and the urgency to respond quickly to the climate crisis, what selection criteria might policymakers adopt to inform prioritization choices for action and research investment?
- How can plural processes be constructed in the context of the high uncertainties associated with the techniques?
- Given the requirement for interdisciplinary research at scale,
  - how might SRM in particular, but also CDR research be governed?
  - what funding mechanisms might be most suited to the challenge?
- Who should decide when any given technique is ready for 'out of doors' research testing at a scale, particularly any that might cause a discernible impact?

Session 2 - Review of international governance arrangements, gaps and current initiatives

- In your opinion, what are the main gaps in current arrangements?
- What are or should the main actors be, for international governance of CDR and SRM?

Session 3 - Addressing risks and resolving trade-offs in governance

- In your opinion, what are the most significant risks and trade-offs when developing international governance of SRM and CDR?
- What recommendations to governments would you provide for addressing these risks and trade-offs?

Session 4: Elements and steps for global governance; policy options and approaches for potential future regimes on the international governance of CDR and SRM

- What are the main principles and criteria for evaluating policy options?
- What do you think of the following policy options:
  - distinguish between CDR and solar radiation modification (SRM) in dedicated governance
  - accelerate authoritative international scientific assessment
  - encourage the research, development, and responsible use of CDR technologies as well as the design of associated financial incentive systems
  - facilitate the elaboration and implementation of non-state governance
  - explore potential further governance of SRM while refraining from judgements concerning its ultimate use.
- In your view, what legal instruments and/or institutions should be tasked with international governance of CDR and/or SRM?

References and endnotes

Introduction

C2G (2020) Emerging Technologies Terminology — A Living Guide. Carnegie Climate Governance Initiative website. Available at: https://www.c2g2.net/terminology-guide/ (Accessed: 10 May 2020).

CBD (2016) Decision XIII/14, 'Climate-Related Geoengineering' UN Doc CBD/COP/DEC/XIII/14.

Djelic, M. and Sahlin-Andersson, K. (eds) (2006) Transnational Governance: Institutional Dynamics of Regulation. Cambridge: Cambridge University Press. doi: DOI: 10.1017/CBO9780511488665.

Gupta, A. and Möller, I. (2018) 'De facto governance: how authoritative assessments construct climate engineering as an object of governance', Environmental Politics. doi: 10.1080/09644016.2018.1452373.

Heyward, C. (2013) 'Situating and Abandoning Geoengineering: A Typology of Five Responses to Dangerous Climate Change', PS: Political Science & Politics, 46. doi: 10.1017/S1049096512001436.

IPCC (2012) Managing the risks of extreme events and disasters to advance climate change adaptation: A special report of working groups I and II of the Intergovernmental Panel on Climate Change. Edited by C. B. Field et al. Cambridge, UK, and New York, USA.

IPCC (2014) Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Edited by Core Writing Team, R. K. Pachauri, and L. A. Meyer. Geneva, Switzerland. Available at: http://www.ipcc.ch/report/ar5/syr (Accessed: 15 July 2019).

IPCC (2018a) 'Annex I: Glossary', in Masson-Delmotte, V. et al. (eds) Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. In press. Available at: https://www.ipcc.ch/sr15/chapter/glossary/.

IPCC (2018b) Global warming of 1.5 °C: An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of change, sustainable development, and efforts to eradicate poverty. Edited by Masson- Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma- Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, T. Waterfield. Geneva, Switzerland. Available at: https://www.ipcc.ch/sr15/ (Accessed: 10 July 2019).

IPCC (2019a) Climate change and land: IPCC Special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems (SRCCL). Edited by P. R. Shukla et al. Available at https://www.ipcc.ch/srccl-report-download-page/(Accessed: 10 April 2020).

IPCC (2019b) IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC). Edited by N. M. W. H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama. In press. Available at: https://report.ipcc.ch/srocc/(Accessed: 10 May 2020).

Keith, D. W. (2000) 'Geoengineering The Climate: History and Prospect', Annual Review of Energy and Environment, 25, pp. 245–84.

Minx, J. C. et al. (2018) 'Negative emissions—Part 1: Research landscape and synthesis', Environmental Research Letters. IOP Publishing, 13(6), p. 63001. doi: 10.1088/1748-9326/aabf9b.

NAS (National Academies of Sciences Engineering and Medicine) (2019) Negative Emissions Technologies and Reliable Sequestration: A Research Agenda. Washington, DC: The National Academies Press. doi: 10.17226/25259.

Ostrom, E. (2005) Understanding institutional diversity. Princeton: Princeton University Press.

Ostrom, E. (2010) 'Polycentric systems for coping with collective action and global environmental change', Global Environmental Change, 20(4), pp. 550–557. doi: 10.1016/j.gloenvcha.2010.07.004.

Pacala, R. and Socolow, S. (2004) 'Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies', Science, 305(5686), pp. 968–972. doi: 10.1126/science.1100103.

Rockström, J. et al. (2017) 'A roadmap for rapid decarbonization', Science, 355, pp. 1269–1271. doi: 10.1126/science.aah3443.

van Vuuren, D. P. et al. (2018) 'Alternative pathways to the 1.5 °C target reduce the need for negative emission technologies', Nature Climate Change, 8(5), pp. 391–397. doi: 10.1038/s41558-018-0119-8.

UNEP (2017) The Emissions Gap Report 2017. A UN Environment Synthesis Report. Nairobi, Kenya: United Nations Environment Programme (UNEP). Available at: https://wedocs.unep.org/bitstream/handle/20.500.11822/22070/EGR_2017.pdf

Chapter 1

ACIRA (2019) 'Atmospheric Climate Intervention Research Act'. Washington: House - Science Space and Technology. 116th Congress H.R.5519. Available at: https://www.congress.gov/bill/116th-congress/house-bill/5519/all-info.

Adams, E. *et al.* (2002) 'International Field Experiment on Ocean Carbon Sequestration', *Environmental Science & Technology*. American Chemical Society, 36(21), pp. 399A-399A. doi: 10.1021/es022442b.

Albrecht, B. (1989) 'Aerosols, Cloud Microphysics, and Fractional Cloudiness', *Science*, 245(4923), pp. 1227–1230. doi: 10.1126/science.245.4923.1227.

Alexander D: Rounsevell, M: Hillier, J: Smith, P, P. M. (2014) 'Cost and potential of carbon abatement from the UK perennial energy crop market', *GCB Bioenergy*, 6(2), pp. 156–168. doi: 10.1111/gcbb.12148.

Andersson, V. et al. (2003) Hydrates for Deep Ocean Storage of CO2. IEA Greenhouse Gas R&D Programme. Available at: https://ieaghg.org/docs/General_Docs/Reports/PH4-26 CO2 hydrates.pdf.

Asayama, S. and Hulme, M. (2019) 'Engineering climate debt: temperature overshoot and peak-shaving as risky subprime mortgage lending', *Climate Policy*. Taylor & Francis, 19(8), pp. 937–946. doi: 10.1080/14693062.2019.1623165.

Aziz, A. *et al.* (2014) 'Long-term stabilization of reflective foams in sea water', *RSC Adv.*, 4. doi: 10.1039/C4RA08714C.

Bain Bonn, A., Stoneman, R., Chapman, S., Coupar, A., Evans, M., Gearey, B., Howat, M., Joosten, H., Keenleyside, C., Labadz, J., Lindsay, R., Littlewood, N., Lunt, P., Miller, C.J., Moxey, A., Orr, H., Reed, M., Smith, P., Swales, V., Thompson, D.B.A., C. G. (2011) *IUCN Commission of Inquiry on Peatlands*, *The Peatland Programme*. Edinburgh, UK. Available at: https://www.iucn-uk-peatlandprogramme.org/sites/default/files/2019-07/IUCN%20UK%20Commission%20of%20Inquiry%20on%20Peatlands%20Full%20Report%20spv%20web_0.pdf

Barret (2019) 'Some Thoughts on Solar Geoengineering Governance', in Stowe., R. N. S. and R. C. (ed.) *Governance of the Deployment of Solar Geoengineering*. Cambridge, USA: Harvard Project on Climate Agreements, February 2019, p. 33.

Bellamy, R., Lezaun, J. and Palmer, J. (2017) 'Public perceptions of geoengineering research governance: An experimental deliberative approach', *Global Environmental Change*, 45, pp. 194–202. doi: 10.1016/j.gloenvcha.2017.06.004.

Berdahl, M. *et al.* (2014) 'Arctic cryosphere response in the Geoengineering Model Intercomparison Project G3 and G4 scenarios', *Journal of Geophysical Research: Atmospheres*, 119(3), pp. 1308–1321. doi: 10.1002/2013jd020627.

Beuttler, C. *et al.* (2019) *The Role of Atmospheric Carbon Dioxide Removal in Swiss Climate Policy: Fundamentals and Recommended Actions*. Bern: Report by Risk Dialogue Foundation. Commissioned by the Federal Office for the Environment. Available at: https://www.bafu.admin.ch/dam/bafu/en/dokumente/klima/externe-studien-berichte/the-role-of-atmospheric-carbon-dioxide-removal-in-swiss-climate-policy.pdf.download.pdf/The_Role_of_Atmospheric_Carbon_Dioxide_Removal_in_Swiss_Climate_Policy.pdf.

Bopp, L. *et al.* (2013) 'Multiple stressors of ocean ecosystems in the 21st century: Projections with CMIP5 models', *Biogeosciences*, 10(10), pp. 6225–6245. Available at: https://doi.org/10.5194/bg-10-6225-2013.

Boyd, Philip W. (2013) 'Ocean Fertilization for Sequestration of Carbon Dioxide from the Atmosphere BT - Geoengineering Responses to Climate Change: Selected Entries from the Encyclopedia of Sustainability Science and Technology', in Lenton, T. and Vaughan, N. (eds). New York, NY: Springer New York, pp. 53–72. doi: 10.1007/978-1-4614-5770-1_5.

Brewer, P. *et al.* (2005) 'Deep ocean experiments with fossil fuel carbon dioxide: Creation and sensing of a controlled plume at 4 km depth', *Journal of Marine Research*, 63, pp. 9–33. doi: 10.1357/0022240053693860.

Breyer, C., Faishi, M. and Aghahosseini, A. (2019) 'Carbon Dioxide Direct Air Capture For Effective Climate Change Mitigation Based On Renewable Electricity: A New Type Of Energy System Sector Coupling', *Mitigation and Adaptation Strategies for Global Change*, 25, pp. 43–65. doi: 10.1007/s11027-019-9847-y.

BRF (2018) 'Barrier Reef Foundation. Media release: Reef "sun shield" trials show promise to prevent coral bleaching'. Available at: https://www.barrierreef.org/latest/news/reef-sun-shield-trials-show-promise-to-prevent-coral-bleaching.

Burns, E. T. *et al.* (2016) 'What do people think when they think about solar geoengineering? A review of empirical social science literature, and prospects for future research', *Earth's Future*, 4(11), pp. 536–542. doi: 10.1002/2016ef000461.

C2G (2020) Carnegie Climate Governance Initiative Publications: Evidence and Policy Briefs, Infographics and Reports 2019 – 2020.

CCS (2018) *Global Status Report 2018*. Online: Global CCS Institute. Available at: https://www.globalccsinstitute.com/.

CE (2019) *Carbon Engineering*. Available at: https://carbonengineering.com/.

Cecco, L. (2019) 'Canadian cities take wooden skyscrapers to new heights ', *The Guardian Newspaper*. Available at: https://www.theguardian.com/cities/2019/jul/22/canadian-cities-take-wooden-skyscrapers-to-new-heights.

Chung, I. K. *et al.* (2013) 'Installing kelp forests/seaweed beds for mitigation and adaptation against global warming: Korean Project Overview', *ICES Journal of Marine Science*, 70(5), pp. 1038–1044. doi: 10.1093/icesjms/fss206.

Chung, I. K., Sondak, C. F. A. and Beardall, J. (2017) 'The future of seaweed aquaculture in a rapidly changing world', *European Journal of Phycology*. Taylor & Francis, 52(4), pp. 495–505. doi: 10.1080/09670262.2017.1359678.

Climeworks (2019) *Climeworks - capturing CO2 from air - our technology*. Available at: http://www.climeworks.com/our-technology/.

Corner, A., Capstick, S. and Pidgeon, N. (2014) Public Perceptions Of Ocean Acidification: Summary Findings Of Two Nationally Representative Surveys Of The British Public Conducted During September 2013 And May 2014, Understanding Risk Research Group Working Paper 14-01,Cardiff University.

Cottier-Cook, E. J. et al. (2016) Safeguarding the future of the global seaweed aquaculture industry.

Cowie, A. *et al.* (2017) 'biochar as a strategy for sustainable land management and climate change mitigation', in *Proceedings of the global symposium on soil organic carbon*. Rome, Italy: FAO.

Cziczo, D. J. *et al.* (2019) 'Unanticipated Side Effects of Stratospheric Albedo Modification Proposals Due to Aerosol Composition and Phase', *Scientific Reports*, 9, p. 18825.

Daggash, H. et al. (2019) Bioenergy with carbon capture and storage, and direct air carbon capture and storage: Examining the evidence on deployment potential and costs in the UK , UK Energy Research Centre Technology and Policy Assessment . Edited by C. for E. P. and Technology. Imperial College Centre for Energy Policy and Technology . Available at:

http://www.ukerc.ac.uk/programmes/technology-and-policy-assessment/bioenergy-with-ccas.html.

Desch, N. *et al.* (2017) 'Arctic ice management', *Earth's Future*, 5(1), pp. 107–127. doi: 10.1002/2016ef000410.

Eisaman, M. D. *et al.* (2018) 'Indirect ocean capture of atmospheric CO2: Part II. Understanding the cost of negative emissions', *International Journal of Greenhouse Gas Control*, 70, pp. 254–261. doi: 10.1016/j.ijggc.2018.02.020.

FCP (2020) *What is REDD+?*, *Forest Carbon Partnership*. Available at: https://www.forestcarbonpartnership.org/what-redd (Accessed: 1 April 2020).

Fuss, S. *et al.* (2018) 'Negative emissions—Part 2: Costs, potentials and side effects', *Environmental Research Letters*. IOP Publishing, 13(6), p. 63002. doi: 10.1088/1748-9326/aabf9f.

Gammon, K. and Hulme, M. (2017) 'Geoengineering at the "Edge of the World": Exploring Perceptions of Ocean Fertilization through the Haida Salmon Restoration Corporation.', in Economcs, L. S. of (ed.) *Grantham Research Institute on Climate Change and the Environment*. Available at: http://www.lse.ac.uk/GranthamInstitute/wp-content/uploads/2017/09/Working-Paper-280-Gannon-Hulme-1.pdf.

Genesio, L. *et al.* (2012) 'Surface albedo following biochar application in durum wheat', *Environmental Research Letters*. IOP Publishing, 7(1), p. 14025. doi: 10.1088/1748-9326/7/1/014025.

GeoMIP (2020) *Geoengineering Model Intercomparison Project.* Rutgers University. Available at: http://climate.envsci.rutgers.edu/GeoMIP/ (Accessed: 10 April 2020).

GESAMP (2019) *High Level Review of a Wide Range of Proposed Marine Geoengineering Techniques*, *GESAMP Reports and Studies*. Joint Group of Experts on the Scientific Aspects of Marine Environment Protection (GESAMP). Available at: http://www.gesamp.org/publications/high-level-review-of-a-wide-range-of-proposed-marine-geoengineering-techniques.

Gewin, V. (2002) 'Ocean carbon study to quit Hawaii', *Nature*, 417, p. 888.

Goeppert, A. *et al.* (2012) 'Air as the renewable carbon source of the future: an overview of CO2 capture from the atmosphere', *Energy & Environmental Science*. The Royal Society of Chemistry, 5(7), pp. 7833–7853. doi: 10.1039/C2EE21586A.

Goldberg, D. S., Takahashi, T. and Slage, A. L. (2008) 'Carbon dioxide sequestration in deep-sea basalt', *Proceedings of the National Academy of Sciences*, 105, pp. 9920–9925.

Goldthorpe, S. (2017) 'Potential for Very Deep Ocean Storage of CO2 Without Ocean Acidification: A Discussion Paper', *Energy Procedia*, 114, pp. 5417–5429. doi: 10.1016/j.egypro.2017.03.1686.

Govindasamy, B. and Nag, B. (2011) 'Albedo enhancement over land to counteract global warming: Impacts on hydrological cycle', *Climate Dynamics*, 39. doi: 10.1007/s00382-011-1256-1.

GreenWave ClimateWorks and 3Degrees, O. 2050 (2019) 'These are companies or bodies working in the agenda. There websites are https://www.greenwave.org/ http://oceans2050.com/ https://www.climateworks.org/ https://3degreesinc.com/'.

Griscom, B. W. *et al.* (2017) 'Natural climate solutions', *Proceedings of the National Academy of Sciences*, 114(44), pp. 11645–11650. doi: 10.1073/pnas.1710465114.

Gross, R. *et al.* (2018) 'How long does innovation and commercialisation in the energy sectors take? Historical case studies of the timescale from invention to widespread commercialisation in energy supply and end use technology', *Energy Policy*, 123, pp. 682–699. doi: 10.1016/j.enpol.2018.08.061.

Gustavsson Roger, L. S. (2011) 'Energy and CO2 analysis of wood substitution in construction', *Climatic Change*, 105(1), pp. 129–153. doi: 10.1007/s10584-010-9876-8.

Hammond S: Sohi, S: Brownsort, P, J. : S. (2011) 'Prospective life cycle carbon abatement for pyrolysis biochar systems in the UK', *Energy Policy*, 39(5), pp. 2646–2655. doi: 10.1016/j.enpol.2011.02.033.

Harrison, D. P. (2017) 'Global negative emissions capacity of ocean macronutrient fertilization', *Environmental Research Letters*, 12.

Honegger, M., Michaelowa, A. and Poralla, M. (2019) *Net-Zero Emissions: The role of Carbon Dioxide Removal in the Paris Agreement*, *Briefing Report*. Freiburg: Perspectives Climate Research. Available at: https://www.perspectives.cc/fileadmin/Publications/Situating_NETs_under_the_PA.pdf.

Horowitz, H. M. *et al.* (2020) 'Effects of Sea Salt Aerosol Emissions for Marine Cloud Brightening on Atmospheric Chemistry: Implications for Radiative Forcing', *Geophysical Research Letters*, 47(4), p. e2019GL085838. doi: 10.1029/2019gl085838.

Horton, J. (2019) *Evaluating Solar Geoengineering Deployment Scenarios in Governance of the Deployment of Solar Geoengineering*. Edited by R. N. S. and R. C. Stowe. Cambridge, USA: Harvard Project on Climate Agreements, February 2019.

Houghton, R. A. (2013) 'The Emissions Of Carbon From Deforestation And Degradation In The Tropics: Past Trends And Future Potential', *Carbon Management*. Taylor & Francis, 4(5), pp. 539–546. doi: 10.4155/cmt.13.41.

House, K. . *et al.* (2006) 'Permanent carbon dioxide storage in deep-sea sediments', *Proceedings of the National Academy of Sciences*, 103(33), pp. 12291–12295.

Howard, A. *et al.* (2017) 'Clarifying the role of coastal and marine systems in climate mitigation', *Frontiers in Ecology and the Environment*, 15(1), pp. 42–50. doi: 10.1002/fee.1451.

Hu, S. *et al.* (2017) 'Global wetlands: Potential distribution, wetland loss, and status', *Science of The Total Environment*, 586, pp. 319–327. doi: 10.1016/j.scitotenv.2017.02.001.

ICE911 (2019) *ICE911 Annual Reort 2018-2019*. Edited by L. Field. Available at:

https://www.ice911.org/annual-report.

Infinitree (2019) *Carbon Capture Greenhouse Enrichment - Infinitree LCC*. Available at:

http://www.infinitreellc.com/.

International Biochar Initiative (2019) *Details about the initiative are available here*. Available at: https://biochar-international.org/.

IPCC (2007) AR4 Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Solomon SD, Qin D, Manning M, Chen Z, Marquie M, Averyt KB, Tignor M and Miller HL (eds). Cambridge and New York: Cambridge University Press. Available at: https://www.ipcc.ch/report/ar4/wg1/.

IPCC (2013) Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Edited by T. F. [Stocker D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia. Available at:

http://www.climatechange2013.org/images/report/WG1AR5_ALL_FINAL.pdf.

IPCC (2014a) Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Edited by O. Edenhofer R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel & J.C. Minx. Cambridge, United Kingdom.

IPCC (2014b) AR5 Synthesis Report: Climate Change 2014. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Edited by Core Writing Team, R. K. Pachauri, and L. A. Meyer. Geneva, Switzerland. Available at: www.ipcc.ch/report/ar5/syr.

IPCC (2018) Global warming of 1.5 °C: An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change. Edited by . Masson- Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma- Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, T. Waterfield. Geneva, Switzerland. Available at: https://www.ipcc.ch/sr15/.

IUCN (2016) *Nature-based solutions to address climate change*. Paris, France: International Union for Conservation of Nature. Available at: http://www.uicn.fr/solutions-fondees-sur-la-nature.html.

Jiang, J. *et al.* (2019) 'Stratospheric Sulfate Aerosol Geoengineering Could Alter the High-Latitude Seasonal Cycle', *Geophysical Research Letters*, 46(23), pp. 14153–14163. doi: 10.1029/2019gl085758.

Junk Shuqing: Finlayson, C. M.: Gopal, Brij: Květ, Jan: Mitchell, Stephen A.: Mitsch, William J.: Robarts, Richard D., W. J. . A. (2013) ‘Current state of knowledge regarding the world’s wetlands and their future under global climate change: a synthesis’, *Aquatic Sciences*, 75(1), pp. 151–167. doi: 10.1007/s00027-012-0278-z.

Kayranli M. Mustafa, A. Hedmark, A., B. S. (2010) ‘Carbon Storage and Fluxes within Freshwater Wetlands: a Critical Review’, *Wetlands*, 30(1), pp. 111–124. Available at:
https://link.springer.com/article/10.1007%2Fs13157-009-0003-4#citeas.

Keesstra, S. *et al.* (2016) ‘The significance of soils and soil science towards realization of the United Nations sustainable development goals’, *SOIL*, 2(2), pp. 111–128. Available at: 10.5194/soil-2-111-2016.

Keith A, D. P. (2013) ‘The Fate of an Engineered Planet’, *Scientific American*, pp. 34–36.

Keith, D. *et al.* (2016) ‘Stratospheric solar geoengineering without ozone loss’, *Proceedings of the National Academy of Sciences*, 113(52), pp. 14910–14914. doi: 10.1073/pnas.1615572113.

Keith, D. H., St. Angelo, D. and Heidel, K. (2018) ‘A Process for Capturing CO2 from the Atmosphere’, *Joule*. Elsevier, 2(8), pp. 1573–1594. doi: 10.1016/j.joule.2018.05.006.

Keith, D. W. (2000) ‘Geoengineering The Climate: History and Prospect’, *Annual Review of Energy and Environment*, 25, pp. 245–84.

King, D. (2019) ‘David King on Climate repair - an interview’, *Talking Politics*. Edited by D. Rumsfen. Online https://www.talkingpoliticspodcast.com/blog/2019/160-david-king-on-climate-repair.

Kosgui (2011) ‘Climate-economy modeling considering solar radiation management and its termination risk’, *1st International Conference on Simulation and Modeling Methodologies, Technologies and Applications.*

Koytsoumpa, E. I., Bergins, C. and Kakaras, E. (2018) ‘The CO2 economy: Review of CO2 capture and reuse technologies’, *The Journal of Supercritical Fluids*, 132, pp. 3–16. doi: 10.1016/j.supflu.2017.07.029.

Lal, R. (2011) ‘Sequestering carbon in soils of agro-ecosystems’, *Food Policy*, 36, pp. S33–S39. doi: 10.1016/j.foodpol.2010.12.001.

Lal, R. (2013) ‘Soil carbon management and climate change’, *Carbon Management*. Taylor & Francis, 4(4), pp. 439–462. doi: 10.4155/cmt.13.31.

LATHAM, J., RASCH, P., CHEN, C. C., KETTLES, L., GADIAN, A., GETTELMAN, A., MORRISON, H., LAWRENCE, C. R. & NEFF, J. C. 2009. The contemporary physical and chemical flux of aeolian dust: A synthesis of direct measurements of dust deposition. Chemical Geology, 267, 46-63. Available at https://www.sciencedirect.com/science/article/pii/S0009254109000655

LATHAM, J. B., K.: CHOULARTON, T.: COE, H.: CONNOLLY, P.: COOPER, G.: CRAFT, T.: FOSTER, J.: GADIAN, A.: GALBRAITH, L.: IACOVIDES, H.: JOHNSTON, D.: LAUNDER, B.: LESLIE, B.: MEYER, J.: NEUKERMANS, A.: ORMOND, B.: PARKES, B.: RASCH, P.: RUSH, J.: SALTER, S.: STEVENSON, T.: WANG, H.: WANG, Q.: WOOD, R. 2012. Marine cloud brightening. *Philos Trans A Math Phys Eng Sci,* 370**,** 4217-62.

LAW, C. S. 2008. Predicting and monitoring the effects of large-scale ocean iron fertilization on marine trace gas emissions. *Marine Ecology Progress Series,* 364**,** 283-288.

LEESON, D., MAC DOWELL, N., SHAH, N., PETIT, C. & FENNELL, P. S. 2017. A Techno-economic analysis and systematic review of carbon capture and storage (CCS) applied to the iron and steel, cement, oil refining and pulp and paper industries, as well as other high purity sources. *International Journal of Greenhouse Gas Control,* 61**,** 71-84.

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

LENTON, T. M., & VAUGHAN, N. E. (2009). The radiative forcing potential of different climate geoengineering options. Atmospheric Chemistry and Physics, 9(15), 5539–5561. 10.5194/acp-9-5539-2009 Accessed 8 July 2019.

LIVERMONT, E., KOH, Y., BHAWANIN, M., MLAMBO, T., & ZHAO, B. (2011). Carbon Capture and Storage in Deep Ocean Space for the 21St Century (Vol. 1).

https://www.southampton.ac.uk/assets/imported/transforms/content-block/UsefulDownloads_Download/D921E0011577432A819AED0B70D9117E/Gr_A_CCS_in_Deep_Ocean_Space[1].pdf Accessed 3 April 2020

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

LOHMANN, U. G., BLAŽ 2017. A cirrus cloud climate dial? *Science,* 357**,** 248-249.

LUYSSAERT, S. M., GUILLAUME: VALADE, AUDE: CHEN, YI-YING: NJAKOU DJOMO, SYLVESTRE: RYDER, JAMES: OTTO, JULIANE: NAUDTS, KIM: LANSØ, ANNE SOFIE: GHATTAS, JOSEFINE: MCGRATH, MATTHEW J. 2018. Trade-offs in using European forests to meet climate objectives. *Nature,* 562**,** 259-262.

MACE, M. F., C: SCHAEFFER, M : HARE, W.L 2018. Governing large-scale carbon dioxide removal: are we ready? : Carnegie Climate Geoengineering Governance Initiative (C2G2)

MACNAGHTEN, P. O., RICHARD 2011. Good governance for geoengineering. *Nature,* 479**,** 293-293.

MACNAGHTEN, P. & SZERSZYNSKI, B. 2013. Living the global social experiment: An analysis of public discourse on solar radiation management and its implications for governance. *Global Environmental Change,* 23**,** 465-474.

MARCHESIELLO, P., LEFÈVRE, J., VEGA, A., COUVELARD, X. & MENKES, C. 2010. Coastal upwelling, circulation and heat balance around New Caledonia's barrier reef. *Marine pollution bulletin,* 61**,** 432-48.

MATEAR, R. J. & ELLIOTT, B. 2004. Enhancement of oceanic uptake of anthropogenic CO_2 by macronutrient fertilization. *Journal of Geophysical Research: Oceans,* 109.

MATTER, J. M. & KELEMEN, P. B. 2009. Permanent storage of carbon dioxide in geological reservoirs by mineral carbonation. *Nature Geoscience,* 2**,** 837.

MATTHEWS, H. & CALDEIRA, K. 2007. Transient Climate-Carbon Simulations of Planetary Geoengineering. *Proceedings of the National Academy of Sciences,* 104**,** 9,949–54.

MCCLELLAN, J., KEITH, D. W. & APT, J. 2012. Cost analysis of stratospheric albedo modification delivery systems. *Environmental Research Letters,* 7**,** 034019.

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

MERCADO, L. M., BELLOUIN, N., SITCH, S., BOUCHER, O., HUNTINGFORD, C., WILD, M. & COX, P. M. 2009. Impact of changes in diffuse radiation on the global land carbon sink. Nature, 458, 1014-1017 Available at https://www.ncbi.nlm.nih.gov/pubmed/19396143

MERK, C., KLAUS, G., POHLERS, J., ERNST, A., OTT, K. & REHDANZ, K. 2019. Public perceptions of climate engineering: Laypersons' acceptance at different levels of knowledge and intensities of deliberation. *GAIA – Ecological Perspectives for Science and Society,* 28**,** 348-355.

MERK, C. P., GERT: KNIEBES, CAROLA: REHDANZ, KATRIN: SCHMIDT, ULRICH 2015. Exploring public perceptions of stratospheric sulfate injection. *Climatic Change,* 130**,** 299-312.

METZ, B., DAVIDSON, O., DE CONINCK, H., LOOS, M. & MEYER, L. 2005. IPCC Special Report on Carbon dioxide Capture and Storage. *Policy Stud.*

MINASNY, B. M., BRENDAN P.: MCBRATNEY, ALEX B.: ANGERS, DENIS A.: ARROUAYS, DOMINIQUE: CHAMBERS, ADAM: CHAPLOT, VINCENT: CHEN, ZUENG-SANG: CHENG, KUN: DAS, BHABANI S.: FIELD, DAMIEN J.: GIMONA, ALESSANDRO: HEDLEY, CAROLYN B.: HONG, SUK YOUNG: MANDAL, BISWAPATI: MARCHANT, BEN P.: MARTIN, MANUEL: MCCONKEY, BRIAN G.: MULDER, VERA LEATITIA: O'ROURKE, SHARON: RICHER-DE-FORGES, ANNE C.: ODEH, INAKWU: PADARIAN, JOSÉ: PAUSTIAN, KEITH: PAN, GENXING: POGGIO, LAURA: SAVIN, IGOR: STOLBOVOY, VLADIMIR: STOCKMANN, UTA: SULAEMAN, YIYI: TSUI, CHUN-CHIH: VÅGEN, TOR-GUNNAR: VAN WESEMAEL, BAS: WINOWIECKI, LEIGH 2017. Soil carbon 4 per mille. *Geoderma,* 292**,** 59-86.

MOORE, J. C. 2018. Geoengineer polar glaciers to slow sea-level rise. *Nature,* 555.

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

MORTON, O. 2015. *The planet remade. How geoengineering could change the world.,* Great Britian, Granta Books.

NALAM, A., GOVINDASAMY, B. & MODAK, A. 2017. Arctic Geoengineering: Effects on precipitation in tropical monsoon regions. Available at https://link.springer.com/article/10.1007/s00382-017-3810-y

N'YEURT, A. D. R. C., DAVID P.: CAPRON, MARK E.: STEWART, JIM R.: HASAN, MOHAMMED A. 2012. Negative carbon via Ocean Afforestation. *Process Safety and Environmental Protection,* 90**,** 467-474.

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

NRC 2015. Climate Intervention: Reflecting Sunlight to Cool Earth, Washington, DC, The National Academies Press.

OCEANEOS (2019). Ocaneaous website. http://oceaneos.org/company/ Accessed 4 July 2019

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

ONC (2019) The Ocean Nourishment Corporation Pty Ltd website Available http://www.oceannourishment.com/ Accessed on 5 July 2019

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

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

PAN, Y., FAN, W., ZHANG, D., CHEN, J., HUANG, H., LIU, S., JIANG, Z., DI, Y., TONG, M. & CHEN, Y. 2016. Research progress in artificial upwelling and its potential environmental effects. *Science China Earth Sciences,* 59**,** 236-248.

PAN, Y., LI, Y., FAN, W., ZHANG, D., QIANG, Y., JIANG, Z.-P. & CHEN, Y. 2019. A Sea Trial of Air-Lift Concept Artificial Upwelling in the East China Sea. *Journal of Atmospheric and Oceanic Technology,* 36**,** 2191-2204.

PARK, C.-E., JEONG, S.-J., FAN, Y., TJIPUTRA, J., MURI, H. & ZHENG, C. 2019. Inequal Responses of Drylands to Radiative Forcing Geoengineering Methods. *Geophysical Research Letters,* 46**,** 14011-14020

PARKER, A. & IRVINE, P. J. 2018. The Risk of Termination Shock From Solar Geoengineering. *Earth's Future,* 6**,** 456-467.

PEREIRA, R. Y., CHARLES: CRITCHLEY, ALAN T. 2013. Seaweed Aquaculture for Human Foods in Land-Based and IMTA Systems. *In:* CHRISTOU, P. S., ROXANA: COSTA-PIERCE, BARRY A.: MISZTAL, IGNACY: WHITELAW, C. BRUCE A. (ed.) *Sustainable Food Production.* New York, NY: Springer New York.

PIDGEON, N. C., A.: PARKHILL, K.: SPENCE, A.: BUTLER, C.: POORTINGA, W. 2012. Exploring early public responses to geoengineering. *Philos Trans A Math Phys Eng Sci,* 370**,** 4176-96.

PIDGEON, N. F. & SPENCE, E. 2017. Perceptions of enhanced weathering as a biological negative emissions option. *Biology Letters,* 13**,** 20170024.

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

POWLSON, D. S. G., P. J.: WHALLEY, W. R.: QUINTON, J. N.: HOPKINS, D. W.: WHITMORE, A. P.: HIRSCH, P. R.: GOULDING, K. W. T. 2011. Soil management in relation to sustainable agriculture and ecosystem services. *Food Policy,* 36**,** S72-S87.

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

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

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

RENFORTH, P. 2012. The potential of enhanced weathering in the UK. *International Journal of Greenhouse Gas Control,* 10**,** 229-243.

REYNOLDS, J. 2019. Solar geoengineering to reduce climate change: a review of governance proposals. Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences, 475, 20190255. Available at https://royalsocietypublishing.org/doi/10.1098/rspa.2019.0255

RICKE, K. L., MORENO-CRUZ, J. B. & CALDEIRA, K. 2013. Strategic incentives for climate geoengineering coalitions to exclude broad participation. *Environmental Research Letters,* 8**,** 014021.

RIDGWELL, A., SINGARAYER, J. S., HETHERINGTON, A. & VALDES, P. 2009. Tackling regional climate change by leaf albedo biogeoengineering. *Current Biology,* 19**,** 146-150.

ROBOCK, A., MARQUARDT, A., KRAVITZ, B. & STENCHIKOV, G. 2009. Benefits, risks, and costs of stratospheric geoengineering. *Geophysical Research Letters,* 36.

ROBOCK, A. 2018. Stratospheric Sulfur Geoengineering—Benefits and Risks American Metrological Society 98th Annual Meeting Austin, Texas.

ROBOCK, A. 2020. Benefits and Risks of Stratospheric Solar Radiation Management for Climate Intervention (Geoengineering). *The Bridge – linking engineering and society. The National Academies of Sciences, Engineering and Medicine.* Spring 2020.

RODRÍGUEZ, A. C., SABRINA: BRITO, ALBERTO: HERNÁNDEZ, JOSÉ CARLOS 2018. Effects of ocean acidification on algae growth and feeding rates of juvenile sea urchins. *Marine Environmental Research,* 140**,** 382-389.

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

RUSSELL, L. M., SOROOSHIAN, A., SEINFELD, J. H., ALBRECHT, B. A., NENES, A., AHLM, L. WONASCHÜTZ, A 2013. Eastern pacific emitted aerosol cloud experiment. Bulletin of the American Meteorological Society, 94**,** 709-729.Available at https://arizona.pure.elsevier.com/en/publications/eastern-pacific-emitted-aerosol-cloud-experiment

RRAP 2020. Reef Restoration and Adaptation Program. In: KOOPMAN, D. (ed.) A partnership helping the Great Barrier Reef resist, adapt and recover.

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

SAMARI, M., RIDHA, F., MANOVIC, V., MACCHI, A. & ANTHONY, E. J. 2019. Direct capture of carbon dioxide from air via lime-based sorbents. *Mitigation and Adaptation Strategies for Global Change*.

SÁNCHEZ J-P, MCINNES CR (2015) Optimal Sunshade Configurations for Space-Based Geoengineering near the Sun-Earth L_1 Point. PLoS ONE 10(8): e0136648. 10.1371/journal.pone.0136648

SANDALOW, D., FRIEDMANN, J., MCCORMIC, C. & MCCOY, S. 2018. Direct Air Capture of Carbon Dioxide. *ICEF Roadmap 2018.* Innovation for Cool Earth Forum.

SANZ-PÉREZ, E. S., MURDOCK, C. R., DIDAS, S. A. & JONES, C. W. 2016. Direct Capture of CO_2 from Ambient Air. *Chemical Reviews,* 116**,** 11840-11876.

SAREWITZ, D. 2010. Not by experts alone. Nature, 466 (688) Available at https://www.nature.com/articles/466688a

SCOPEX. 2019. Stratospheric Controlled Perturbation Experiment (SCoPEx) [Online]. 12, Oxford St, Cambridge, MA 02138, USA: Harvard University. Available : https://projects.iq.harvard.edu/keutschgroup/scopex

SCU 2020. Scientists trial world-first 'cloud brightening' technique to protect corals. *In:* UNIVERSITY, S. C. (ed.). Online: https://www.gbrrestoration.org/

SEITZ, R. 2011. Bright water: hydrosols, water conservation and climate change. *Climatic Change,* 105**,** 365-381.

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

SHACKLEY, S. H., J: GAUNT, J: IBARROLA, R 2015. CostsBiochar.

SHAKHOVA, N., SEMILETOV, I., SALYUK, A., YUSUPOV, V., KOSMACH, D. & GUSTAFSSON, Ö. 2010. Extensive Methane Venting to the Atmosphere from Sediments of the East Siberian Arctic Shelf. *Science,* 327**,** 1246-1250.

SHEPHERD, J. 2009. Geoengineering the climate – science, governance and uncertianty. *RS Policy Document 10/09.* London: The Royal Society.

SIGFÚSSON, B., ARNARSON, M. Þ., SNÆBJÖRNSDÓTTIR, S. Ó., KARLSDÓTTIR, M. R., ARADÓTTIR, E. S. & GUNNARSSON, I. 2018. Reducing emissions of carbon dioxide and hydrogen sulphide at Hellisheidi power plant in 2014-2017 and the role of CarbFix in achieving the 2040 Iceland climate goals. *Energy Procedia,* 146**,** 135-145.

SILVER, M. W., BARGU, S., COALE, S. L., BENITEZ-NELSON, C. R., GARCIA, A. C., ROBERTS, K. J., SEKULA-WOOD, E., BRULAND, K. W. & COALE, K. H. 2010. Toxic diatoms and domoic acid in natural and iron enriched waters of the oceanic Pacific. *Proceedings of the National Academy of Sciences,* 107**,** 20762-20767.

SIMPSON, I. R., TILMES, S., RICHTER, J. H., KRAVITZ, B., MACMARTIN, D. G., MILLS, M. J., FASULLO, J. T. & PENDERGRASS, A. G. 2019. The Regional Hydroclimate Response to Stratospheric Sulfate Geoengineering and the Role of Stratospheric Heating. *Journal of Geophysical Research: Atmospheres,* 124**,** 12587-12616.

SKYTREE. 2019. *Air recirculation in closed spaces. Water and carbon dioxide extraction solutions* [Online]. Available: https://www.skytree.eu/ [Accessed 6 December 2019].

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

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

SMITH, P. D., STEVEN J.: CREUTZIG, FELIX: FUSS, SABINE: MINX, JAN: GABRIELLE, BENOIT: KATO, ETSUSHI: JACKSON, ROBERT B.: COWIE, ANNETTE: KRIEGLER, ELMAR: VAN VUUREN, DETLEF P.: ROGELJ, JOERI: CIAIS, PHILIPPE: MILNE, JENNIFER: CANADELL, JOSEP G.: MCCOLLUM, DAVID: PETERS, GLEN: ANDREW, ROBBIE: KREY, VOLKER: SHRESTHA, GYAMI: FRIEDLINGSTEIN, PIERRE: GASSER, THOMAS: GRÜBLER, ARNULF: HEIDUG, WOLFGANG K.: JONAS, MATTHIAS: JONES, CHRIS D.: KRAXNER, FLORIAN: LITTLETON, EMMA: LOWE, JASON: MOREIRA, JOSÉ ROBERTO: NAKICENOVIC, NEBOJSA: OBERSTEINER, MICHAEL: PATWARDHAN, ANAND: ROGNER, MATHIS: RUBIN, ED: SHARIFI, AYYOOB: TORVANGER, ASBJØRN: YAMAGATA, YOSHIKI: EDMONDS, JAE: YONGSUNG, CHO 2015. Biophysical and economic limits to negative CO_2 emissions. *Nature Climate Change,* 6**,** 42.

SMITH, P. L., GARY: KUTSCH, WERNER L.: BUCHMANN, NINA: EUGSTER, WERNER: AUBINET, MARC: CESCHIA, ERIC: BÉZIAT, PIERRE: YELURIPATI, JAGADEESH B.: OSBORNE, BRUCE: MOORS, EDDY J.: BRUT, AURORE: WATTENBACH, MARTIN: SAUNDERS, MATT: JONES, MIKE 2010. Measurements necessary for assessing the net ecosystem carbon budget of croplands. *Agriculture, Ecosystems & Environment,* 139**,** 302-315.

SMITH, W. & WAGNER, G. 2018. Stratospheric aerosol injection tactics and costs in the first 15 years of deployment. *Environmental Research Letters,* 13**,** 124001.

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

SONDAK, C. F. A. A., PUT O.: BEARDALL, JOHN: BELLGROVE, ALECIA: BOO, SUNG MIN: GERUNG, GREVO S.: HEPBURN, CHRISTOPHER D.: HONG, DANG DIEM: HU, ZHENGYU: KAWAI, HIROSHI: LARGO, DANILO: LEE, JIN AE: LIM, PHAIK-EEM: MAYAKUN, JARUWAN: NELSON, WENDY A.: OAK, JUNG HYUN: PHANG, SIEW-MOI: SAHOO, DINABANDHU: PEERAPORNPIS, YUWADEE: YANG, YUFENG: CHUNG, IK KYO 2017. Carbon dioxide mitigation potential of seaweed aquaculture beds (SABs). *Journal of Applied Phycology,* 29**,** 2363-2373.

SOUSSANA, J.-F. L., SUZANNE: EHRHARDT, FIONA: ROSENSTOCK, TODD: LAMANNA, CHRISTINE: HAVLÍK, PETR: RICHARDS, MERYL: WOLLENBERG, EVA: CHOTTE, JEAN-LUC: TORQUEBIAU, EMMANUEL: CIAIS, PHILIPPE: SMITH, PETE: LAL, RATTAN 2019. Matching policy and science: Rationale for the '4 per 1000 – soils for food security and climate' initiative. *Soil and Tillage Research,* 188**,** 3-15.

STAVINS, R & STOWE R 2019 Governance of the Deployment of Solar Geoengineering. Cambridge, Mass.: Harvard Project on Climate Agreements, February 2019.

https://geoengineering.environment.harvard.edu/files/sgrp/files/harvard_project_sg_governance_briefs_volume_feb_2019.pdf

STILGOE, J. 2015. *Experiment Earth. Responsible innovation in geoengineering,* Abingdon, Oxford, Earthscan.

STRAND, S. E. & BENFORD, G. 2009. Ocean Sequestration of Crop Residue Carbon: Recycling Fossil Fuel Carbon Back to Deep Sediments. *Environmental Science & Technology,* 43**,** 1000-1007.

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

STRONG, A.L., J.J. CULLEN, AND S.W. CHISHOLM. (2009). Ocean fertilization: Science, policy, and commerce. Oceanography 22(3):236–261,

SUGIYAMA, M., ASAYAMA, S. & KOSUGI, T. 2020. The North–South Divide on Public Perceptions of Stratospheric Aerosol Geoengineering?: A Survey in Six Asia-Pacific Countries. *Environmental Communication***,** 1-16.

SYKES, A., MACLEOD, M., EORY, V., REES, B., PAYEN, F., MYRGIOTIS, V., WILLIAMS, M., SOHI, S., HILLIER, J., MORAN, D., MANNING, D., GOGLIO, P., SEGHETTA, M., WILLIAMS, A., HARRIS, J., DONDINI, M., WALTON, J., HOUSE, J. & SMITH, P. 2019. Characterising the biophysical, economic and social impacts of soil carbon sequestration as a greenhouse gas removal technology. *Global Change Biology*.

TEMPLE, J. 2017. Harvard scientists moving ahead on plans for atmospheric geoengineering experiments [Online]. MIT. Available : https://www.technologyreview.com/s/603974/harvard-scientists-moving-ahead-on-plans-for-atmospheric-geoengineering-experiments/

THERMOSTAT, G. 2019. *Global Thermostat A carbon negative solution* [Online]. Available: https://globalthermostat.com/ [Accessed 6 December 2019].

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

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

TILMES, S. & MILLS, M. 2014. Stratospheric sulfate aerosols and planetary albedo. In: FREEDMAN, B. (ed.) Global Environmental Change. Dordrecht: Springer Netherlands.

TRICK, C. G., BILL, B. D., COCHLAN, W. P., WELLS, M. L., TRAINER, V. L. & PICKELL, L. D. 2010. Iron enrichment stimulates toxic diatom production in high-nitrate, low-chlorophyll areas. *Proceedings of the National Academy of Sciences,* 107**,** 5887-5892.

UK Biochar Research Centre 2020 https://www.biochar.ac.uk/

UKRI. 2019. *Strategic Priority Fund (SPF) Wave 2 Greenhouse Gas Removal Programme.* [Online]. UK Research and Innovation. Available: https://bbsrc.ukri.org/funding/filter/2019-greenhouse-gas-removal-demonstrators/ [Accessed 20 December 2019].

UN. 2014. *New York Declaration On Forests – Declaration and Action Agenda* [Online]. Climate Summit 2014: UN. Available:

https://www.undp.org/content/dam/undp/library/Environment%20and%20Energy/Forests/New%20York%20Declaration%20on%20Forests_DAA.pdf [Accessed 20 August 2019].

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

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

VIEBAHN, P., SCHOLZ, A. & ZELT, O. 2019. The Potential Role of Direct Air Capture in the German Energy Research Program—Results of a Multi-Dimensional Analysis. *Energies,* 12**,** 3443.

WAGNER, G & ZIZZAMIA, D 2020. Green moral hazards C2C Guess blog 9 January 2020, Carnegie Climate Governance Initiative https://www.c2g2.net/green-moral-hazards/

WANG, T., LACKNER, K. S. & WRIGHT, A. B. 2013. Moisture-swing sorption for carbon dioxide capture from ambient air: a thermodynamic analysis. *Physical Chemistry Chemical Physics,* 15**,** 504-514.

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

WHITE, A., BJÖRKMAN, K., GRABOWSKI, E., LETELIER, R., POULOS, S., WATKINS, B. & KARL, D. 2010. An Open Ocean Trial of Controlled Upwelling Using Wave Pump Technology. *Journal of Atmospheric and Oceanic Technology – J ATMOS OCEAN TECHNOL,* 27.

WHITEMAN, G., HOPE, C. & WADHAMS, P. 2013. Vast costs of Arctic change. *Nature,* 499**,** 401.

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

WILLAUER, H., DIMASCIO, F. & HARDY, D. 2017. Extraction of Carbon Dioxide and Hydrogen from Seawater by an Electrolytic Cation Exchange Module (E-CEM) Part V: E-CEM Effluent Discharge Composition as a Function of Electrode Water Composition. Washington, DC Naval Research Laboratory – United States Navy.

WILLIAMSON P, WALLACE DWR, LAW CS, BOYD PW, COLLOS Y, CROOT P, ET AL. (2012) Ocean fertilization for geoengineering: A review of effectiveness, environmental impacts and emerging governance. Process Safety and Environmental Protection. 2012 Nov;90(6):475–88.

WILLIAMSON, C., ZEPP, R., LUCAS, R., MADRONICH, S., AUSTIN, A., BALLARÉ, C., NORVAL, M., SULZBERGER, B., BAIS, A., MCKENZIE, R., ROBINSON, S., HÄDER, D., PAUL, N. & BORNMAN, J. 2014. Solar ultraviolet radiation in a changing climate. *Nature Climate Change,* 4**,** 434-441.

WINCKLER, J. L., QUENTIN: REICK, CHRISTIAN H.: PONGRATZ, JULIA 2019. Nonlocal Effects Dominate the Global Mean Surface Temperature Response to the Biogeophysical Effects of Deforestation. *Geophysical Research Letters,* 46**,** 745-755.

WNA. 2019. *Nuclear Power in the World Today* [Online]. World Nuclear Association. Available: https://www.world-nuclear.org/information-library/current-and-future-generation/nuclear-power-in-the-world-today.aspx%20[Accessed 10 December 2019].

WOOD, R. 2018 Marine Cloud Brightening: Science, Feasibility and a Plan for Research. Presentation by Robert Wood Department of Atmospheric Sciences, University of Washington, Seattle at Caltech. Available at http://workshop.caltech.edu/geoengineering/presentations/10-wood.pdf

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

WRIGHT, M., J.: TEAGLE, D.: FEETMAN, P. 2014. A quantitative evaluation of the public response to climate engineering. *Nature Climate Change,* 4.

WU, P., ATA-UL-KARIM, S. T., SINGH, B. P., WANG, H., WU, T., LIU, C., FANG, G., ZHOU, D., WANG, Y. & CHEN, W. 2019. A scientometric review of biochar research in the past 20 years (1998–2018). *Biochar,* 1**,** 23-43

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

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

ZHANG, Y. & ZHAI, W.-D. 2015. Shallow-ocean methane leakage and degassing to the atmosphere: triggered by offshore oil-gas and methane hydrate explorations. *Frontiers in Marine Science,* 2.

ZHANG, Z., MOORE, J. C., HISSING, D. & ZHAO, Y. 2015. Review of geoengineering approaches to mitigating climate change. *Journal of Cleaner Production,* 103**,** 898-907

ZHOU, S. & FLYNN, P. (2005). Geoengineering downwelling ocean currents: a cost assessment. Climate Change, 71, 203-220

Chapter 2

[1] Chiara Armeni and Catherine Redgwell, 'International legal and regulatory issues of climate geoengineering governance: rethinking the approach' (2015) Climate Geoengineering Governance Project Working Paper 21, University of Oxford <http://geoengineering-governance-research.org/cgg-working-papers.php> accessed 30 March 2020.

2 The Legality of the Threat or Use of Nuclear Weapons (Advisory Opinion) [1996] ICJ Rep 226, 505.

3 Robert Jennings, 'Sovereignty and International Law' in Gerard Kreijen and others (eds), State, Sovereignty, and International Governance (Oxford University Press 2002) 31.

4 Franz Perrez, Cooperative Sovereignty: From Independence to Interdependence in the Structure of International Environmental Law (Kluwer Law International 2000), 331-343.

5 UNGA 'Declaration on Principles of International Law Concerning Friendly Relations and Co-operation among States in Accordance with the Charter of the United Nations' (24 October 1970) UN Doc A/RES/25/2625.

6 See, e.g., UNGA 'Declaration on Principles of International Law Concerning Friendly Relations and Co-operation among States in Accordance with the Charter of the United Nations' (24 October 1970) UN Doc A/RES/25/2625, preamble, which refers to the codification and progressive development of the '[t]he duty of States to co-operate with one another in accordance with the Charter.'

[7] See, e.g., Antarctic Treaty (1959) 402 UNTS 71, preamble, arts 2 and 3; Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and other Celestial Bodies (1967) 6 ILM 386 (Outer Space Treaty), preamble, arts I, III, IX; LOSC, Part XI on The Area.

[8] See *Mox Plant Case* (Provisional Measures, Sep. Op. Wolfrum) 4 stating: 'I fully endorse, however, paragraphs 82 to 84 of the Order, considering that the obligation to cooperate is the overriding principle of international environmental law, in particular when the interests of neighbouring States are at stake. The duty to cooperate denotes an important shift in the general orientation of the international legal order. It balances the principle of sovereignty of States and thus ensures that community interests are taken into account *vis-à-vis* individualistic State interests.'

[9] Rio Declaration, preamble, principles 5, 7, 9, 12–14 and 24.

[10] UNGA 'Declaration on Principles of International Law Concerning Friendly Relations and Co-operation among States in Accordance with the Charter of the United Nations' (24 October 1970) UN Doc A/RES/25/2625, declares in relation to the 'duty of States to cooperate in accordance with the Charter' that 'States should cooperate in the economic, social and cultural fields as well as in the field of science and technology.'

[11] See n 8, above.

[12] Declaration of the UN Conference on the Human Environment (Stockholm) (5-16 June 1972) UN Doc A/CONF/48/14/REV.1 (Stockholm Declaration).

[13] This notion of common but differentiated responsibilities relating to international cooperation on the protection of the environment is referenced in the chapeau of draft Article 6(2), which qualifies the duty to cooperate 'in accordance with their respective capabilities' and is based on the framework of the UNFCCC.

[14] In the international context, see LOSC, Part XII, Vienna Convention for the Protection of the Ozone Layer, preamble, art 2(2)(a), (c) and (d), art 3(3) and art 4; UNFCCC, preamble, art 3(3) and (5), 4(1)(c), (d), (e), (g)–(i), art 5(c) and art 6(b); Convention on Long-Range Transboundary Air Pollution (adopted 13 November 1979, entered into force 16 March 1983) 18 ILM 1442 (LRTAP), preamble; LOSC, Part XII, Sections 2–5, including arts 194 and 197. In the regional context, see North American Agreement on Environmental Co-operation (1993) 32 ILM 1482, art 1. See further Patricia Birnie, Alan Boyle and Catherine Redgwell, *International Law and the Environment*, 3rd ed. (Oxford: Oxford University Press, 2009), 175–76; Rüdiger Wolfrum 'International Law of Cooperation' in *Max Plank Encyclopaedia of Public International Law* (April 2010), paras 28–31.

[15] Rüdiger Wolfrum, 'International Law' in *Max Plank Encyclopaedia of Public International Law* (November 2006). See also Alex G Oude Elferink, 'Governance Principles for Areas Beyond National Jurisdiction' (2012) 27 *International Journal of Marine and Coastal Law* 205, 218, regarding the duty to cooperate under the LOSC, stating that: 'Although the Convention does not formulate a general duty of States to cooperate, it contains numerous references to the duty to cooperate. However, in such cases the object of cooperation is always specified.' It is also pointed out that the duty to cooperate may be implicitly required in order to ensure that certain requirements are effectively implemented.

[16] See, e.g., OSPAR Convention for the Protection of the Marine Environment of the North-East Atlantic (adopted 22 September 1992, entered into force 25 March 1998) 2354 UNTS 67 (OSPAR Convention) art 7. See generally Wolfrum (n15).

[17] See, e.g., LRTAP, preamble: 'Affirming their willingness to reinforce active international cooperation to develop appropriate national policies and by means of exchange of information, consultation, research and monitoring to coordinate national action for combating air pollution including long-range transboundary air pollution.'

[18] Regarding international cooperation in areas beyond national jurisdiction, see, e.g., LOSC, Part VII and XI; Antarctic Treaty, Preamble, arts 2 and 3; Outer Space Treaty, art I. See also 'Our Common Future: Report of the World Commission on Environment and Development' UN Doc A/42/427, Annex (4 August 1987), ch 10 'Managing the Commons.'

[19] See, e.g., LOSC, art 242.

[20] Vienna Convention for the Protection of the Ozone Layer, art 3; United Nations Convention against Illicit Traffic in Narcotic Drugs and Psychotropic Substances (adopted 20 December 1988, entered into force 11 November 1990) 28 ILM 493, Art 9; LRTAP, art 7; Convention on the Protection of the Alps (1991) 31 ILM 767 (Alpine Convention), art 3; Convention on the Protection and Use of Transboundary Watercourses and International Lakes (adopted 17 March 1992, entered into force 6 December 1996) 31 ILM 1312 (Helsinki Water Convention), art 5; OSPAR Convention, art 8, Annex IV, art 2; Desertification Convention, art 10(4) and 12.

[21] Antarctic Treaty, Art. III; International Convention for the Regulation of Whaling (adopted 2 December 1946, entered into force 10 November 1948) 161 UNTS 72 (ICRW), art VIII; OSPAR Convention, art 9.

[22] For example, article 4(4) of the Alpine Convention is particularly far-reaching in requiring that 'Contracting Parties shall ensure that the public are regularly kept informed in an appropriate manner about the results of research, monitoring and action taken.' See also LRTAP, art 4.

[23] See, e.g., LOSC, art 202 and 203, Parts XIII and XIV; UNFCCC, art 6; Vienna Convention for the Protection of the Ozone Layer, art 4(2); CBD, preamble and art 12; Desertification Convention, art 10(4), 12, 17 and 18.

[24] See, e.g., LRTAP, art 10; ICRW, Art. VIII; OSPAR Convention, art 8.

[25] *The Legality of the Threat or Use of Nuclear Weapons* (Advisory Opinion) [1996] ICJ Rep 226, para. 29. This principle is codified in Declaration of the UN Conference on the Human Environment (Stockholm) UN Doc A/CONF/48/14/REV.1 (Stockholm Declaration), Principle 21 and in the Declaration of the UN Conference on the Environment and Development, (12 August 1992) UN Doc. A/CONF.151/26/Rev.1, Principle 2.

[26] *Pulp Mills on the River Uruguay (Argentina v Uruguay)* (Judgment of 20 April 2010) [2010] ICJ Rep 14, para. 101.

[27] ILC, Third report on the protection of the atmosphere by Shinya Murase, Special Rapporteur (25 February 2016) UN Doc A/CN.4/692, 8.

[28] ILC, Report of the Commission to the General Assembly on the work of its fifty-third session, Draft Articles on Prevention of Transboundary Harm from Hazardous Activities, with commentaries (10 August 2001) UN Doc A/56/10 (Draft Articles on the Prevention of Transboundary Harm), 148, para. (2). See also *Gabčíkovo-Nagymaros Dam Case (Hungary v Slovakia)* [1997] ICJ Rep 7, 77-78, para. 140.

[29] Draft Articles on the Prevention of Transboundary Harm, 152.

[30] Roda Verheyen, Climate Damage and International Law: Prevention Duties and State Responsibilities (Martinus Nijhoff 2005) 317–321.

[31] *Pulp Mills on the River Uruguay (Argentina v Uruguay)* (Judgment of 20 April 2010) [2010] ICJ Rep 14, para. 197.

[32] Scott Barrett, 'The Incredible Economics of Geoengineering' (2008) 39 *Environmental and Resource Economics* 45.

[33] See Patricia Birnie, Alan Boyle and Catherine Redgwell, *International Law and the Environment*, 3rd ed. (Oxford: Oxford University Press, 2009),137.

[34] Draft Articles on the Prevention of Transboundary Harm, 154.

Alan E. Boyle, 'Globalising Environmental Liability: The Interplay of National and International Law' (2015) 17 *Journal of Environmental Law* 3, 8.

[35] ILA 'Legal Principles relating to Climate Change' (7–11 April 2014) 76th Conference of the ILA Resolution 2/2014 http://www.ila-hq.org/en/committees/index.cfm/cid/1029 accessed 31 March 2020 (ILA Legal Principles relating to Climate Change), 24.

[36] ILC Draft Articles on the Prevention of Transboundary Harm, 155.

[37] Pulp Mills on the River Uruguay (Argentina v Uruguay) (Judgment of 20 April 2010) [2010] ICJ Rep 14, para. 204; Construction of a Road in Costa Rica along the San Juan River (Nicaragua v Costa Rica) (Judgment of 16 December 2015) [2015] ICJ Reports 665, paras. 104, 153.

[38] Draft Articles on the Prevention of Transboundary Harm, 155.

[39] Draft Articles on the Prevention of Transboundary Harm, 155.

[40] Draft Articles on the Prevention of Transboundary Harm, 154.

[41] Responsibilities and Obligations of States Sponsoring Persons and Entities with respect to Activities in the Area (No 17) (Advisory Opinion of 1 February 2011), ITLOS Reports 2011, para. 117.

[42] See generally Jutta Brunnée, 'International Legal Accountability through the Lens of the Law of State Responsibility' (2005) 36 *Netherlands Yearbook of International Law* 21.

[43] ibid., 27.

[44] ibid. On the issue of SRM and the requirement of causation under the principle on the prevention of transboundary harm, see David Reichwein and others, 'State Responsibility for Environmental harm from Climate Engineering' (2015) 5 *Climate Law* 142.

[45] ibid, 27-28.

[46] Gerhard Hafner and Isabelle Buffard, 'Obligations of Prevention and the Precautionary Principle' in James Crawford, Alain Pallet and Simon Olleson (eds), The Law of International Responsibility (Oxford University Press 2010) 525.

[47] David Freestone, 'Satya Nandan's Contribution to the Development of the Precautionary Approach in International Law' in Michael W Lodge and Myron H Nordquist (eds), *Peaceful Order in the World's Oceans: Essays in Honour of Satya N Nandan* (Brill 2014), 311–12.

[48] Responsibilities and Obligations of States Sponsoring Persons and Entities with respect to Activities in the Area (No 17) (Advisory Opinion of 1 February 2011), ITLOS Reports 2011, para 131.

[49] Responsibilities and Obligations of States Sponsoring Persons and Entities with respect to Activities in the Area (No 17) (Advisory Opinion of 1 February 2011), ITLOS Reports 2011, para 135.

[50] Declaration of the UN Conference on the Environment and Development, (12 August 1992) UN Doc. A/CONF.151/26/Rev.1, Principle 15.

[51] See Franz Perrez, 'Risk Regulation, Precaution and Trade' in Thomas Cottier and Daniel Wüger (eds) *Genetic Engineering and the World Trade System*, (CUP, 2008) 255-58.

[52] The ITLOS Seabed Disputes Chamber in its advisory opinion on the *Responsibilities and Obligations of States Sponsoring Persons and Entities with respect to Activities in the Area (No 17) (*Advisory Opinion of 1 February 2011), ITLOS Reports 2011, para 31, discusses the level of proof required to trigger the application of the precautionary principle in the face of threatened damage by referring to 'plausible indications of potential risks'.

The International Law Association, 'Legal Principles relating to Climate Change' (7–11 April 2014) 76th Conference of the ILA Resolution 2/2014 <https://www.ila-hq.org/index.php/committees> accessed 30 March 2020 (ILA Legal Principles relating to Climate Change) adopts a similar interpretation, substituting the phrase of a 'reasonably foreseeable threat.'

[53] Cass R. Sunstein, 'The Paralysing Principle: Does the Precautionary Principle Point Us in Any Helpful Direction?' (2002) 25 *Regulation* 32.

[54] UK House of Commons Science and Technology Select Committee on 'The Regulation of Geoengineering' (HC 2009 – 10, 2 21 – V) 34. See also Daniel Bodansky, 'May We Engineer the Climate?' (1996) 33 *Climatic Change* 309, 319.

[55] Andy Stirling, 'Precaution in the Governance of Technology', in Roger Brownsword, Eloise Scotford, and Karen Yeung (eds.), *The Oxford Handbook of Law, Regulation and Technology* (Oxford University Press 2017).

[56] European Commission, 'European Union Communication on the Precautionary Principle' COM (2000) 1 final.

[57] ibid. 3-4. It should be noted that precaution is generally regarded as an element of risk management, and builds on, but is not part of, risk assessment. As such, precaution would become relevant once risk assessment has indicated that there are uncertainties linked threat of serious or irreversible damage. See Franz Perrez, 'GMOs and International Law: The Swiss Example' (2005) 14 *RECIEL* 161, 69.

[58] ibid.

[59] Construction of a Road in Costa Rica along the San Juan River (Nicaragua v Costa Rica) (Judgment of 16 December 2015) [2015] ICJ Reports 665, para. 153.

[60] *Pulp Mills on the River Uruguay (Argentina v Uruguay)* (Judgment of 20 April 2010) [2010] ICJ Rep 14, para. 204. See further Alan Boyle, 'Developments in the International Law of Environmental Impact Assessments and their Relation to the Espoo Convention', (2011) 20 *RECIEL* 227.

[61] *Pulp Mills on the River Uruguay (Argentina v Uruguay)* (Judgment of 20 April 2010) [2010] ICJ Rep 14, para. 204.

[62] ILC, Third report on the protection of the atmosphere by Shinya Murase, Special Rapporteur (25 February 2016) UN Doc A/CN.4/692, 32.

[63] ibid. On the application of international law requirement to conduct an environmental impact assessment to climate engineering measures, see Alastair N. Craik, 'International EIA law and geoengineering: do emerging technologies require special rules?' (2015) 5 *Climate Law* 111.

[64] *Lac Lanoux Arbitration (France v Spain)* [1957] 24 ILR 101. See also *Gabčíkovo-Nagymaros Dam Case*, paras 140–47. See generally Rio Declaration, principles 7, 9, 12, 13, 14, 18, 19 and 27.

[65] Draft Principles of Conduct for the Guidance of States in the Conservation and Harmonious Exploitation of Natural Resources Shared by Two or More States, UNEP Programme Governing Council, XII Plenary meeting (May 1978) UN Doc UNEP/GC/1-1.

[66] ILC, Report of the Commission to the General Assembly on the work of its fifty-third session, Draft Articles on Prevention of Transboundary Harm from Hazardous Activities, with commentaries (10 August 2001) UN Doc A/56/10 (ILC Draft Articles on the Prevention of Transboundary Harm), art 4.

[67] See Patricia Birnie, Alan Boyle and Catherine Redgwell, *International Law and the Environment*, 3rd ed. (Oxford: Oxford University Press, 2009), 177.

[68] Lac Lanoux Arbitration; North Sea Continental Shelf Cases (Germany v Denmark; Germany v Netherlands) (Judgment) [1969] Rep 3, 119.

[69] ibid., para 85.

[70] United Nations Framework Convention on Climate Change (adopted 9 May 1992, entered into force 21 March 1994) (1992) 31 ILM 851 ('UNFCCC').

[71] UNFCCC, Art. 2.

[72] UNFCCC, Art. 3.

[73] UNFCCC, Art. 4(1)(f).

[74] UNFCCC, Art. 4(1)(g); see also UNFCCC, Art. 5.

[75] Daniel Bodansky, 'May we engineer the climate?' (1996) 33 *Climatic Change* 309, 313.

[76] Paris Agreement (signed 22 April 2016, entered into force 4 November 2016) UN Doc FCCC/CP/2015/10/Ad.1, preambular recital 3.

[77] Paris Agreement, Art. 2(1)(a).

[78] IPCC, 'Summary for Policymakers' in V Masson-Delmotte and others (eds), Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty (WMO 2018) <https://www.ipcc.ch/sr15/> accessed on 31 March 2020.

[79] Ying Chen and Yuan Xin, 'Implications of geoengineering under the 1.5 °C target: Analysis and policy suggestions' (2017) 8 *Advances in Climate Change Research* 123.

[80] Paris Agreement, preambular recital 8, 11, 13.

[81] Paris Agreement, preambular recital 3.

[82] Paris Agreement, preambular recital 7.

[83] Lavanya Rajamani, 'The Durban Platform for Enhanced Action and the Future of the Climate Regime' (2012) 61 *International and Comparative Law Quarterly* 501, 517.

[84] Paris Agreement, Art 2(2).

[85] Paris Agreement, preamble, Arts 2(3), 4(3). See, generally, Rajamani; Christina Voigt and Felipe Ferreira, 'Differentiation in the Paris Agreement' (2016) 6 *Climate Law* 58;
Annalisa Savaresi, 'The Paris Agreement: a new beginning?' (2016) 34 *Journal of Energy & Natural Resources Law* 16.

[86] The Royal Society (2009) Geoengineering the climate: science, governance and uncertainty. London. Available at: https://royalsociety.org/topics-policy/publications/2009/geoengineering-climate [Accessed: 14 April 2020]. 51.

[87] See, generally, W C G Burns, 'Climate geoengineering: solar radiation management and its implications for intergenerational equity' (2011) 1 Stanford Journal of Law, Science & Policy

39; M Goes, N Tuana and K Keller, 'The Economics (or Lack Thereof) of Aerosol Geoengineering' (2011) 109 Climatic Change 719; N Tuana, 'The Ethical Dimensions of Geoengineering: Solar Radiation Management through Sulphate Particle Injection' (2013) Geoengineering Our Climate Working Paper and Opinion Article Series

[88] David Reichwein and others, 'State Responsibility for Environmental harm from Climate Engineering' (2015) 5 *Climate Law* 142.

[89] See draft Article 9, below. Liability and compensation schemes for geoengineering have been proposed in the literature, but are only roughly hewn at this stage. See Pak-Hang Wong, Tom Douglas and Julian Savulescu, 'Compensation for Geoengineering Harms and No-Fault Climate Change Compensation', (Geoengineering Our Climate Working Paper and Opinion Article Series 2014) <http://geoengineering-governance-research.org/perch/resources/workingpaper8wongdouglassavulescucompensationfinal-.pdf> accessed 12 September 2014; Tony Svobota and Peter Irvine 'Ethical and Technical Challenges in Compensating for (2014) 17 *Ethics, Policy & Environment* 157; Martin Bunzl, 'Geoengineering Harms and Compensation' (2011) 4 *Stanford Journal of Law, Science and Policy* 71.

[90] Juan Moreno-Cruz, Katherine L Ricke and David W Keith, 'A simple model to account for regional inequalities for Solar Radiation Management' (2012) 110 *Climate Change Journal* 649.

[91] Christina Voigt and Felipe Ferreira, 'Differentiation in the Paris Agreement' (2016) 6 *Climate Law* 58, 59.

[92] Tony Svoboda and others, 'Sulfate Aerosol Geoengineering: The Question of Justice' (2011) 25 *Public Affairs Quarterly* 157;

[93] David E Winickoff, Jane A. Flegal and Asfawossen Asrat, 'Engaging the Global South on climate engineering research' (2015) 5 *Nature Climate Change* 627,

[94] Paris Agreement, art 11. See also UNFCCC, art 4(1)(c) and 4(5).

[95] Solar Radiation Management Governance Initiative (SRMGI) (2011) Solar Radiation Management: The Governance Of Research. Available at: www.srmgi.org/files/2012/01/DES2391_SRMGIreport_%0Dweb_11112.pdf (Accessed: 10 June 2020).

[96] David Ockwell and others, 'Collaborative research and development (R&D) for climate technology transfer and uptake in developing countries: towards a needs driven approach' (2015) 131 *Climatic Change* 401.

[97] UNFCCC, Art. 1(4).

[98] UNFCCC, Art. 1(8).

[99] Paris Agreement, Art. 4.

[100] A significant concern surrounding SRM is that it will contribute to a 'moral hazard' or 'mitigation deterrence' problem that researching and developing SRM measures may undermine support for policies to reduce GHGs which could increase the risks of a termination. See Albert Lin, 'Does Geoengineering Pose a Moral Hazard?' (2012) 40 *Ecology Law Quarterly* 673.

[101] Paris Agreement, Art. 4(2).

[102] Daniel Bodansky, Jutta Brunnée, and Lavanya Rajamani, *International Climate Change Law* (OUP 2017) 231.

[103] Paris Agreement, Art. 4(3).

[104] Paris Agreement, Art. 2(b).

[105] Paris Agreement, Art. 2(c).

[106] Paris Agreement, Art. 4(4).

[107] Paris Agreement, Art. 10.

[108] Paris Agreement, Art. 13.

[109] Paris Agreement, Art. 4(13).

[110] Paris Agreement, Art. 14.

[111] Alistair N. Craik and William C.G. Burns, 'Climate Engineering Under the Paris Agreement' (2019) 49 *Environmental Law Reporter.*

[112] Paris Agreement, Art. 10.

[113] Paris Agreement, Art. 10(1).

[114] Adoption of the Paris Agreement, para 68(d). UNFCC (2015) Adoption of the Paris Agreement, Conference of the Parties on its twenty-first session. Paris. Retrieved from: https://undocs.org/pdf?symbol=en/FCCC/CP/2015/L.9. See also UNFCCC, art 4(1).

[115] Vienna Convention for the Protection of the Ozone Layer (adopted 22 March 1985, entered into force 22 September 1988) 1513 UNTS 293 ('Vienna Convention'), Art 2(1).

[116] The Vienna Convention for the Protection of the Ozone Layer and the original 1987 Montreal Protocol have 197 Parties. Subsequent amendments to the Montreal Protocol have fewer parties

[117] Montreal Protocol on Substances that Deplete the Ozone Layer (1987) 1522 UNTS 3 ('Montreal Protocol'), Art 3.

[118] Montreal Protocol, preambular recitals 3 and 4.

[119] Montreal Protocol, preambular recital 6.

[120] See Montreal Protocol, Art. 11.

[121] Stephen O. Anderson, 'We can and must govern climate engineering' (2017) 551 *Nature* 415.

[122] Ralph Bodle and others, 'The Regulatory Framework for Climate-Related Geoengineering Relevant to the Convention on Biological Diversity' Part II: Geoengineering in Relation to the Convention on Biological Diversity: Technical and Regulatory Matters (Secretariat of the Convention on Biological Diversity, Technical Series No. 66 2012) 129.

[123] US National Research Council, *Climate Intervention: Reflecting Sunlight to Cool Earth* (The National Academies Press 2015) 70-71.

[124] Vienna Convention, Art. 2(1).

[125] Vienna Convention, Art. 1(2).

[126] See also Montreal Protocol, preambular recital 4.

[127] UN Environment, 'The Kigali Amendment to the Montreal Protocol: Another Global Commitment to stop climate change' (Nairobi, December 2016) <https://www.unenvironment.org/news-and-stories/story/kigali-amendment-montreal-protocol-another-global-commitment-stop-climate> accessed 30 March 2020.

[128] Convention on Long-Range Transboundary Air Pollution (adopted 13 November 1979, entered into force 16 March 1983) 18 ILM 1442 ('LRTAP'), Art. 1(b).

[129] LRTAP, Art. 2.

[130] LRTAP, Arts. 3, 4 and 7.

[131] 1985 Helsinki Protocol on the Reduction of Sulphur Emissions or their Transboundary Fluxes by at least 30 percent (entry into force 2 September 1987) 1480 UNTS 215.

[132] Protocol to the 1979 Convention on Long-Range Transboundary Air Pollution on Further Reduction of Sulphur Emission (entry into force 5 August 1998) 2030 UNTS 122.

[133] 1994 Oslo Protocol, art. 2(1).

[134] IBPES, Summary for Policymakers of the Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES Secretariat 2019) 18.

[135] ibid.

[136] Convention on Biological Diversity (adopted 5 June 1992, entered into force 29 December 1993) 1760 UNTS 79 ('CBD'), Art. 1.

[137] CBD, preambular recital 9.

[138] CBD, Art. 3.

[139] CBD, Art. 4(a).

[140] CBD, Art. 4(b).

[141] CBD, Decision X/33, 'Biodiversity and Climate Change' (19 December 2010) UN Doc UNEP/CBD/COP/10/27 ('CBD Decision X/33').

[142] See Responsibilities and Obligations of States Sponsoring Persons and Entities with respect to Activities in the Area (No 17) (Advisory Opinion of 1 February 2011), ITLOS Reports 2011, para. 110 stating that the characterization of an obligation 'to ensure' constitutes an obligation 'of conduct' and of 'due diligence'.

[143] For a definition and discussion of the concept of moratoria in international law, see Wenqiang Yin, 'Moratorium in International Law' (2012) 11 *Chinese Journal of International Law* 321.

[144] CBD, Decision XIII/14, 'Climate-Related Geoengineering' (8 December 2016) UN Doc CBD/COP/DEC/XIII/14, para. 3.

[145] ibid, para. 5.

[146] Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (1972) 11 ILM 1358 ('London Convention').

[147] Protocol to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (1996) 36 ILM 1 ('London Protocol').

[148] London Protocol, Art. 2.

[149] London Protocol, Art. 3(1).

[150] London Protocol, Art. 4.1.1.

[151] London Protocol, Art. 1.4.1.3.

[152] Resolution LC-LP.1(2008) (31 October 2008), para.4.

[153] Resolution LP.1(1) (2 November 2006).

[154] LC 34/15 (2 November 2012), annex 8.

[155] London Protocol, Art. 6.

[156] Resolution LP.3(4)(2009) (30 October 2009).

[157] London Protocol, Art. 21.3.

[158] See Nigel Bankes, 'Provisional Application of an Amendment to the London Protocol to Facilitate Collaborative CCS Projects' (*ABlawg*, 10 December 2019) https://ablawg.ca/2019/12/10/provisional-application-of-an-amendment-to-the-london-protocol-to-facilitate-collaborative-ccs-projects accessed on 30 March 2019.

[159] Resolution LP.4(8) on the Amendment to the London Protocol to Regulate the Placement of Matter for Ocean Fertilization and Other Marine Geoengineering Activities (adopted on 18 October 2013), Report of the Thirty-Fifth Consultative Meeting and the Eighth Meeting of Contracting Parties, LC 35/15, 21 October 2015 ('Resolution LP.4(8)').

[160] Resolution LP.4(8), Preamble.

[161] Resolution LP.4(8), Article 5*bis*.

[162] See discussion of IPCC definitions, below.

[163] In addition, in order to be considered for a listing in Annex 4, the technique must also fall within the scope of the London Protocol as the introduction of matter into the sea with the potential to cause harm to the marine environment.

[164] Description of Arrangements for a Roster of Experts on Marine Geoengineering in the Consultation Process (with regard to paragraph 12 of Annex 5 to the London Protocol), LC 36/16 Annex 4, 1 July 2013.

[165] Resolution LC-LP.1(2008) (31 October 2008); Resolution LC-LP.2(2010) (11–15 October 2010).

[166] Resolution LP.4(8), Annex 4.1.3.

[167] Resolution LP.4(8), Annex 5.

[168] London Protocol, Annex 5, para. 1.2.

[169] United Nations Convention on the Law of the Sea (adopted 10 December 1982, entered into force 16 November 1994) 1833 UNTS 3 ('LOSC').

[170] Alan Boyle, 'Law of the Sea Perspectives on Climate Change' (2012) 27 *International Journal of Marine and Coastal Law* 831, 831.

[171] Jill Barrett, 'The UN Convention on the Law of the Sea: A "Living" Treaty?" in Jill Barrett and Richard Barnes (eds), *Law of the Sea - UNCLOS as a Living Treaty* (BIICL 2016).

[172] *Southern Bluefin Tuna Cases (Nos 3 & 4) (New Zealand v Japan; Australia v Japan)* (Provisional Measures, Order 27 August 1999) ITLOS Reports 1999, 40-41, para. 52.

[173] LOSC, Art. 2(1) and (2).

[174] LOSC, Art 2(3).

[175] LOSC, Art. 57.

[176] LOSC, Art. 56(1)(a).

[177] LOSC, Art. 56(1)(b).

[178] LOSC, Art. 56(2).

[179] LOSC, Art. 58(3).

[180] In the future, climate engineering activities carried out on the high seas may potentially interfere with the exploration and exploitation of the mineral resources of the Area, comprised by the ocean floor and its subsoil beyond the limits of national jurisdiction.

[181] LOSC, Art. 87(1).

[182] LOSC, Art. 89.

[183] LOSC, Art. 87(1).

[184] LOSC, Art. 87(1).

[185] LOSC, Art. 87(2).

[186] LOSC, Art. 94(1).

[187] Request for an Advisory Opinion Submitted by the Sub-Regional Fisheries Commission (SRFC) (No 21) (Advisory Opinion of 2 April 2015), ITLOS Reports 2015, paras. 118-136.

[188] See 'Revised draft text of an agreement under the United Nations Convention on the Law of the Sea on the conservation and sustainable use of marine biological diversity of areas beyond national jurisdiction' (advance, unedited version) (27 November 2019) <https://www.un.org/bbnj/> accessed on 31 March 2020.

[189] Also relevant is Part XIII of the LOSC on marine scientific research. Regarding the regulation of marine scientific research with the potential to adversely affect the marine environment under Part XIII of the LOSC and the regulation of climate engineering, see Anna-Maria Hubert, 'Marine scientific research and the protection of the seas and oceans' in Rosemary Rayfuse (ed), *Research Handbook on International Marine Environmental Law* (Edward Elgar 2017).

[190] *South China Sea Arbitration (Philippines v. China) (Merits)* (2016) PCA Case No. 2013-19, Award of 29 October 2015, para. 927.

[191] International Seabed Authority, Mining Code, Regulation 1(3): ISBA/16/A/12/Rev. 1 (polymetalic sulphides), 2010; ISBA/18/A/11 (cobalt-rich crusts) 2012; ISBA/18/C/17 (polymetallic nodules) 2013.

[192] See ILC, 'First report on the protection of the atmosphere Prepared by Special Rapporteur Mr. Shinya Murase' (14 February 2014) UN Doc A/CN.4/667.

[193] ibid., para. 941.

[194] ibid.

[195] ibid.

[196] *South China Sea Arbitration (Philippines v. China) (Merits)* (2016) PCA Case No. 2013-19, Award of 29 October 2015, para. 941.

[197] Alan Boyle, 'Further Development of the Law of the Sea Convention: Mechanisms for Change' (2005) 54 *The International and Comparative Law Quarterly* 563.

[198] Alan Boyle, 'Law of the Sea Perspectives on Climate Change' (2012) 27 *The International Journal of Marine and Coastal Law* 831, 832-33.

[199] *South China Sea Arbitration (Philippines v. China) (Merits)* (2016) PCA Case No. 2013-19, Award of 29 October 2015, para. 944.

[200] LOSC, Art 194(5).

[201] LOSC, Art. 196.

[202] LOSC, Art. 197.

[203] LOSC, Art. 200.

[204] LOSC, Art. 202.

[205] LOSC, Art. 204

[206] LOSC, Art. 205.

[207] LOSC, Art. 206.

[208] LOSC, Arts. 212.

[209] LOSC, Art. 235(1).

[210] LOSC, Art. 235(2).

[211] Robin Churchill, 'The LOSC regime for protection of the marine environment – fit for the twenty-first century?' in Rosemary Rayfuse (ed.), *Research Handbook on International Marine Environmental Law* (Edward Elgar 2015) 3.

[212] Elizabeth L. Chalecki and Lisa L. Ferrari, 'A New Security Framework for Geoengineering' (2018) 12 *Strategic Studies Quarterly* 82, 89.

[213] ibid 83.

[214] UNSC Statement by the President of the Security Council (2011) UN Doc S/PRST/2011/15.

[215] ibid.

[216] Ken Conca, 'Is There a Role for the UN Security Council on Climate Change?' (2019) 61 *Environment: Science and Policy for Sustainable Development* 4.

[217] ibid.

[218] See further Philippe Sands and Jacqueline Peel, Principles of International Environmental Law, 3rd Ed. (2014), 58-60.

[219] See United Nations Sustainable Development Goals <https://www.un.org/sustainabledevelopment/sustainable-development-goals/> accessed 31 March 2020.

[220] UNGA Res 70/1 (21 October 2015) UN Doc A/RES/70/1.

[221] Matthias Honegger and others, 'Carbon Removal and Solar Geoengineering: Potential implications for delivery of the Sustainable Development Goals' (2018) Carnegie Climate Geoengineering Governance Initiative (May 2018) <https://www.c2g2.net/wp-content/uploads/C2G2-Geoeng-SDGs_20180521.pdf> accessed 31 March 2020, 7.

[222] See further Franz Perrez, 'The Role of the United Nations Environment Assembly in Emerging Issues of International Environmental Law', forthcoming in a special issue of the journal Sustainability on *Global Environmental Policy and Governance in Sustainability.*

[223] UN Environment Programme <https://www.unenvironment.org> accessed 31 March 2020.

[224] Draft Resolution for consideration for the 4th United Nations Environment Assembly, Geoengineering and its Governance, submitted by Switzerland, supported by Burkina Faso, Federated States of Micronesia, Mali, Mexico, Niger, version 21 January 201

<https://papersmart.unon.org/resolution/uploads/switzerland_-_resolution_submission_-_geoengineering_and_its_governance_-_unea_4_.pdf> accessed 31 March 2020.

[225] For a comprehensive discussion of the UNEA resolution, further Franz Perrez, 'The Role of the United Nations Environment Assembly in Emerging Issues of International Environmental Law', forthcoming in a special issue of the journal Sustainability on *Global Environmental Policy and Governance in Sustainability.* See also Sikina Jinnah and Simon Nicholson, 'The hidden politics of climate engineering' (2019) 12 *Nature Geoscience* 876.

[226] See, e.g., David E. Winickoff, Jane A. Flegal and Asfawossen Asrat, 'Engaging the Global South on climate engineering research' (2015) 5 *Nature Climate Change* 627.

[227] UN Development Programme <https://www.undp.org/content/undp/en/home.html> accessed 31 March 2020.

[228] UN Development Programme, 'Our Focus: Six Solutions' <https://www.undp.org/content/undp/en/home/six-signature-solutions.html> accessed 31 March 2020.

[229] UN Development Programme, 'Global SDG Integration' <https://sdgintegration.undp.org/> accessed 31 March 2020.

[230] United Nations Charter, (entered into force 24 October 1945) 1 UNTS XVI, Article 13(1)(a)

[231] ILC, 'Draft articles on Responsibility of States for Internationally Wrongful Acts, with commentaries' (2001) UN Doc A/56/10.

[232] See David Reichwein and others, 'State Responsibility for Environmental harm from Climate Engineering' (2015) 5 *Climate Law* 142; Barbara Saxler, Jule Siegfried J, and Alexander Proelss, 'International liability for transboundary damage arising from stratospheric aerosol injections' (2015) 7 *Law, Innovation, and Technology* 112.

[233] Draft Articles on the Prevention of Transboundary Harm.

[234] Karen Brent, Jeff McGee and A. Maguire, 'Does the "no-harm" rule have a role in preventing transboundary harm and harm to the global atmospheric commons from geoengineering?' (2015) 5 *Climate Law* 35.

[235] See ILC, 'Analytical Guide to the Work of the International Law Commission: Protection of the Atmosphere' <https://legal.un.org/ilc/guide/8_8.shtml> accessed 31 March 2020.

[236] ILC, Third report on the protection of the atmosphere by Shinya Murase, Special Rapporteur (25 February 2016) UN Doc A/CN.4/692, 44-51.

[237] ILC, Protection of the Atmosphere: Texts and titles of draft guidelines and preamble adopted by the Drafting Committee on first reading (6 June 2018) UN Doc A/CN.4/L.909, draft Article 7.

[238] Southern Bluefin Tuna Cases (Nos 3 & 4) (New Zealand v Japan; Australia v Japan) (Provisional Measures, Order 27 August 1999) ITLOS Reports 1999, para. 77.

[239] Philippe Sands and Jacqueline Peel, *Principles of International Environmental Law*, 3rd Ed. (2014), 225. See Separate Opinion of Judge Treves, para 8, 'In the present case, it would seem to me that the requirement of urgency is satisfied only in light of such precautionary approach. I regret that this is not staled explicitly in the order'.

[240] ILC, Protection of the Atmosphere: Texts and titles of Draft Guidelines and Preamble adopted by the Drafting Committee on first reading (6 June 2018) UN Doc A/CN.4/L.909, draft Article 7.

[241] ILC, First report on the protection of the atmosphere Prepared by Special Rapporteur Mr. Shinya Murase (14 February 2014) UN Doc A/CN.4/667, 50-51; ILC, Third report on the protection of the atmosphere by Shinya Murase, Special Rapporteur (25 February 2016) UN Doc A/CN.4/692.

[242] See Anna-Maria Hubert and David Reichwein, 'An exploration of a code of conduct for responsible scientific research involving geoengineering' (2015) IASS Working Paper, InSIS Occasional Paper No 1. <https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3513900> accessed 31 March 2020.

[243] UNGA Res 67/290 (23 August 2013) UN Doc A/RES/67/290.

[244] ibid.

[245] Will C. Burns and Jane Flegal, ‘Climate geoengineering and the role of public deliberation: a comment on the US National Academy of Sciences’ recommendations on public participation’ (2015) 5 *Climate Law* 252.

[246] UNESCO, ‘UNESCO Strategy for Action on Climate Change’ (2 October 2017) UN Doc 39 C/46.

[247] See further Anna-Maria Hubert and David Reichwein, ‘An exploration of a code of conduct for responsible scientific research involving geoengineering’ (2015) IASS Working Paper, InSIS Occasional Paper No 1. <https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3513900> accessed 31 March 2020; Anna-Maria Hubert, ‘The Human Right to Science and its Relationship to International Environmental Law’ forthcoming in the *European Journal of International Law*
<https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3450879> accessed 31 March 2020.

[248] UNESCO, ‘Declaration of Ethical Principles on Climate Change’ (2017) UN Doc SHS/BIO/PI/2017/2.

[249] Intergovernmental Oceanographic Commission <http://www.ioc-unesco.org/> accessed 31 March 2020.

[250] Doug Wallace and others, *Ocean Fertilisation: A Scientific Summary for Policy Makers (*IOC/BRO/2010/2, 2010) <https://unesdoc.unesco.org/ark:/48223/pf0000190674> accessed 30 March 2020.

[251] GESAMP, *High level review of a wide range of proposed marine geoengineering techniques* (IMO/FAO/UNESCO-IOC/UNIDO/WMO/IAEA/UN/UN Environment UNDP/ISA Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection, Rep. Stud. GESAMP No. 98, 2019) <http://www.gesamp.org/publications/high-level-review-of-a-wide-range-of-proposed-marine-geoengineering-techniques> accessed 30 March 2020.

[252] World Meteorological Organization <https://public.wmo.int/en> accessed 30 March 2020.

[253] Roelof T. Bruintjes, Report from Export Team on Weather Modification Research For 2015/2016 (WMO)
<https://www.wmo.int/pages/prog/arep/wwrp/new/documents/WMO_weather_mod_2015_2016.pdf> accessed 30 March 2020.

[254] IPCC <https://www.ipcc.ch> accessed 30 March 2020.

[255] IPCC, *Climate Change 2014: Synthesis Report*. Contribution of Working Groups I, II, and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (CUP 2014).

[256] IPCC, *Climate Change 2014: Synthesis Report*. Contribution of Working Groups I, II, and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (CUP 2014), Glossary.

[257] ibid.

[258] IPCC, ‘Summary for Policymakers’ in V Masson-Delmotte and others (eds), Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty (WMO 2018) <https://www.ipcc.ch/sr15/> accessed on 31 March 2020.

[259] ibid.

[260] ibid, 17.

[261] ibid, 17.

[262] ibid, 17.

[263] ibid, 12-13.

[264] Arti Gupta and Ina Möller, ‘De facto governance: how authoritative assessments construct climate engineering as an object of governance’ (2018) 28 *Environmental Politics* 480.

[265] Justin Mikulka, ‘Are ISO's Draft Guidelines on Climate Action the First Steps Toward Geoengineering?’ (*DESMOG*, 18 September 2019) available at <https://www.desmogblog.com/2019/09/18/iso-draft-guidelines-climate-solar-geoengineering> accessed 30 March 2020.

[266] Steve Rayner and others, ‘The Oxford Principles’ (2013) 121 *Climatic Change* 499.

[267] ibid., 509.

[268] Asilomar Scientific Organizing Committee (ASOC), 2010: The Asilomar Conference Recommendations on Principles for Research into Climate Engineering Techniques, Climate Institute, Washington DC, 20006.

269 Anna-Maria Hubert, David Reichwein, An exploration of a code of conduct for responsible scientific research involving geoengineering, IASS Working Paper, InSIS Occasional Paper No 1. Potsdam & Oxford [online] (2015). Available from: https://ssrn.com/abstract=3450879 [Accessed 17 November 2019]; Anna-Maria Hubert, Code of Conduct for Responsible Geoengineering Research [online] (2017). Available from: https://www.ucalgary.ca/grgproject/files/grgproject/revised-code-of-conduct-for-geoengineering-research-2017-hubert.pdf [Accessed 16 November 2019]; Anna-Maria Hubert, Geoengineering Research Governance Project (GRGP) Oxford Workshop on a Code of Conduct for Responsible Geoengineering Research (2017) Available from:

https://ceassessment.org/geoengineering-research-governance-project-grgp-oxford-workshop-on-a-code-of-conduct-for-responsible-geoengineering-research-anna-maria-hubert/ [Accessed 18 November 2019]; Anna-Maria Hubert, 'A Code of Conduct for Geoengineering Research' forthcoming in *Global Policy*.

270 Simon Nicholson, Sikina Jinnah, and Alexander Gillespie, 'Solar radiation management: a proposal for immediate polycentric governance' (2018) 18 *Climate Policy* 332; Anna-Maria Hubert, 'A Code of Conduct for Geoengineering Research' forthcoming in *Global Policy*.

271 Chiara Armeni and Catherine Redgwell, 'International legal and regulatory issues of climate geoengineering governance: rethinking the approach' (2015) Climate Geoengineering Governance Project Working Paper 21, University of Oxford <http://geoengineering-governance-research.org/cgg-working-papers.php> accessed 30 March 2020.

272 Rüdiger Wolfrum and Nele Matz, *Conflicts in International Environmental Law* (Springer 2003) 3.

273 ILC, 'Fragmentation of International Law: Difficulties Arising from the Diversification and Expansion of International Law, Report of the Study Group of the International Law Commission' (July 18, 2006) UN Doc A/CN.4/L.702, 8.

274 International Law Association, New Delhi Declaration of Principles of International Law relating to Sustainable Development (9 August 2002) UN Doc A/CONF.199/8, art 7.

Chapter 3

Beuttler, C. et al. (2019). The Role of Atmospheric Carbon Dioxide Removal in Swiss Climate Policy – Fundamentals and Recommended Actions. Report by Risk Dialogue Foundation. Commissioned by the Federal Office for the Environment, Bern.

Bunn, M. (2019). Governance of solar geoengineering: learning from nuclear regimes. In: *Governance of the Deployment of Solar Geoengineering.* Robert N. Stavins and Robert C. Stowe, eds. Cambridge, USA*: Harvard Project on Climate Agreements, February 2019*.

Burns, E. T et al. (2016). What do people think when they think about solar geoengineering? A review of empirical social science literature, and prospects for future research. *Earth's Future*, *4*(11), 536-542.

Campbell-Arvai, V. et al. (2017). The influence of learning about carbon dioxide removal (CDR) on support for mitigation policies. *Climatic Change*, *143*(3-4), 321-336.

EASAC (2018). Negative emission technologies: What role in meeting Paris Agreement targets? EASAC policy report 35, February 2018. European Academies' Science Advisory Council, Halle.

Fuss, S. et al. (2018). Negative emissions—Part 2: Costs, potentials and side effects. *Environmental Research Letters*, *13*(6), 063002.

Graham, J. D. and Wiener, J. B., eds. (1995): Risk vs. Risk: Trade-offs in Protecting Health and Environment. Harvard Univ. Press.

Grieger, K. D. et al. (2019). Emerging risk governance for stratospheric aerosol injection as a climate management technology. Environment Systems and Decisions, 39(4), 371-382.

Haywood, J. M. et al. (2013). Asymmetric forcing from stratospheric aerosols impacts Sahelian rainfall. *Nature Climate Change*, *3*(7), 660-665.

Heyen, D., Horton, J., and Moreno-Cruz, J. (2019). Strategic implications of counter-geoengineering: Clash or cooperation? Journal of Environmental Economics and Management, 95, 153–177. doi: 10.1016/j.jeem.2019.03.005

Honegger, M. (2019). Assessing Solar Geoengineering – What, Who, and How? In *Governance of the Deployment of Solar Geoengineering*. Edited by R. N. Stavins and R. C. Stowe. Cambridge, USA: Harvard Project on Climate Agreements, February 2019.

Honegger, M. et al. (2018). Carbon Removal and Solar Geoengineering: Potential implications for delivery of the Sustainable Development Goals. Carnegie Climate Governance Initiative, May 2018, New York, U.S.

Honegger, M., and Reiner, D. (2018). The political economy of negative emissions technologies: consequences for international policy design. Climate Policy, 18(3), 306-321.

Irvine, P. J., Ridgwell A., and Lunt D. J. (2010). Assessing the regional disparities in geoengineering impacts. Geophysical Research Letters, 37, 1-6.

IPCC (2018) Global warming of 1.5 °C: An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of change, sustainable development, and efforts to eradicate poverty. Edited by Masson- Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma- Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, T. Waterfield. Geneva, Switzerland. Available at: https://www.ipcc.ch/sr15/

IRGC (2015) Guidelines for Emerging Risk Governance. Lausanne: International Risk Governance Council (IRGC). Available at https://infoscience.epfl.ch/record/228053/files/Guidelines%20for%20Emerging%20Risk%20Governance.pdf

Jones, A. C. et al. (2018). Regional climate impacts of stabilizing global warming at 1.5 K using solar geoengineering. *Earth's Future*, *6*(2), 230-251.

Jones, A. C. et al. (2017). Impacts of hemispheric solar geoengineering on tropical cyclone frequency. *Nature communications*, *8*(1), 1-10.

Keith, D. W., and MacMartin, D. G. (2015). A temporary, moderate and responsive scenario for solar geoengineering. *Nature Climate Change*, *5*(3), 201-206.

Kravitz, B. et al. (2014). A multi-model assessment of regional climate disparities caused by solar geoengineering. *Environmental Research Letters*, 9, 074013.

Kravitz, B. et al. (2011). The geoengineering model intercomparison project (GeoMIP). *Atmospheric Science Letters*, *12*(2), 162-167.

Keohane, R. O., and Victor, D. G. (2016). Cooperation and discord in global climate policy. *Nature Climate Change*, *6*(6), 570-575.

Lin, A. C. (2013) 'Does Geoengineering Present a Moral Hazard', *Ecology Law Quarterly, 40*, p. 673.

Long, J. C., and Shepherd, J. G. (2014). The strategic value of geoengineering research. *Global environmental change*, *1*, 757-770.

MacMartin, D. G., Ricke, K. L. and D. W. Keith (2018). Solar Geoengineering as part of an overall strategy for meeting the 1.5°C Paris target. *Philosophical Transactions of the Royal Society* A*: Mathematical, Physical and Engineering Sciences*, 376, 1-19

MacMartin, D. G., Caldeira, K., and Keith, D. W. (2014). Solar geoengineering to limit the rate of temperature change. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *372*(2031), 20140134.

Markusson, N., McLaren, D., and Tyfield, D. (2018). Towards a cultural political economy of mitigation deterrence by negative emissions technologies (NETs). *Global Sustainability*, *1*.

McLaren, D. (2016). Mitigation deterrence and the 'moral hazard' of solar radiation management. *Earth's Future*, *4*(12), 596-602.

McLaren, D. P et al. (2019). Beyond 'Net-Zero': A case for separate targets for emissions reduction and negative emissions. *Frontiers in Climate*, *1*, 4.

Minx, J. C., et al. (2018). Negative emissions—Part 1: Research landscape and synthesis. *Environmental Research Letters*, *13*(6), 063001.

Morrow, D., and Svoboda, T. (2016). Geoengineering and non-ideal theory. *Public Affairs Quarterly*, *30*(1), 83-102.

Muri, H. et al. (2018). Climate response to aerosol geoengineering: a multimethod comparison. *Journal of Climate*, *31*(16), 6319-6340.

National Academies of Science (2015a). Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration. National Academies Press, Washington, DC.

National Academies of Science (2015b). Climate Intervention: Reflecting Sunlight to Cool Earth. National Academies Press, Washington, DC.

Nemet, G. F. et al. (2018). Negative emissions—Part 3: Innovation and upscaling. *Environmental Research Letters*, *13*(6), 063003.

Nicholson, S., Jinnah, S., and Gillespie, A. (2018). Solar radiation management: a proposal for immediate polycentric governance. *Climate Policy*, *18*(3), 322-334.

Nerini, F.F. et al. (2019). Connecting climate action with other sustainable development goals. *Nature Sustainability*, *2*(8), 674-680.

Parker, A., Horton, J. B., and Keith, D. W. (2018). Stopping Solar Geoengineering Through Technical Means: A Preliminary Assessment of Counter-Geoengineering. *Earth's Future,* 6(8), 1058–1065. doi: 10.1029/2018EF000864

Parker, A., & Irvine, P. J. (2018). The risk of termination shock from solar geoengineering. *Earth's Future*, *6*(3), 456-467.

Philippe, S. (2019). Monitoring and Verifying the Deployment of Solar Geoengineering. In: Governance of the Deployment of Solar Geoengineering. Edited by Robert N. Stavins and Robert C. Stowe. Cambridge, USA: Harvard Project on Climate Agreements, February 2019.

Rahman, A. A. et al. (2018). Developing countries must lead on solar geoengineering research. *Nature* 556, 22-24.

Raimi, K. T. et al. (2019). Framing of geoengineering affects support for climate change mitigation. *Environmental Communication*, *13*(3), 300-319.

Reynolds, J. L., and Fleurke, F. (2013). Climate engineering research: a precautionary response to climate change. *Carbon and Climate Law Review*, 101.

Rickels, W. et al. (2011): Large-Scale Intentional Interventions into the Climate System? Assessing the Climate Engineering Debate. Scoping report conducted on behalf of the German Federal Ministry of Education and Research (BMBF), Kiel Earth Institute, Kiel.

Ricke, K. L., M. G. Morgan, and M. R. Allen (2010). Regional climate response to solar-radiation management, Nature Geoscience, 3, 537—541.

Royal Society (2009). Geoengineering the climate — science, governance and uncertainty. Royal Society Policy document 10/09, London.

Sandin, P. (1999). Dimensions of the precautionary principle. *Human and Ecological Risk Assessment: An International Journal*, *5*(5), 889-907.

Schäfer, S. et al. (2015). The European Transdisciplinary Assessment of Climate Engineering (EuTRACE): Removing Greenhouse Gases from the Atmosphere and Reflecting Sunlight away from Earth. Berlin.

Smith, P., Adams, J., Beerling, D. J., Beringer, T., Calvin, K. V., Fuss, S., ... & Minx, J. C. (2019). Impacts of land-based greenhouse gas removal options on ecosystem services and the United Nations Sustainable Development Goals. *Annual Review of Environment and Resources*, 44. Smith, P., and Friedmann, J. (2017). Bridging the Gap: Carbon Dioxide Removal-The Emissions Gap Report 2017 Chapter 7. *The Emissions Gap Report 2017: A UN Environment Synthesis Report*.

Stephens, J. C., and Surprise, K. (2020). The hidden injustices of advancing solar geoengineering research. *Global Sustainability*, *3*.

Sugiyama, M. et al. (2018). Next steps in geoengineering scenario research: limited deployment scenarios and beyond. *Climate Policy*, *18*(6), 681-689.

Sunstein, C. R. (2005). Laws of fear: Beyond the precautionary principle (Vol. 6). Cambridge University Press.

Thiele, L. P. (2019). Geoengineering and sustainability. *Environmental Politics*, *28*(3), 460-479.

Tilmes, S. et al. (2013). The hydrological impact of geoengineering in the Geoengineering Model Intercomparison Project (GeoMIP). *Journal of Geophysical Research: Atmospheres*, *118*(19), 11-036.

Ürge-Vorsatz, D. et al. (2014). Measuring the co-benefits of climate change mitigation. *Annual Review of Environment and Resources*, *39*, 549-582.

Victor, D. G. (2011). Global warming gridlock: creating more effective strategies for protecting the planet. Cambridge University Press.

Weitzman, M. L. (2015). A voting architecture for the governance of free-driver externalities, with application to geoengineering. *The Scandinavian Journal of Economics*, *117*(4), 1049-1068.

Wiener, J. B. (2002). Precaution in a Multi-risk World in: D. Paustenbach, ed., *Human and Ecological Risk Assessment*, 1509-1531. John Wiley.

Chapter 4

Beuttler, C. et al. (2019) The Role of Atmospheric Carbon Dioxide Removal in Swiss Climate Policy: Fundamentals and Recommended Actions. Zurich: Risk Dialogue Foundation. Available at: https://www.bafu.admin.ch/dam/bafu/en/dokumente/klima/externe-studien-berichte/the-role-of-atmospheric-carbon-dioxide-removal-in-swiss-climate-policy.pdf.download.pdf/The_Role_of_Atmospheric_Carbon_Dioxide_Removal_in_Swiss_Climate_Policy.pdf.

Bodansky, D. (2013). 'The Who, What, and Wherefore of Geoengineering Governance', Climatic Change, 121(3), pp. 539-551. doi: 10.1007/s10584-013-0759-7.

Bodle, R. et al. (2014) Options and Proposals for the International Governance of Geoengineering, Climate Change. Umweltbundesamt / Federal Environment Agency (Germany). Available at: https://www.umweltbundesamt.de/publikationen/options-proposals-for-the-international-governance.

Chhetri, N. et al. (2018) Governing Solar Radiation Management. Forum for Climate Engineering Assessment. Available at: http://ceassessment.org/srmreport.

Cox, E. and Edwards, N. R. (2019). 'Beyond Carbon Pricing: Policy Levers for Negative Emissions Technologies. Climate Policy, 19(9), pp.1144-1156. doi: 10.1080/14693062.2019.1634509

Davies, G. (2010) 'Framing the Social, Political, and Environmental Risks and Benefits of Geoengineering: Balancing the Hard-to-Imagine against the Hard-to-Measure', Tulsa Law Review, 46(2), pp. 261–282. Available at https://digitalcommons.law.utulsa.edu/tlr/vol46/iss2/2/

Department of Economic and Social Affairs (2018) World Economic and Social Survey 2018: Frontier Technologies For Sustainable Development. United Nations Secretariat. Available at: https://www.un.org/development/desa/dpad/wp-content/uploads/sites/45/publication/WESS2018_full_web.pdf.

Engineering and Physical Sciences Research Council (2012) 'SPICE Update'. Available at: https://epsrc.ukri.org/newsevents/news/spiceupdateoct/.

German Research Foundation (DFG) Foundation's Priority Programme 1689 (2019) Climate Engineering and Our Climate Targets: A Long-Overdue Debate. Available at: https://www.spp-climate-engineering.de/news.html?file=files/ce-projekt/media/download_PDFs/climateengineering_spp1689_english.pdf

Grieger, K. D., Felgenhauer, T., Renn, O., Wiener, J. and Borsuk, M. (2019) 'Emerging Risk Governance for Stratospheric Aerosol Injection as a Climate Management Technology', Environment Systems and Decisions, 39(4), pp.371-382. doi: 10.1007/s10669-019-09730-6.

Honegger, M. et al. (2018) Carbon Removal and Solar Geoengineering: Potential Implications for Delivery of the Sustainable Development Goals. New York: Carnegie Climate Geoengineering Governance Initiative. Available at: https://www.c2g2.net/wp-content/uploads/C2G2-Geoeng-SDGs_20180521.pdf.

Honegger, M., Michaelowa, A. and Poralla, M. (2019) Net-Zero Emissions: The Role of Carbon Dioxide Removal in the Paris Agreement, Briefing Report. Freiburg: Perspectives Climate Research. Available at: https://www.perspectives.cc/fileadmin/Publications/Situating_NETs_under_the_PA.pdf.

IPCC (2013) Principles Governing IPCC Work. Available at: https://www.ipcc.ch/site/assets/uploads/2018/09/ipcc-principles.pdf.

IPCC (2018) Global Warming of 1.5°C. Geneva: IPCC. Available at: https://www.ipcc.ch/sr15/.

IPBES (2020) Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) website. Available at: https://ipbes.net.

International Law Commission (ILC) (2001) 'Draft Articles on Prevention of Transboundary Harm from Hazardous Activities, with Commentaries', in Report of the International Law Commission on the Work of its Fifty-Third Session, UN Doc A/56/10. New York: United Nations, pp. 148–170. Available at: https://legal.un.org/ilc/reports/2001/

International Risk Governance Center (IRGC) (2015). Guidelines for Emerging Risk Governance. Lausanne: EPFL International Risk Governance Council. Available at: https://irgc.org/risk-governance/emerging-risk/a-protocol-for-dealing-with-emerging-risks/.

International Risk Governance Center (IRGC) (2016) Planning Adaptive Risk Regulation, Conference Report. Lausanne: EPFL International Risk Governance Center. Available at: https://irgc.org/wp-content/uploads/2018/09/IRGC-Conference-Planned-Adaptive-Regulation-Summary-Report-final-WEB.pdf.

Irvine, P. J. and Keith, D. W. (2020) 'Halving Warming with Stratospheric Aerosol Geoengineering Moderates Policy-Relevant Climate Hazards', Environmental Research Letters, 15(4), article 44011. doi: 10.1088/1748-9326/ab76de.

Jones, P. (2015) Track Two Diplomacy in Theory and Practice. Stanford: Stanford University Press.

Keith, D. W., Wagner, G. and Zabel, C. L. (2017) 'Solar Geoengineering Reduces Atmospheric Carbon Burden', Nature Climate Change, 7(9), pp. 617–619. doi: 10.1038/nclimate3376.

Long, J. C. S. and Shepherd, J. G. (2014) 'The Strategic Value of Geoengineering Research', in Global Environmental Change. Edited by B. Freedman. Dordrecht, The Netherlands: Springer. doi: 10.1007/978-94-007-5784-4_24.

Marchant, G. E., Allenby, B. R. and Herkert, J. R. (2011) The Growing Gap Between Emerging Technologies and Legal-Ethical Oversight: The Pacing Problem, The International Library of Ethics, Law and Technology. Edited by G. E. Marchant, B. R. Allenby, and J. R. Herkert. Dordrecht, The Netherlands: Springer. doi: 10.1007/978-94-007-1356-7.

McCray, L. E., Oye, K. A. and Petersen, A. C. (2010) 'Planned Adaptation in Risk Regulation: An Initial Survey of US Environmental, Health, and Safety Regulation', Technological Forecasting and Social Change, 77(6), pp. 951–959. doi: 10.1016/j.techfore.2009.12.001.

Morgan, M. G. and Ricke, K. (2010) Cooling the Earth Through Solar Radiation Management: The need for research and an approach to its governance. Geneva: International Risk Governance Council. Available at: https://irgc.org/wp-content/uploads/2018/09/SRM_Opinion_Piece_web.pdf.

National Research Council (2015a) Climate Intervention: Reflecting Sunlight to Cool Earth. Washington: National Academies Press. doi: 10.17226/18988.

National Research Council (2015b) Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration. Washington: National Academies Press. doi: 10.17226/18805.

Nerini, F. F. et al. (2019) 'Connecting Climate Action with Other Sustainable Development Goals', Nature Sustainability, 2(8), pp. 674–680. doi: 10.1038/s41893-019-0334-y.

Parson, E. A. and Herzog, M. M. (2016) 'Moratoria for Global Governance and Contested Technology: The Case of Climate Engineering', UCLA Public Law & Legal Theory Series. Available at: https://escholarship.org/uc/item/2c28w2tn.

Rahman, A. A. et al. (2018) 'Developing Countries Must Lead on Solar Geoengineering Research', Nature, 556, pp. 22-24. doi: 10.1038/d41586-018-03917-8.

Rayner, S. et al. (2013) 'The Oxford Principles', Climatic Change, 121(3), pp. 499–512. doi: 10.1007/s10584-012-0675-2.

Reynolds, J. L., Contreras, J. L. and Sarnoff, J. D. (2017) 'Solar Climate Engineering and Intellectual Property: Toward a Research Commons', Minnesota Journal of Law, Science & Technology, 18(1), pp. 1–110. Available at: https://scholarship.law.umn.edu/mjlst/vol18/iss1/1/.

Reynolds, J. L. and Parson, E. A. (2020) 'Non-state Governance of Solar Geoengineering Research', Climatic Change, available online ahead of print. doi: 10.1007/s10584-020-02702-9.

Rickels W., et al. (2011) Large-Scale Intentional Interventions into the Climate System? Assessing the Climate Engineering Debate. Kiel, Germany: Kiel Earth Institute. Available at: https://www.kiel-earth-institute.de/scoping-report-climate-engineering.html

Schmidt, V. A. (2013) 'Democracy and Legitimacy in the European Union Revisited: Input, Output and 'Throughput'', Political Studies, 61(1), pp. 2–22. doi: 10.1111/j.1467-9248.2012.00962.x.

Swiss Academies of Arts and Sciences (2018) Reverse Emissions or Influence Solar Radiation: Is 'Geoengineering' Worthwhile, Feasible and If So, at What Price? Available at: http://www.swiss-academies.ch/dms/E/Publications/Factsheets/Geoengineering_E_Web-compressed.pdf.

United Nations Commission on Human Rights (2000) 'The Role of Good Governance in the Promotion of Human Rights (E/CN.4/RES/2000/64)'. Available at: https://ap.ohchr.org/documents/E/CHR/resolutions/E-CN_4-RES-2000-64.doc.

United Nations General Assembly (2015) 'Transforming Our World: The 2030 Agenda for Sustainable Development (A/RES/70/1)'. Available at: https://undocs.org/A/RES/70/1.

United Nations General Assembly (1972) 'Institutional and Financial Arrangements for International Environmental Cooperation (A/RES/2997(XXVII))'. Available at: https://undocs.org/en/A/RES/2997(XXVII)

United Nations General Assembly (1988) 'Protection of Global Climate for Present and Future Generations of Mankind (A/RES/43/53)'. Available at: https://undocs.org/A/RES/43/53.

United Nations General Assembly (2012) 'The Future We Want (A/RES/66/288)'. Available at: https://undocs.org/A/RES/66/288.

World Meteorological Organisation (2015) Seventeenth World Meteorological Congress, Geneva, 25 May–12 June 2015, Abridged Final Report with Resolutions. Available at: https://library.wmo.int/?lvl=notice_display&id=18648

World Meteorological Organization (2016) WMO Operating Plan 2016–2019. Available at: https://www.wmo.int/pages/about/documents/WMOOP2016-2019_October2016version.pdf.

Zürn, M. and Schäfer, S. (2013) ‚The Paradox of Climate Engineering', Global Policy, 4(3), pp.266–277. doi: 10.1111/gpol.12004.

Acknowledgments

The authors of this report are **Paul Rouse**, Carnegie Climate Governance Initiative (C2G) for chapter 1; **Anna-Maria Hubert,** University of Calgary for chapter 2; **Matthias Honegger**, Institute for Advanced Sustainability Studies (IASS) for chapter 3; and **Jesse Reynolds**, University of California (UCLA) for chapter 4. **Marie-Valentine Florin**, IRGC (EPFL) acted as editor and main author of the introduction and conclusion.

This report, in particular the conclusion, elaborates from insights developed during a workshop with external experts held online on 23 April 2020. Participants from governments, universities, research institutes and non-governmental organizations made critical comments and suggestions on the draft report, which were taken into account by the authors of the report. Chapter 3 benefitted from particular inputs from Mark Lawrence, Jonathan Wiener, and Ortwin Renn. Additional research and editing on this report were done by Alexandra Solinski and Anca G. Rusu.

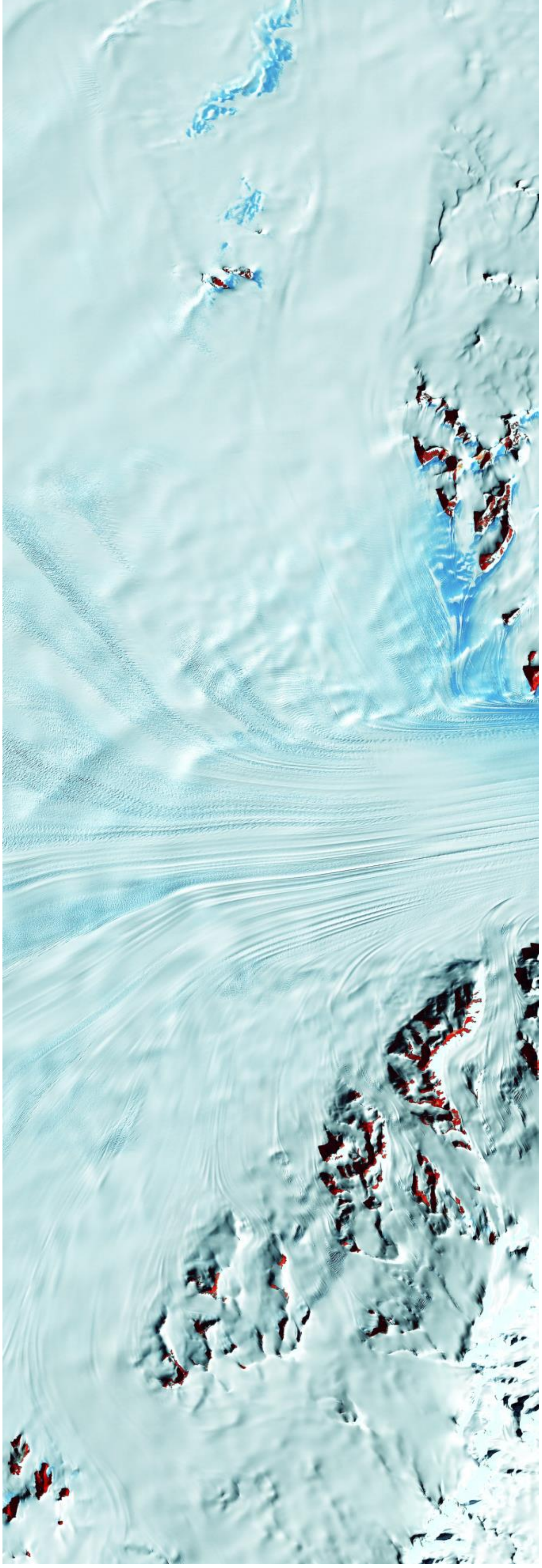
Participants from research and academia were: **Silke Beck**, Helmholtz Centre for Environmental Research; **Christoph Beuttler**, Climeworks & Risk Dialogue Foundation; **Ralph Bodle**, Ecologic Institute; **Gérard Escher**, Ecole polytechnique fédérale de Lausanne (EPFL) & Geneva Science and Diplomacy Anticipator (GESDA); **Oliver Geden**, German Institute for International and Security Affairs (SWP); **Daniel Heyen**, ETH Zürich; **Anna-Maria Hubert**, University of Calgary; **Matthias Honegger**, IASS; **Peter Irvine**, University College London (UCL); **Chukwumerije (Chuks) Okereke**, University of Reading; **Andreas Oschlies**, GEOMAR Helmholtz Centre for Ocean Research Kiel; **Andy Parker**, Solar Radiation Management Governance Initiative (SRMGI); **Edward A. (Ted) Parson**, University of California (UCLA); **Jesse Reynolds**, UCLA; **Paul Rouse**, C2G; **John Shepherd,** University of Southampton; **Shuchi Talati**, Union of Concerned Scientists (UCS); **Eduardo Viola**, University of Brasilia; **Jonathan Wiener**, Duke Law School; and **David Winickoff**, Organisation for Economic Co-operation and Development (OECD).

The views and recommendations contained in this report do not necessarily represent the views of individual workshop participants or their employers.

About IRGC

The International Risk Governance Center at EPFL (Ecole polytechnique fédérale de Lausanne) helps to improve the understanding and governance of systemic risks that have impacts on human health and safety, the environment, the economy and society at large. IRGC's mission includes developing risk governance concepts and providing risk governance policy advice to decision-makers in the private and public sectors on key emerging or neglected issues. It emphasises the role of risk governance for issues marked by complexity, uncertainty and ambiguity, and the need for appropriate policy and regulatory environments for new technologies where risk issues may be important.

irgc.epfl.ch



EPFL International Risk
Governance Center

EPFL IRGC
Station 5 BAC (Bassenges)
1015 Lausanne
Switzerland

+41 21 693 82 90

irgc@epfl.ch