Carnegie Climate Geoengineering Governance Initiative

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Technical Briefing Paper:

Knowledge gaps on climate-related geoengineering in relation to the Convention on Biological Diversity (CBD)

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Summary

This technical briefing presents an assessment of knowledge gaps on climate-related geoengineering relevant to the Convention on Biological Diversity (CBD) based on a recent workshop with members of the Subsidiary Body on Science, Technical and Technological Advice (SBSTTA) and validated by a review of relevant academic literature.

It is presented as part of an ongoing collaboration between the Carnegie Climate Geoengineering Governance Initiative (C2G2) and the Secretariat of the Convention on Biological Diversity and aims to provide a technical evidence-based input to inform Parties, observers and others as they consider future action on climate-related geoengineering research and governance.

Knowledge gaps around ethics, governance, deployment and research are identified and suggestions made for next steps to progress the development of research and governance relevant to SBSTTA and the CBD.

Substantial knowledge gaps were identified in relation to governance and research of climate-related geoengineering, including:

- *Governance:* With regards to existing regulatory frameworks (local, regional and international), who are the decision-making actors? What institutional(s) are (or would be) responsible for the monitoring, evaluation and verification of geoengineering technologies?
- *Research:* What type of capacity development is needed? How might knowledge-sharing and enhanced access to information strengthen research? Why is there a lack of interest in on-the-ground research and more interest on processes?

Despite some existing literature, further knowledge gaps were also identified in relation to ethics, governance and deployment of climate-related geoengineering, including:

- *Ethics:* What are the risks associated with a focus on geoengineering technologies diverting attention/focus/effort from other techniques and approaches to emission reductions? What safeguards and emergency measures are being researched/proposed for the various scales of research taking place? What is being researched/proposed in terms of liability and redress measures?
- *Governance:* What existing regulatory frameworks are in place at the local, regional and international levels and how is the policy process being shaped? How can society effectively design a decision-making process that ensures multi-stakeholder engagement? What is the public perception of these technologies in developing countries? What is the minimum legal framework required for a country to govern geoengineering broadly, but also for specific technologies such as Solar Geoengineering?

- *Deployment:* How might geoengineering technologies impact biodiversity? What are the cost/benefits of nature-based solutions (e.g. ecosystem-based approaches) vs other geoengineering technologies? How applicable is research conducted in one country, for another country/region?

A range of governance, research and knowledge sharing needs were identified together with possible next steps for how these needs could be addressed through the CBD, including:

- Identify and involve relevant institutions and actors.
- Assess which existing institutions can lead the discussions.
- Identify and enhance synergies between processes and discussions.
- Enhance multilateral and multi-disciplinary learning through establishing research groups or an international conference.
- Develop frameworks or guidance for national governments on how to take on these issues.
- Create or foster creation of protocols, ethical frameworks or codes of conduct for research.

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Acknowledgements

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Disclaimer

Any views expressed in this paper do not necessarily reflect the official positions of the authors, C2G2, The Mercator Research Institute for Global Commons and Climate Change or the Secretariat of the Convention on Biological Diversity.

1. Introduction

Parties to the Convention on Biological Diversity (CBD) have been addressing the issue of climate-related geoengineering for ten years now[1]. Decisions taken during Conferences of the Parties COP-9, COP-10, COP-11, COP-12 and COP-13 all reaffirmed the importance of taking a precautionary approach to the issue and an increasing emphasis has been placed on promoting better understanding of the impacts it could on achieving the Convention's core objectives. Most recently, decision XIII/14 taken during COP-13 noted:

> "*…that more transdisciplinary research and sharing of knowledge among appropriate institutions is needed in order to better understand the impacts of climate-related geoengineering on biodiversity and ecosystem functions and services, socio-economic, cultural and ethical issues and regulatory options*" [2]

and recommendation XXI/1 made during the 21st Meeting of the CBD's Subsidiary Body on Science, Technical and Technological Advice (SBSTTA-21):

> "*Invites the scientific and other relevant communities working on scenarios and related assessments to take into account the following issues which are relevant to the development of the post-2020 global biodiversity framework: […] (h) Technology developments that may have positive or negative impacts on the achievement of the three objectives of the Conventions as well as on the lifestyles and traditional knowledge of indigenous peoples and local communities*" [3]

In support of these decisions and recommendations, in December 2017, the Carnegie Climate Geoengineering Governance Initiative (C2G2) convened a workshop in collaboration with the CBD Secretariat on the side-lines of SBSTTA-21 in Montreal, Canada to explore the issue of '*Transdisciplinary research and governance on climate-related geoengineering in relation to the CBD*'[4]. The workshop brought together 47 international experts (including SBSTTA members and observers) with discussions stimulated by presentations from leading voices from policy, academia, research, civil-society and indigenous people's groups. During two breakout-group sessions, participants discussed and identified a range of knowledge gaps around transdisciplinary research and regulatory options for governing geoengineering research (see Annex of Workshop report[5]) which were provided as an information input to SBSTTA-22[6] by the CBD Secretariat.

C2G2, with the support of colleagues at the Mercator Research Institute on Global Commons and Climate Change[7] then undertook a review of knowledge gaps identified during the workshop, assessing them against existing academic literature to provide a more reliable synthesis of current knowledge gaps[8]. This analysis is not intended to serve as an exhausted assessment of knowledge gaps but is presented here as an evidence-based technical input to inform CBD Parties and observers as they consider future action on climate-related geoengineering research and governance.

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[1] See: https://www.cbd.int/climate/geoengineering/
[2] See CBD COP Decision XIII/14 (paragraph 5): https://www.cbd.int/decisions/cop/13/14
[3] See CBD SBSTTA-21 Rec. XXI/1 (paragraph 7h): https://www.cbd.int/recommendations/sbstta/?m=sbstta-21
[4] See Workshop Report and Resources here: https://www.c2g2.net/workshop-and-conference-reports/
[5] https://www.cbd.int/doc/c/debf/bebf/bbaee42e539a255417181997/sbstta-22-inf-33-en.pdf
[6] See: https://www.cbd.int/doc/c/debf/bebf/bbaee42e539a255417181997/sbstta-22-inf-33-en.pdf
[7] See: www.mcc-berlin.net
[8] Noting the nascent stage of Solar Geoengineering in the debate at the science-policy interface and the much more pronounced role that Carbon Removal plays in the context of the 1.5°C pathways following the Paris Agreement, this briefing will be more detailed with respect to the latter while trying to make the differences concerning Solar Geoengineering explicit.

In the following Section 2, we present analysis of 16 questions (knowledge gaps) identified during the December 2017 workshop, clustered into the following categories: ethics, governance, deployment and research. Table-1 presents these 16 questions (knowledge gaps) categorised based on a review of recent existing academic literature.

In Section 3 we provide more detailed commentary on the literature that helps address some of these knowledge gaps and in Section 4 we go on to discuss remaining knowledge gaps.

In Section 5 we present a synthesis of the insights from the workshop in relation to institutions and regulatory options for climate-related geoengineering and in Section 6 we conclude with some key observations for consideration.

It is important to note that in contrast to many scientists and other bodies, the CBD continues to categorize Solar Geoengineering and Carbon Removal together as ‘climate-related geoengineering’. This makes assessment challenging as the two categorisations conceptually and practically differ and are associated with different technologies, risks, ethical considerations and implications for governance[9]. The reader will note that this briefing includes references to a variety of different terms used to describe Solar Geoengineering and Carbon Removal, reflecting the current diversity of terms in use in the literature[10]. Box 1 provides a guide to the various terms used and briefly describes the different technologies involved.

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[9] Amongst different Carbon Removal options, ocean fertilization and – to a lesser extent – some forms of enhanced weathering have been noted to come closer to Solar Geoengineering in some governance respects. Note that the London Protocol of the International Maritime Organization has asserted authority for regulation of ocean fertilisation (Strong *et al* 2009), which is widely viewed as a moratorium on commercial ocean fertilisation activities.

[10] See C2G2's Terminology Guide: https://www.c2g2.net/terminology-guide/ and Glossary: www.c2g2.net/glossary

Box 1. Climate-related geoengineering technologies and terminology

Climate-related Geoengineering

Alternate terms: *Geoengineering, Climate Geoengineering, Climate Intervention, Climate Engineering*

Climate-related geoengineering refers to intentional large-scale human interference in the Earth system to combat climate change. It is an umbrella term covering a variety of technologies and while terminology and classifications are contested, C2G2 refers to them in two categories: *Carbon Removal* and *Solar Geoengineering*

Carbon Removal

Alternate terms: *Carbon Dioxide Removal, Negative Emissions Technologies (NETs), Carbon Geoengineering*

Techniques which remove CO_2 from the atmosphere, thus addressing the primary cause of anthropogenic climate change

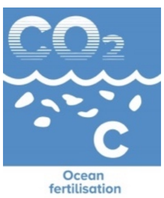
Afforestation and Forest Ecosystem Restoration (AR)
Planting of forests and restoration of ecosystems that result in long-term storage of carbon in above- and below-ground biomass

Biomass Energy with Carbon Capture and Storage (BECCS)
Burning biomass for energy generation and capturing and permanently storing the resulting CO_2

Direct Air Carbon Capture and Storage (DACCS)
Capturing CO_2 directly from ambient air by a chemical process, followed by permanent storage or use

Enhanced Weathering (EW) & Ocean Alkalinity (OA) Enhancing natural weathering of rocks by extracting, grinding and dispersing carbon-binding minerals on land or by adding alkaline minerals to the ocean to enhance oceanic carbon uptake.

Enhancing Soil Carbon Content with Biochar (Biochar)
Biomass burning under low-oxygen conditions (pyrolysis) yields charcoal "biochar" which is then added to the soil to enhance soil carbon levels.

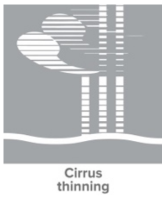


Ocean Fertilisation (OF)
Fertilising ocean ecosystems with nutrients to accelerate phytoplankton growth, which partly sinks to the seabed thus moving carbon from the atmosphere to the seabed.

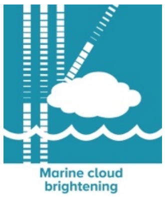
Solar Geoengineering

Alternate terms: *Albedo Modification, Solar Radiation Management, Radiation Modification Measures, Radiative Forcing Geoengineering*

Techniques to reflect more solar radiation into space, reducing temperatures and addressing a symptom (but not cause) of climate change



Cirrus Thinning (ST)
A form of solar geoengineering, reducing the absorption of radiation by cirrus clouds



Marine Cloud Brightening (MCB)
A form of solar geoengineering which makes clouds brighter to increase planetary albedo

Stratospheric Aerosol Injection (SAI) Injecting reflective aerosol particles or particle precursors into the lower stratosphere to increase the planetary albedo and thereby reduce temperatures

Surface Albedo Modification (SAM) Making various surfaces such as urban areas, roads, agricultural land, grasslands, deserts, polar ice-caps or oceans brighter to prevent solar radiation from heating up the areas covered.

2. Assessment of knowledge gaps

In Table 1 we present an assessment of knowledge gaps identified during the December 2017 C2G2 Workshop on *Transdisciplinary research and governance on climate-related geoengineering*. The list of gaps identified (see Annex) was initially reorganized and partially merged resulting in 16 questions which were then assigned to four different categories: ethics, governance, deployment and research. Each question was then assessed against available academic literature and classified using a traffic-light-system as follows:

- **No literature (or very little)** found addressing the question
- **Some literature** addresses this question, but it is insufficient for decision-making or different parts of the literature disagree;
- **Substantial literature** is available on the topic;

Key references are provided as a first indication of the extent of knowledge (but should not be considered as exhaustive).

Table 1: Categorization of knowledge gaps

Category	Question	Extent of Knowledge	References
ETHICS	1. What are the risks associated with a focus on geoengineering technologies diverting attention/focus/effort from other techniques and approaches to emissions reductions?		- **Ethical** (Lenzi, 2018; Minx et al 2018; Lawford-Smith and Currie 2017; Shue 2017; Preston 2013; Hale 2012; Morrow 2014; Anderson and Peters 2016; Lackner et al 2016, Lin, 2013). - **Empirical evidence of moral hazard** (Dana 2018; Burns et al 2016; Corner and Pidgeon 2014; Campbell-Arvai et al 2017; Fairbrother 2016; Kahan et al 2015; Wibeck et al 2015; Merk et al 2016; McLaren et al 2016). - **Dependence** (Fuss et al 2014).
	2. What safeguards and emergency measures are being researched / proposed for the various scales of research taking place? (national, regional international)		- **Legal aspects** (Gerrard and Hester, 2018). - **Safeguards on research** (Rayner et al, 2009, 2013; Hubert, 2017; McKinnon, 2018). - **Security and counter-geoengineering** (Nightingale and Cairns, 2014; Parker et al., 2018).
	3. What is being researched / proposed in terms of liability and redress measures?		- **Insights from comparable cases** (Horton et al., 2015) **.** - **Uncertainties & possibility of unilateral action** (Hester and Gerard, 2018). - **Maintenance concerns** (Wong, 2014). - **Reparations** (Heyward, 2014). - **Legal liability and compensation** (Hester, 2018).

GOVERNANCE	4. What existing regulatory frameworks are in place at the local, regional and international levels and how is the policy process being shaped?		- **Overview** (Burger and Gundlach 2016; Geden et al 2018, Hester and Gerrard 2018; Hester 2018; Liu and Chen 2015) - **Legal, regulatory and policy frameworks** (Gerard and Hester, 2018; Reynolds, 2018; Morrow, 201) - **Bioenergy** (EU Commission 2003; 2017, Scarlat et al 2015). - **CCS** (Dixon et al 2015, Mace et al 2007). - **International Maritime Organization** (IMO 1972; 1996; 2010). - **CBD** (CBD 2008; 2010). - **SRM** (Bodle 2010). - **Research principles** (Rayner et al 2009; 2013; Hubert, 2017). - **Scientific efforts** (National Academy of Sciences 2015; The Royal Society 2009; Meadowcroft 2013; Creutzig 2017). - **Political economy** (Reiner 2017). - **Importance of engaging the global south** (Rayman et al, 2018).
	5. With regards to existing regulatory frameworks (local, regional and international), who are the decision-making actors?		..
	6. How can we effectively design a decision-making process that ensures multi-stakeholder engagement? (especially the integration of local and global public concerns in decision-making)		- **Consent and liability** (Wong, 2016; Horton et al., 2015) - **Interaction between research and deployment** (McKinnon, 2018) - **Other institutional/organisational dimensions** (Hester and Gerrard, 2018; Reynolds, 2018; Nicholson et al., 2017) - **Importance of engaging the global south** (Winickoff et al 2015; Parker 2014; Rayman et al, 2018; McKinnon 2018; Moe and S. Røttereng 2018; Burns 2016b, 2016a.)

	7. What institutional body is or would be responsible for the monitoring, evaluation and verification of geoengineering technologies?		- **Need for MEV identified** (Hester and Gerrard, 2018; Reynolds, 2018; Nicholson et al., 2017; UNEP, 2017).
	8. What is the public perception of these technologies in developing countries?		- **Broad/Global North** (Lomax et al 2015, Nemet et al 2018, Wright et al 2014) - **SRM** (Mahajan et al 2018) Visschers) - **CCS/DACCS** (Gough et al 2014, Mabon et al 2013, Wallquist et al 2012, Boot-Handford et al 2014) - **BECCS** (Fridahl 2017, Gough and Upham 2011, Robledo-Abad et al 2017) - AR and Global South (Nijnik and Halder 2013, Trevisan et al 2016; Schirmer and Bull 2014) - **SCS** (Jørgensen and Termansen 2016, Glenk and Colombo 2011) - Biochar (Wright et al 2014) - **EW** (Taylor et al 2016, Wright et al 2014) - **Global South** (Winickoff et al 2015; Rayman et al., 2018)
	9. What is the minimum legal framework required for a country to govern geoengineering broadly, but also for specific geoengineering? technologies such as SRM?		- **Overview of legal dimensions** (Gerard and Hester, 2018).
DEPLOYMENT	10. What are the outcomes/impacts/side effects of geoengineering technologies?		- **Albedo** (BECCS, AR, biochar). - **AR** (Anderson et al 2011, Arora and Montenegro 2011, Betts et al 2007, Jackson et al 2008, Wang et al 2014; Jackson et al 2005, Smith and Torn 2013, Smith et al 2016); - **AR, nutrients and soil** (Laganiere et al 2010, Deng et al 2017). - **AR and Livelihood** (Greve et al 2013, Locatelli et al 2015, Renner et al 2008);

			- **BECCS** (Bright et al 2015, Jones et al 2015; Mutopo et al 2011, Creutzig et al 2013, Hunsberger et al 2014, Schoneveld et al 2010, Buck 2016); - **BECCS and water** (Smith et al 2016, Smith and Torn 2013, Fajardy and Mac Dowell 2017, Mathioudakis et al 2017, Lampert et al 2016, Mouratiadou et al 2016, Wei et al 2016, Gheewala et al 2011, Gerbens-Leenes et al 2009, Bonsch et al 2016). - **BECCS and degraded land** (Lemus and Lal 2005). - **BECCS and LUC/iLUC** (Plevin et al 2010, 2014, Smith et al 2016, Smith and Torn 2013, Fajardy and Mac Dowell 2017); - **BECCS and land-use competition** (Heck et al 2018, National Academy of Sciences 2015, Beringer et al 2011, Creutzig et al 2015, Smith et al 2016); - **BECCS and food security** (Smith et al 2013, Edenhofer et al 2013, Popp et al 2011, Reilly et al 2012, Müller et al 2008, Zilberman et al 2013, Roberts and Schlenker 2010, Timilsina et al 2012) - **BECCS, tenure, displacement** (Borras and Franco 2010, Rist et al 2010) - **Biochar and soil carbon** (Bozzi et al 2015; Kammann et al 2017; Bamminger et al 2016; Smith, 2016; Nayak et al 2015, Liao et al 2015). - **CBD** (Williamson and Bodle 2016). - **EW** (Rau and Caldeira 1999, Harvey 2008, Kheshgi 1995, Köhler et al 2013b, National Academy of Sciences 2015; Leonardos et al 1987, Nkouathio et al 2008; Taylor et al 2016, Hartmann et al 2013; Strefler et al 2018a, Edwards et al 2017, Kantola et al 2017). - **DACCS** (Keith 2009, Lackner et al 2012, Holmes and Keith 2012, National Academy of Sciences 2015); AR (Smith and Torn 2013, Houghton et al 2015); - **OF** (Matear 2004, Denman 2008, Russell et al 2012, Sarmiento and Orr 1991, Bertram 2010, Trick et al 2010; Cullen and Boyd 2008)
	11. How might geoengineering technologies impact biodiversity?		- **Overview** (Williamson and Bodle 2016). - **BECCS** (Dale et al 2015, Newbold et al 2015, Tarr et al 2017, Barlow et al 2007, Holland et al 2015, Immerzeel et al 2014, Kline et al 2015, Santangeli et al 2016). - **AR** (Cunningham et al 2015, Díaz et al 2009, Greve et al 2013, Hall et al 2012, Locatelli et al 2015, Ryan et al 2010, Paul et al 2016, Venter et al 2012, McKinley et al 2011).

			- **Ocean EW** (Köhler et al 2013a).
	12. What are the cost/benefits of nature-based solutions (e.g. ecosystem-based approaches) vs other geoengineering technologies?		- **Nature-based Solutions** (Cohen-Shacham et al 2016; Nesshöver et al 2017, Eggermont et al 2015, Erb et al 2017, Keesstra et al 2018, Turner 2018, Rockström et al 2017). - **Improvements to ecosystem services** (Lafortesza and Chen 2016, Keesstra et al 2018).
	13. How applicable is research conducted in one country, for another country/region?		- **Carbon Removal - afforestation more effective in the tropics** (Jones et al 2015; Jackson et al 2008; Kreidenweis et al 2016).
	14. What type of capacity development is needed?		- **For Global South** (Rayman et al., 2018; Winickof et al 2015).
	15. Why is there a lack of interest in on-the-ground research and more interest on processes?		- ..
	16. How might knowledge-sharing and enhanced access to information strengthen research?		- ..

3. Review of existing literature

In this section we describe the existing body of literature covering the questions categorised in Table 1 as green (●) or yellow (●). Although there is disagreement between categorisations distinguishing Solar Geoengineering from Carbon Removal in the geoengineering literature it is important to know that many of the issues discussed apply differently to these broad groups of technologies and that most literature tends to focus on one particular technology or category. It is important to note that not all literature is covered exhaustively in this section, we instead present a few illustrative examples. For further references, the reader is referred back to Table 1.

Geoengineering as competition to emission reductions (Ethics-1)
What are the risks associated with a focus on geoengineering technologies diverting attention/focus/effort from other techniques and approaches to emission reductions?

Much of the early ethics literature uses the term geoengineering but discusses a lot of issues more (or exclusively) relevant to Solar Geoengineering. However, as Carbon Removal methods become increasingly prominent there are calls and efforts to assess the ethical implications distinctly relevant to NETs (Lenzi 2018). In consideration of this question it is important to highlight that the Integrated Assessment Modelling (IAM) scenarios, which underpin much of the discussion of Carbon Removal, do not replace ambitious emissions reduction efforts with removals, but rather introduce them to supplement such efforts to reach ambitious targets (Clarke *et al* 2014). As such, the effects of a continued focus on geoengineering has to be assessed considering not only the ethical and empirical risks or drawbacks that such a focus might have, but also the implications of forgoing these technology options, both in policy discourse and deployment. The ethics discussion regarding the deployment of, or further research on Carbon Removal[11] technologies is focused around three major interrelated concerns: moral hazard, betting and hubris and their supporting empirical evidence (Minx *et al* 2018, Shue 2017, Lawford-Smith and Currie 2017, Preston 2013, Lenzi 2018):

- **Moral Hazard:** The moral hazard concern is also considered as mitigation obstruction, risk compensation (Lin 2013) or weakened resolve (Morrow 2014). This refers to the idea that accepting the possibility of geoengineering will decrease emissions reduction efforts, whether through the facilitation of moral corruption (Preston 2013), which allows "passing the buck" to future generations, alleviating political pressure that would demand change, or locking-in path dependencies[12]. This issue is exacerbated/caused by the uneven distribution of costs of quick and aggressive emission reductions and the harm caused by continued inaction. However, some argue that some degree of mitigation obstruction might be warranted if deployment could be ensured to reduce harm (e.g. to the world's poor) (Morrow 2014, Morrow and Svoboda 2016). There is growing interest in the empirical evidence of mitigation obstruction due to moral hazard, with no definitive findings (for reviews see Dana (2018) and Burns *et al* (2016). Support for mitigation measures was found to increase (Merk *et al* 2016, Wibeck *et al* 2015), decrease (Campbell-Arvai *et al* 2017, Kahan *et al* 2015), or remain the same (Fairbrother 2016) after making geoengineering options more salient.

- **Betting:** Another concern is that the current focus on geoengineering implies a policy bet that might be both empirically unwarranted (Anderson and Peters 2016, Anderson 2015) and ethically undesirable (Shue 2017). The ambitious targets of the Paris agreement depend on NETs to an extent that does not seem to be sufficiently acknowledged in the broader discourse nor in government commitments (Anderson and Peters 2016, Fuss *et al* 2014, Rogelj *et al* 2016). Modelling assumes a scale of deployment of Carbon Removal technologies that has not been proven (especially BECCS) as well as perfect information and governance regimes that allow

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[11]Solar Geoengineering-specific concerns revolve around the immediacy of effects and the possibility of sudden termination, he possibility of unilateral wide-spread deployment due to relatively low costs and trans-border effects. Other aspects with sparser literature include concerns around intergenerational equity and consent.
[12] See McKinnon (2018) for Solar Geoengineering lock-in and intergenerational equity arguments.

optimal allocation of resources. This creates a growing dependence on Carbon Removal that risks greater harm if the projections fail to materialize as assumed in the models.

- **Hubris:** The hubris concern pertains to the overconfidence in our capacity to utilize NETs justly, safely or effectively (Lenzi 2018). Related to technological optimism, this discussion encompasses both the oversimplification of assumptions in terms of the reversibility of warming as well as the feasibility and safety of large-scale Carbon Removal deployment (Lenzi 2018, Minx *et al* 2018). The large-scale deployment of Carbon Removal implies major interventions in land, water, nutrient and energy flows (Smith *et al* 2016) that could further increase the strain humans place on planetary systems (Heck *et al* 2018).

Safeguards and Emergency Measures (Ethics-2)

What safeguards and emergency measures are being researched/proposed for the various scales of research taking place?

Recent literature on the legal aspects of geoengineering identify a range of domestic laws in the US which grant extraordinary powers to federal, state, and local governments to act in emergency situations. These could, in principle, allow an agency to halt a climate engineering project (or could conceivably allow an agency to start one) (Gerard and Hester, 2018).

To safeguard against irresponsible research, guiding principles (Rayner *et al* 2009, 2013) and a geoengineering research Code of Conduct (Hubert, 2017) have been developed while other proposals are emerging e.g. for how to avoid research leading to lock-in to the deployment of Solar Geoengineering (McKinnon, 2018). Some initial examination of security implications (Nightingale and Cairns, 2014) has been undertaken, along with and some preliminary assessment of technical options to counter solar geoengineering should it ever be deployed (Parker et al., 2018).

In the case of Carbon Removal where parts of the supply chain are already subject to regulation, e.g. for BECCS, there are sustainability criteria accompanying the Renewable Energy Directive of the European Commission for the case of bioenergy, which apply to the sustainability of biomass sourcing. In addition, some countries do have legislation at national level relating to the storage of CO_2, which in some cases is forbidden on land (but allowed offshore) (Gerrard and Hester 2018). Finally, the research on Ocean Fertilization is regulated at international level under the London Protocol of the International Maritime Organization coming close to a ban on commercial-scale Ocean Fertilization activities.

Liability and Redress (Ethics-3)

What is being researched/proposed in terms of liability and redress measures?

When considering the issue of liability and redress in the event that geoengineering is ever deployed and results in damage (or the claim of damage), a substantial body of legal knowledge about international liability provides useful insights into potential features of a future framework to cover geoengineering (Horton et al., 2015). However, due to the complexity of the global climate system, assigning liability for damages resulting from solar geoengineering presents new and novel challenges in relation to the traditional legal requirement of demonstrating causal attribution (Horton et al., 2015). Other issues identified in the literature include concerns around multi-generational liability for the maintenance of interventions once commenced (Wong 2014) and the possibility of reparations if the benefits and costs from deployment are distributed unevenly (Heyward 2014). Recent literature provides a broad examination of the issues of legal liability and compensation under international, transnational and domestic law covering both state and non-state actors (Hester, 2018).

Regulatory Framework and shaping of the policy process (Governance-4)

What existing regulatory frameworks are in place at the local, regional and international levels and how is the policy process being shaped?

Recent literature identifies a range of legal, regulatory and policy frameworks (Gerard and Hester, 2018) including international legal instruments and institutions (Reynolds, 2018; Morrow, 2017) relevant for geoengineering. At national level, recent literature suggests that States either are involved in climate

engineering governance only at the margin or are absent entirely, and some non-state actors have contributed in various ways to governance (Reynolds, 2018). Debate continues as to how centralized or polycentric future global governance will need to be (Reynolds, 2018).

Discussion and acceptance of research on geoengineering is inching forward as there is an increased perception of either necessity or inevitability of deployment due to continuously weak progress in emissions reduction efforts (Hester and Gerrard 2018). However, the literature on its governance is still in its infancy and fragmented (Burger and Gundlach 2016). Regulation is taking place in a disjoint manner, tackling particular components or specific technologies, and being shaped and led by a variety of actors.

These efforts have been dominated by developed countries. For instance, with leadership from the EU, components of BECCS have been the subject of regulation—both through policy aimed at renewable energy (Scarlat *et al* 2015, EU Commission 2017) and regulation of bioenergy seeking to ensure sustainability (e.g. EU-Directive). There is disagreement on whether these regulations have been successful (Frank *et al* 2013). CCS regulation has a long history including the London Convention, OSPAR, guidelines for inventories of the IPCC, an EU CCS directive, and inclusion of CCS into the Clean Development Mechanism under the UNFCCC (see Dixon *et al* 2015 for an overview). Geden, Scott and Palmer (2018) find that although the EU has taken a leading role in climate policy, it is likely to face stronger internal opposition concerning Carbon Removal and particularly BECCS. Efforts to include the global South in terms of capacity building and policy making are important—both to build shared understanding, trust and foster buy-in and to ensure the presence of capacities necessary for effective deployment and monitoring (Winickoff *et al* 2015).

Hester (2018) explores the applicability of existing environmental laws to the regulation of NETs in the US, finding that they are not currently applicable except through side-effects that might trigger regulation (Hester 2018). It is likely that the fast emergence of NETs and restricted time lines in which they are envisioned to play a role will mean that their deployment and/or large-scale experimentation will begin before the international community is able to set up comprehensive governance treaties or regulatory frameworks (Hester and Gerrard 2018).

Progress is seen not just in governance actions but by adoption of guidelines or positions by scientific institutions that either deal with geoengineering technologies or components directly (IPCC 2005, National Academy of Sciences 2015, The Royal Society 2009), or address overarching issues of relevance (e.g. land management, see e.g. the upcoming IPCC SRCCL.

Engagement on geoengineering has resulted in the development of guiding principles (Rayner *et al* 2009, 2013) and a Code of Conduct (Hubert, 2017) for research, and decisions at the international level, e.g. by the International Maritime Organization and the CBD (IMO 1972, 1996, 2010, CBD 2008, 2010).

Commercial interests are also playing a role in the development of Carbon Removal, particularly in DACCS (e.g. UK NERC, Climeworks, Carbon Engineering Inc., The Center for Negative Carbon Emissions, Global Thermostat). Discussions around Carbon Removal focus more on technology development and regulation of implementation to ensure efficacy (e.g. carbon neutrality of BECCS, optimal location for AR) (Nemet *et al* 2018, Fuss *et al* 2018).

In shaping policy and for the policy discourse to go forward it is crucial to explicitly acknowledge that all of the currently existing IAM scenarios underlying the ambitious targets of the Paris Agreement feature negative emissions and that forgoing these options implies risking failure to reach more ambitious climate targets (Fuss *et al* 2014). Several authors have called for scientists to be more transparent and less focused on political acceptability (Anderson 2015, Geden 2015, Parker and Geden 2016) and others have highlighted the importance of nations that are most vulnerable to climate change driving the discussions of modelling, ethics and governance (Rayman et al., 2018).

Designing effective decision-making processes (Governance-6)
How can we effectively design a decision-making process that ensures multi-stakeholder engagement?

Some initial literature provides insights into potential models for decision-making, covering the issues of consent (Wong, 2016), the interaction between research and deployment (McKinnon, 2018), liability (Horton et al., 2015) and other institutional and organisational dimensions (e.g. Hester and Gerrard, 2018; Reynolds, 2018; Nicholson et al., 2017). Various sources (e.g. Winickof et al, 2015; Rayman et al., 2018) emphasize the importance of engaging the Global South, arguing that capacity building leading to co-design would foster the trust needed for effective governance. For Solar Geoengineering, Parker (2014) speaks to the difficulty of adopting a governance-before-research approach and emphasises the involvement of researchers and research funders.

Public Perception of technologies in developing Countries (Governance-8)
What is the public perception of these technologies in developing countries?

Research on public perception reflects the global North bias that is visible in the shaping of the policy process, with little known about perceptions in the global South. Such research seems to be undertaken more broadly for Solar Geoengineering (Mahajan *et al* 2018), for Carbon Removal the focus is on specific technologies, in keeping with vastly different uncertainties, technology readiness levels and potential side effects. Where studied together, Solar Geoengineering is perceived in a more negative light than Carbon Removal (Wright *et al* 2014). The global South is better represented in literature addressing specific contexts where deployment would be focused in these regions (e.g. AR) (Nijnik and Halder 2013, Trevisan *et al* 2016). Fridahl (2017) finds similar patterns in terms of higher investment preferences for regions with higher BECCS potential. However these high bioenergy potential regions are comparatively understudied in the literature (Robledo-Abad *et al* 2017). Some have highlighted the importance of more engagement (and leadership from) the global South in discussions of Solar Geoengineering (Rahman, 2018).

Although there is some literature on public perception, the focus for Carbon Removal options is still largely on research and development and potential side effects (Nemet et al 2018) or on specific affected communities such as farmers (e.g. Jørgensen and Termansen 2016 for SCS, Glenk and Colombo 2011).

Minimum legal framework required (Governance-9)
What is the minimum legal framework required for a country to govern geoengineering broadly, but also for specific geoengineering technologies such as Solar Geoengineering?

Recent literature provides a broad examination of the issues of international, trans-national and domestic law covering both state and non-state actors (Gerard and Hester, 2018).

Impacts of Carbon Removal options (Deployment-10)
What are the outcomes/impacts/side effects of geoengineering technologies?

Given the variety of Carbon Removal technologies and large remaining uncertainties, the potential side-effects associated with their deployment are large in both scope and scale. These impacts have been assessed elsewhere (Fuss 2018, Creutzig *et al* 2015, and Robledo-Abad *et al* 2017 for bioenergy) but an overview is provided here.

Large scale deployment of NETs can have important bio-geophysical effects. Depending on the location of deployment, changes in albedo can counteract the effect of carbon removal for BECCS (Bright et al 2015, Jones et al 2015), AR (Anderson et al 2011, Arora and Montenegro 2011, Betts et al 2007, Jackson et al 2008, Wang et al 2014) and to a lesser extent biochar, if at all (Bozzi et al 2015). The large water footprints of some of these technologies are also of concern, particularly for BECCS (Smith et al 2016, Smith and Torn 2013, Fajardy and Mac Dowell 2017, Mathioudakis et al 2017, Lampert et al 2016, Mouratiadou et al 2016, Wei et al 2016, Gheewala et al 2011, Gerbens-Leenes et al 2009, Bonsch et al 2016) and afforestation (Jackson et al 2005, Smith and Torn 2013, Smith et al 2016), where irrigation might be used to grow bioenergy crops or trees. However, even without irrigation, the large-scale deployment of BECCS and AR would alter natural water flows. Although less mature, there

is also literature regarding this aspect of biochar (Bamminger et al 2016, Smith 2016) and EW (Rau and Caldeira 1999, Harvey 2008, Kheshgi 1995, Köhler *et al* 2013b, National Academy of Sciences 2015). These land based options can also impact soil characteristics and nutrient cycling. The effects depend on implementation and tend to be more positive when deployment occurs on degraded land (Laganiere *et al* 2010, Deng *et al* 2017, Lemus and Lal 2005).

Although aiming to remove carbon dioxide from the atmosphere, some of the Carbon Removal options could result in the emission of other greenhouse gasses, particularly N_2O and CH_4. SCS could lead to a release of methane (Nayak et al 2015) or nitrous oxide (Liao et al 2015) depending on the method use to increase soil carbon. These same gasses could be released with OF (Bertram 2010, Matear 2004, Sarmiento and Orr 1991, Cullen and Boyd 2008, Denman 2008). Biochar, on the other hand, could result in lower emissions of these gasses (Kammann et al 2017).

BECCS faces related concerns regarding increased GHG emissions (carbon and others) and carbon debts due to land use change (LUC). The issue of carbon debt and LUC pressures due to BECCS has received ample attention (Plevin et al 2010, 2014, Smith et al 2016, Smith and Torn 2013, Fajardy and Mac Dowell 2017). This is closely linked to the sheer amount of land that BECCS and AR would require if deployed at the scales indicated in the scenario literature. These land use requirements (for BECCS see (Heck et al 2018, National Academy of Sciences 2015, Beringer et al 2011, Creutzig et al 2015, Smith et al 2016); AR (Smith and Torn 2013, Houghton et al 2015)) are closely linked to food security concerns. An increased competition for land for food and feed could result in price increases and distributional shortages (discussion focused largely on BECCS (Smith et al 2013, Edenhofer et al 2013, Popp et al 2011, Reilly et al 2012, Müller et al 2008, Zilberman et al 2013, Roberts and Schlenker 2010, Timilsina et al 2012)).

Some Carbon Removal options can also have direct impacts on people and economic activities. On the one hand, BECCS and other land intensive options can exacerbate tenure conflicts and lead to displacement of small-holders (Borras and Franco 2010, Rist et al 2010, Creutzig et al 2013, Mutopo et al 2011). On the other hand, if adequately applied, there can be benefits such as higher or diversified income, but this can also expose small-holders to the volatility of global markets (Creutzig et al 2013, Hunsberger et al 2014, Greve et al 2013). Biochar and Soil Carbon Sequestration can improve productivity through enhanced yields and improved soil quality (Jeffery et al 2011, Lal 2004, Pan et al 2009).

Table 2 Summary assessed characteristics of Carbon Removal options

Technology	Potential by 2050 *$GtCO_2\ yr^{-1}$*	Costs *$\$/tCO_2$*	Side Effects	Permanence
AR	0.5-3.6	5-50		
SCS	2-5	0-100		
Biochar	0.5-2	30-120		
BECCS	0.5-5	100-200		
DACCS	0.5-5	100-300		
EW	2-4	50-200		
OF	Extremely limited	??		(uncertain)

Side-effects
(positive, risk of negative)

Reversible
Stable

Air pollution
Albedo
Biodiversity
Ecosystem changes
Food security
Ground/water pollution
Mining and extraction
Soil quality
Trace GHGs

Note: Potential and cost estimates are author judgments based on a systematic review of the literature for each technology. Listed side-effects are not exhaustive, they reflect impacts that were found to have a critical mass in the literature. Source: Minx et al 2018, Fuss et al 2018

Impact on biodiversity (Deployment-11)
How might geoengineering technologies impact biodiversity?

Both Carbon Removal and Solar Geoengineering are likely to have significant effects on biodiversity when implemented at large scale. Although the volume of literature for certain options is significant, there is still substantial uncertainty. The CBD has prepared a detailed report on the potential impacts various geoengineering options will have on biodiversity (Williamson and Bodle 2016). Here we present a brief summary highlighting some of these aspects.

An important consideration when discussing the ramifications of geoengineering on biodiversity is that if effective at keeping the global climate at lower temperatures, these options prevent the harm to biodiversity associated with higher temperature levels (Newbold et al 2015). Some have tried to quantify this trade-off, finding that fossil-fuel-based business-as-usual scenarios are worse for biodiversity than bioenergy deployment (Dale et al 2015, Newbold et al 2015), but that large-scale bioenergy deployment can also represent a significant loss of biodiversity (Newbold et al 2015, Santangeli et al 2016). Even within implementation options there will be different potential benefits and risks. Immerzeel et al (2014) review such potential distinctions. Previous use of land mediates the impacts; deployment on degraded land can help restore ecosystem services and biodiversity (Kline et al 2015). So do the choice of feedstocks – with 2nd generation feedstocks generally being more positive (Immerzeel et al 2014, Holland et al 2015). Deployment decisions might imply trade-offs between species and landscapes (Tarr et al 2017). This highlights the importance of regulation that considers location and type of deployment as well as management practices (Dale et al 2015, Immerzeel et al 2014).

Afforestation and reforestation impacts on biodiversity have also received a fair amount of attention, with forests generally thought to be beneficial or at least compatible with biodiversity preservation. However,

biodiversity should be given explicit consideration throughout the process (Díaz et al 2009) as implementation must manage trade-offs between carbon storage, biodiversity and other ecosystem services (Greve et al 2013, Hall et al 2012, Paul et al 2016, Venter et al 2012). Given that as with other options, impacts are dependent on implementation and local conditions, a lot of the literature focuses on case studies (Fuss et al 2018). However, there is consensus around certain aspects. For example, using a native species as well as a mixture of species – as opposed to exotics and monocultures—is better for biodiversity and forest resilience (Locatelli et al 2015, McKinley et al 2011).

Nature-based vs other options (Deployment-12)

What are the cost/benefits of nature-based solutions (e.g. ecosystem-based approaches) vs other geoengineering technologies?

Nature Based Solutions (NBS) encompass solutions that rely on nature to provide solutions for climate mitigation and adaptation challenges (Cohen-Shacham et al 2016). It is an umbrella term that includes actions focused on restoring natural environments (utilizing terms such as reforestation, ecosystem restoration, blue carbon, natural reforestation and rewilding), avoiding further degradation (avoided deforestation), management practices (including forest management, fire management, conservation agriculture, agro-forestry, organic farming practices) and green and blue infrastructures. The hazy conceptual definition has drawbacks but may help to promote the implementation of genuinely sustainable solutions (Nesshöver et al 2017).

When discussed in opposition to geoengineering, the debate refers mostly to ecosystem restoration and management practices (without mention of other technological or hybrid techniques. However, there seems to be a lack of literature performing a comparative assessment of costs and benefits. Recent studies explore a broad range of options for conservation, restoration and improved land management as mitigation options, with abatement potentials estimated between 9.6-25 Gt CO2 (Roe et al. 2017) and up to 23 Gt CO2 in 2030 (Griscom et al 2017). Some Carbon Removal options such as afforestation and soil carbon sequestration lie under the umbrella of NBS when deployed conscientiously. Erb and colleagues find that the already huge carbon stocks (1,085Gt, 194Gt, 176Gt and 190Gt CO2 for tropical, subtropical, temperate and boreal biomes, respectively) could be greatly enhanced by conservation and restoration (Erb et al 2017). The benefits of NBS are ample and multifaceted (Keesstra et al 2018), but still require adequate planning and governance (Nesshöver et al 2017) and an understanding of trade-offs and uncertainties (Eggermont et al 2015). Some of the benefits include the improvement or preservation of other ecosystem services (beyond carbon sequestration) (Lafortezza and Chen 2016), particularly with regards to water and land (Keesstra et al 2018).

As with discussion of traditional emissions reduction and Carbon Removal options, it is important to keep in mind that most evidence refers to the need for concurrent deployment of options “urgently, globally and in parallel” (Turner 2018, Rockström et al 2017).

Applicability across countries (Deployment-13)

How applicable is research conducted in one country, for another country/region?

While for some Carbon Removal options like DACCS the applicability across countries is not a concern raised in the literature, the land-based options are clearly tied to a number of suitability factors. For example, large-scale plantations – be it for the bioenergy component of BECCS or for an afforestation project – can change the albedo and lead to increased warming when implemented in Northern latitudes thereby offsetting parts of the Carbon Removal effect (Jones et al 2015, Jackson et al 2008, Kreidenweis et al 2016), and suggesting these solutions may be better suited to Southern latitudes. Some have also argued that nations that are most vulnerable to climate change must drive discussions of modelling, ethics and governance (Rayman et al., 2018).

4. Remaining knowledge gaps

In this section we discuss the remaining questions categorised in Table 1 as red (●).

Who are decision making actors (Governance-5)
With regards to existing regulatory frameworks (local, regional and international), who are the decision-making actors?

Existing regulation can be at national scale, regional level (e.g. European Union) and international level (e.g. the International Maritime Organization) but does not cover Carbon Removal comprehensively focusing on particular technologies or components of Carbon Removal supply chains (e.g. biomass or CO2 storage). Actors affected can range from farmers that change management practices to enhance soil carbon to one government deciding to inject reflective aerosol particles into the lower stratosphere in the case of Solar Geoengineering. To the best of our knowledge, there has to date not been a comprehensive assessment across all actors encompassing all Carbon Removal and Solar Geoengineering techniques.

Monitoring, Evaluation and Verification (Governance-7)
What institutional(s) are (or would be) responsible for the monitoring, evaluation and verification of geoengineering technologies?

While the need for Monitoring, Evaluation and Verification (MEV) is identified in the literature (e.g. Hester and Gerrard, 2018; Reynolds, 2018; Nicholson et al., 2017) including the role for government in ensuring transparency and consistent reporting methods (e.g. UNEP, 2017), substantial questions remain which institutional body would be best suited to the task. With regard to Carbon Removal, existing institutions and agreements might have relevant provisions (e.g. carbon sinks and removals under the UNFCCC) which could provide a starting point for the MEV framework, complemented by aspects from other fields or by provisions under other agreements and further investigation is required to explore this.

Capacity development and access to information (Research-14 and -16)
What type of capacity development is needed? How might knowledge-sharing and enhanced access to information strengthen research?

Capacity building is needed both in terms of researchers from the Global South that bring insight about concerns and realities in different contexts (Rayman et al., 2018), as well as in terms of the data underlying IAMs and other elements that are informing global decision-making (Winickof et al 2015). In this context, knowledge-sharing and enhanced access to information are obviously important enablers. However, there appears to be a knowledge gap, as there is little geoengineering-specific literature studying the required processes associated with this.

Missing on-the-ground research (Research-15)
Why is there a lack of interest in on-the-ground research and more interest on processes?

This element highlights the importance of distinguishing between Carbon Removal and Solar Geoengineering. There is considerable on-the-ground research for many of the Carbon Removal options, particularly the land-based ones that are not as dependent on further technological improvements (AR, biochar, SCS, NBS). Bioenergy also receives substantial on-the ground attention in particular contexts (e.g. Brazil, Scandinavian countries). Solar Geoengineering research and governance is precisely grappling with the difficulties inherent in this technology group with on the ground research.

Importantly, in both cases, there is a need for transdisciplinary research and multi-stakeholder engagement that can feed on-the-ground insights and developments to higher levels of decision-making.

5. Moving forward: Governance, research and action

In this section we present a synthesis of knowledge gaps identified during the December 2017 C2G2 Workshop on Transdisciplinary research and governance on climate-related geoengineering which focused on needs and challenges for governance. On this topic, participants took a forward-looking perspective and their insights are summarized under the headings of: (i) Governance and regulatory needs; (ii) Transdisciplinary research and knowledge sharing needed to understand regulatory options; and (iii) Possibilities for action through the CBD.

Governance and regulatory needs

There are considerations in developing regulation at various levels. Several factors play a role here. From an ethics perspective, workshop participants recommended taking a precautionary approach, with ethics committees at local and national levels. Furthermore, regulatory options were required to ensure that developing countries are not used as experiment fields.

Stakeholders play a key role in these considerations. Again, there was a call for ensuring a fair and equitable inclusion of developing countries in the governance and conduct of geoengineering research. In particular, the involvement of the global South has been emphasized for ethical considerations, to foster trust and buy-in and because local capacity will be crucial for the effectiveness of research, deployment and regulation.

However, workshop participants did not perceive the involvement of stakeholders as the only important need – it is also of utmost importance to build capacity: capacity building across stakeholders will be key to ensure effectiveness (see above). Capacities for governing of emerging technologies will be different - though lessons can be drawn each option has its own set of features that must be examined separately. Enhancing access to information (particularly in developing countries) was assessed as useful to support effective decision-making.

The workshop participants then addressed differentiating characteristics including different forms of Carbon Removal and Solar Geoengineering, issues considering both local/national and global/local aspects including policy lags, the capability of addressing research at various scales and stages, and the involvement of various actors in the public and private sectors (e.g. governments, scientific institutions, commercial interests), but also indigenous people and local communities.

With respect to transparency, workshop participants discussed confidentiality agreements for governments and companies. They also emphasized considerations for strong monitoring and enforceability at all levels: a regional level governance framework for MRV, environmental impact assessment at national and regional level and a binding agreement and corresponding institution needed at global level.

Finally, several aspects were highlighted for consideration when designing research governance:

- Bringing together relevant actors to exploit and foster synergies across groups
- Fostering involvement of the global South
- Knowledge sharing
- Including indigenous peoples and social scientists in transdisciplinary research
- Ensuring a balanced distribution of research resources internationally
- Targeting the regulations easiest for researchers to comply with

Transdisciplinary research and knowledge sharing needed to understand regulatory options

Moving from governance to research needs, the workshop participants identified a comprehensive analysis (and regulation) of technologies/approaches as one of the most important items of a transdisciplinary research agenda. This should encompass potentials, costs, side-effects, implications and aims and also offer information on the uncertainties and the unknowns related to geoengineering, including natural and induced phenomena.

Policymakers need to understand how Carbon Removals are being integrated in modelling and how the economics of BECCS and the impact on different stakeholders are taken into account. As climate change is transboundary, governance is already extremely difficult. The workshop participants wondered how good geoengineering governance could then be achieved and there was a call for compiling and assessing lessons learned (both positive and negative) from using market mechanisms for regulation.

With respect to ethics, Solar Geoengineering governance was identified as the most challenging topic. In particular, the participants discussed who, how and when decisions about deployment can be made, given a potentially unequal distribution of impacts. Similarly, although Carbon Removal is often viewed as a national intervention, cumulative impacts may also affect other countries, which then presents similar governance challenges as described for Solar Geoengineering.

Possibilities for action through the CBD

A range of actions were identified by workshop participants for next steps that could be pursued under the CBD which we summarise here:

- **Identify and involve relevant institutions and actors** by considering (i) at what stage should they be involved? (ii) How can non-parties to the CBD be involved and treated in the CBD and other processes (e.g. IPCC, IPBES, International Resources Panel, UNEA, UNFCCC).

- **Assess which existing institutions can lead the discussions** or whether there is a need for a new institution to regulate climate-related geoengineering research governance.

- **Identify and enhance synergies between processes and discussions** held at UNFCCC and CBD (and other biodiversity-related conventions) e.g. through meeting and discussion between the chairs/co-chairs of respective SBIs.

- **Enhance multilateral and multi-disciplinary learning** through, for example, establishing an international research group or organising an international conference to enhance synergies between different fora and to improve understanding of climate-related geoengineering issues.

- **Develop a frameworks and/or guidance for national governments** on how to address these issues at a national level (e.g. through enhanced discussions between CBD focal points).

- **Create or foster creation of protocols, ethical frameworks or codes of conduct and guidelines** for research (and/or deployment) of climate-related geoengineering options.

6. Conclusion

In this briefing we have assessed knowledge gaps identified by participants of the December 2017 C2G2 Workshop on Transdisciplinary research and governance on climate-related geoengineering against existing research literature to afford a clearer view of the gaps which remain.

While questions raised around possible impacts are (to some extent) addressed in the literature reviewed for this paper, many research questions remain substantially (see section 3) or largely unexplored (see section 4).

In particular, on the ethics questions, the discipline of philosophy has engaged extensively with the ethics of geoengineering. However, this work has almost exclusively focused on Solar Geoengineering and not Carbon Removal. Assuming that the conclusions on the ethics of Solar Geoengineering can be extended towards Carbon Removal is highly misleading, so more work is needed that explicitly addresses Carbon Removal. Engaging representatives of indigenous peoples and local communities, theologians and faith communities around these issues could also help develop insights into the deep moral and religious dimensions which require consideration.

The (sparse) ethics discussion regarding the deployment or further research on geoengineering technologies is focused around three major interrelated concerns: moral hazard, betting and hubris. It is empirically unclear to what extent moral hazard is an issue, so more work is needed. However, it seems highly unlikely that moral hazard caused by anticipation of negative emissions has led to the delay in emission reductions in past decades, so there are definitely other factors at work, which should not be neglected in the analysis.

For deployment, there is now a substantial literature on potentials, costs and side effects of different Carbon Removal options. A systematic assessment of these shows that almost all options have relevant potentials, although some are still expensive or come at other socio-economic or environmental costs if deployed at large scale. A broad societal discourse is now needed to consider possible portfolios of options for deploying Carbon Removal in ways that complement emission reductions to avert global warming higher than 1.5°C above pre-industrial levels.

Dependence on Carbon Removal can be reduced by drastic and rapid emissions reductions that also extend to the demand side. However, for 1.5°C there is currently low evidence that this could be achieved without Carbon Removal. There is therefore more work needed on the incremental impacts between 1.5°C and higher temperature goals, should the latter be preferred to circumvent the use of Carbon Removal.

There is a disconnect between actual investments and where 2°C or even 1.5°C pathways see Carbon Removal deployment in the near-term, which is also reflected in the literature, which mostly focuses on the innovation stage of research and development only. This is a gap that urgently needs to be closed as well.

Various governance options are explored in recently published literature although many questions remain, including around which institution(s) would govern the deployment, monitoring, evaluation and verification of Carbon Removal or Solar Geoengineering. Compared to conventional mitigation, new governance aspects could require new forms of governance alongside a new accounting regime.

Despite recent assessment of relevant legal frameworks, substantial knowledge gaps still remain. Further gaps were also identified in relation to design of governance arrangements to effectively address risk and liability for different Carbon Removal and Solar Geoengineering options, and with respect to regulatory frameworks and the accompanying institutions.

There is evidence that public perception has played an important role in driving policy decisions connected to Carbon Removal, so effective forms of multi-stakeholder engagement need to be explored in relation to this and Solar Geoengineering.

As for research, there is currently no comprehensive strategy for capacity development in this context. However, if modelling is to continue to shape the political discourse more broadly, perhaps there is a need to incorporate a broader portfolio of options – something which actually is being done now in the first IAMs (Strefler et al 2018b).

Finally, there was a discussion on how to integrate insights from on-the-ground research to assessments of technology options at global scale. Improved communication on the part of scientists including synthesis of case studies, engineers and policymakers, knowledge-sharing and enhanced access to information can help strengthen research.

For the needs and challenges for governance action identified by the workshop participants, special emphasis was given to the involvement of the global South, particularly through capacity development designed to enable better decision making, buy-in and trust as well as making deployment, verification and monitoring more practically feasible.

More work needs to be undertaken by scientists on trade-offs. Development of Carbon Removal is the not yet advanced to the levels required in the models and ethically not a panacea. It is not a replacement but rather a companion to deep emission reductions. Likewise, critics of Carbon Removal must acknowledge that forgoing large-scale Carbon Removal implies none-the-less difficult pathways and is furthermore likely to mean accepting larger than 1.5°C temperature increases.

The CBD has already played a leading international role in addressing climate-related geoengineering over the past decade. Looking ahead, as governments develop their plans towards the CBD's global vision of 'Living in Harmony with Nature', learning about the positive or negative impacts that technology developments such as climate-related geoengineering may pose, becomes increasingly urgent. Developing a better shared understanding of the potential impacts of climate-related geoengineering and the best options for its governance is an important next step towards this vision and leadership through the CBD will have a crucial role to play.

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