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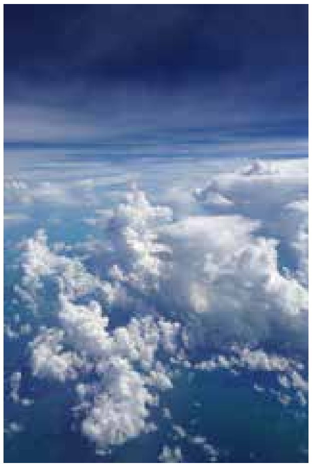

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UPDATE ON CLIMATE GEOENGINEERING IN RELATION TO THE CONVENTION ON BIOLOGICAL DIVERSITY: POTENTIAL IMPACTS AND REGULATORY FRAMEWORK

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Update on Climate Geoengineering in Relation to the Convention on Biological Diversity: Potential Impacts and Regulatory Framework

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FOREWORD

Climate change is increasingly becoming an important driver of biodiversity loss and degradation of ecosystem services. The Paris Agreement, which strengthened international support for limiting global warming, will enter into force on November 2016 and is a positive step, especially from the point of view of conserving and sustainably using biodiversity. Species and ecosystems around the world are already impacted by current temperature rise. Further impacts on biodiversity are inevitable with further increases, particularly for the most vulnerable ecosystems such as coral reefs, mountains and polar ecosystems.

A rapid transition to a low-carbon economy is the first priority to reduce greenhouse gas emissions and in turn reduce the adverse impacts of climate change, including impacts on biodiversity. However, given the current atmospheric greenhouse-gas concentrations, their long atmospheric residence times and the relatively limited action to date to reduce future emissions, the use of geoengineering techniques has been suggested and is being explored as a potential additional means to limit the magnitude of climate change. Such techniques have generated much discussions on their actual effectiveness and safety, and have also raised concerns over their potential impacts on biodiversity and other environmental consequences, as well as the lack of mechanisms for their governance.

The Conference of the Parties (COP) to the Convention on Biological Diversity (CBD), at its tenth meeting, in 2010, considered geoengineering in decision X/33, calling for studies on the possible impacts of geoengineering techniques on biodiversity and associated social, economic and cultural considerations, and on gaps in the regulatory mechanisms for climate-related geoengineering relevant to the CBD.

In response to this request, a first report on the potential impacts of geoengineering on biodiversity and the regulatory framework for geoengineering was published in 2012 (CBD Technical Series No. 66).

The COP, in decision XI/20, requested the Executive Secretary, to prepare an update on the potential impacts of geoengineering techniques on biodiversity, and on the regulatory framework of climate-related geoengineering relevant to the CBD, drawing upon all relevant scientific reports such as the Fifth Assessment Report of the Intergovernmental Panel on Climate Change and discussions under the United Nations Environment Management Group. The present report provides such an update on climate geoengineering in relation to the CBD.

While the amount of literature on geoengineering in recent years has greatly increased, relatively little information directly analyses the potential impacts on biodiversity. CBD Technical Series no. 66 and the present report both contribute greatly to increasing knowledge and awareness of the links between geoengineering and biodiversity and lend support to decision-making.

I commend the authors of this report for their expertise and dedication. I also wish to express gratitude to the Natural Environment Research Council of the United Kingdom of Great Britain and Northern Ireland for their contribution.

I hope that the report will assist in the further integration of biodiversity considerations when addressing climate change.

Braulio Ferreira de Souza Dias
Executive Secretary
Convention on Biological Diversity

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PREFACE AND ACKNOWLEDGEMENTS

In 2012, the CBD Secretariat published Technical Series No. 66: *Geoengineering in Relation to the Convention on Biological Diversity: Technical and Regulatory Matters* comprising two studies: one on the impacts of climate-related geoengineering on biodiversity, the other on the regulatory framework for climate-related geoengineering relevant to the Convention. These studies were prepared pursuant to decision X/33 paragraph 9(l) and (m), and provided the reference basis for the consideration of this issue at the sixteenth meeting of the Convention's Subsidiary Body on Scientific, Technical and Technological Advice and the eleventh meeting of the Conference of the Parties.

The main remit of this report is to provide an update on the potential impacts of geoengineering techniques on biodiversity together with an account of regulatory developments. An interim update was provided to the Subsidiary Body at its eighteenth meeting in 2014. There have been very many scientific papers and reports relevant to climate geoengineering since 2012, as shown by the main reference list and additional bibliographies provided here. Geoengineering has also been addressed by all three Working Groups of the Intergovernmental Panel on Climate Change in its fifth assessment report, and in a number of other major reports. The key messages of this update complement those in the 2012 report, re-provided here (Annex 3) and considered to remain valid.

This main text of this report was prepared for peer review in July 2015, taking account of relevant publications available then; a few further references were added prior to the report's online publication in October 2015 (as Information Paper UNEP/CBD/SBSTTA/19/INF2). An additional bibliography is provided in Annex 4, updated to September 2016.

Acknowledgments

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International bodies: United Nations Division for Ocean Affairs and the Law of the Sea (DOALOS).

Non governmental organizations: Biofuelwatch; Action Group on Erosion, Technology and Concentration (ETC Group).

Individual experts: Elizabeth Burns, Wil Burns, Noah Deich, James R Fleming, Sabine Fuss, Joshua Horton, Anton Laasko, Cliff Law, Andrew Lockley, Andrew Parker, Antti-Ilari Partanen, Greg Rau, Jesse L Reynolds, Chris Vivian.

KEY MESSAGES

1. **Climate-related geoengineering is here defined as a deliberate intervention in the planetary environment of a nature and scale intended to counteract anthropogenic climate change and its impacts**. This definition is the same as used in CBD (2012)[1], and is used here without prejudice to any definition that may subsequently be agreed under the Convention. "Climate engineering" and "climate intervention" may be considered as equivalent to "climate-related geoengineering", hereafter geoengineering. Generally, climate-related geoengineering is divided into two main groups at the technique level: i) techniques involving greenhouse gas removal (GGR), also known as "negative emission techniques"; most existing and proposed techniques fall under the term "carbon dioxide removal" (CDR); and ii) techniques known as sunlight reflection methods (SRM; alternatively "solar radiation management" or "albedo management"). In addition there are other proposed techniques, that could directly increase heat loss, or redistribute energy within the Earth system. Key features of the definition are that the interventions are deliberate, and are on a scale large enough to significantly counter-act the warming effect of greenhouse gases. They are thus distinct from actions to reduce emissions. However, some of the techniques involving greenhouse gas removal, such as afforestation, reforestation, techniques for managing soils to increase carbon sequestration, and the use of bioenergy combined with carbon capture and storage, are also considered climate mitigation techniques. Not all of the latter techniques are considered by all stakeholders to be geoengineering. In any case, interventions (both GGR and SRM) that are carried out at a small scale (e.g. local tree planting projects; roof whitening) are not normally considered as geoengineering. In line with decision X/33, the definition also excludes carbon capture at source from fossil fuels (CCS; i.e. preventing the release of CO_2 into the atmosphere), while recognizing that the carbon storage components of that process may also be shared by other techniques that are considered as geoengineering.

2. **Assessment of the impacts of geoengineering on biodiversity is not straightforward and is subject to many uncertainties.** Relatively little research has *directly* addressed the issue of 'impacts on biodiversity', nor even broader environmental implications: instead effort by natural scientists has mostly focussed on climatic (physico-chemical) issues or impacts on agricultural systems, while social scientists have addressed governance, framing and ethical considerations. This report considers the impacts of geoengineering on the drivers of biodiversity loss, including the potential decrease in the climate change driver from effective geoengineering techniques; changes in other drivers, including land use change, that are inevitably associated with some geoengineering approaches; as well as the other positive and negative side effects of specific techniques. Consequences for biodiversity are therefore mostly discussed in terms of climatic effectiveness, land use change or other indirect impacts; e.g. fertilizer application or water extraction. It is important to note that both decreased and increased productivity tend to be undesirable from a natural ecosystem perspective, although the latter is likely to be beneficial in agricultural systems.

Climate Change

3. **Climate change, including ocean acidification, is already impacting biodiversity and further impacts are inevitable**. It may still be possible that deep and very rapid decarbonization by all countries might allow climate change to be kept within a 2°C limit by emission reduction alone. However, any such window of opportunity is rapidly closing. Even so, climate change associated with 2°C warming will have serious impacts on biodiversity. Emissions under current trajectories, broadly consistent with RCP 8.5 (the highest of the four main scenarios used in the IPCC AR5) would lead to an extremely large loss of biodiversity. Current commitments made by Parties to the UNFCCC would significantly reduce climate change and its impacts (probably to a pathway between RCP 6.0 and RCP 4.5) but are insufficient to keep warming within 2°C. Geoengineering techniques, if viable and effective, would be expected to reduce climate change impacts on biodiversity. However some techniques would lead to biodiversity loss through other drivers such as land use change.

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[1] CBD (Secretariat of the Convention on Biological Diversity) (2012) www.cbd.int/doc/publications/cbd-ts-66-en.pdf

Carbon dioxide removal (Greenhouse gas removal)

4. **Scenarios of future climate change to 2100 that are likely to keep global average temperature increases within a limit of 2°C above pre-industrial levels mostly rely on technologies for carbon dioxide removal (CDR) as well as emission reductions, with pathways that feature net negative emissions in the second half of the century**. **However, the potential to deploy CDR at this scale is highly uncertain**. The deployment of CDR envisaged by scenarios reported in the IPCC Fifth Assessment Report in the period 2050-2100 would allow additional anthropogenic greenhouse gas emissions in the period up to 2050, extending the period of fossil fuel use and potentially reducing the cost of their phase-out. For RCP 2.6, ~90% of the pathways considered in the IPCC AR5 assume the deployment of CDR technologies. Bioenergy with carbon capture and storage (BECCS) and/or afforestation/reforestation (AR) are seen as the most economically viable ways to provide such net negative emissions. The land and water use requirements of BECCS and AR are limiting factors, but those requirements, and their implications, are not well factored into existing models. For BECCS, CO_2 storage capacity may also be limiting.

5. **The removal of a given quantity of a greenhouse gas would not fully compensate for an earlier "overshoot" of emissions.** The occurrence of an overshoot in most RCP 2.6 scenarios allows for current emissions to be offset by future negative emissions. The assumption is made that CDR will be achievable at the scale required, without such actions themselves having significant undesirable consequences; this assumption seems unlikely to be valid. In particular, not all the climatic and environmental consequences of the overshoot will be directly cancelled by future CO_2 removal. The net effect of adding and subsequently subtracting a given quantity of CO_2 only equals zero when there is no significant time difference between the addition and subtraction processes; a delay of ~50 years would lead to significant and potentially irreversible consequences for biodiversity and the Earth system. For those reasons, the evaluation of the potential role of CDR techniques should focus on their effectiveness in helping to reduce net emissions to zero on a shorter timescale than envisaged in most current scenarios, complementing stringent emission reductions.

6. **The large-scale deployment of bioenergy with carbon capture and storage (BECCS) seems likely to have significant negative impacts on biodiversity through land use change.** If BECCS were deployed to a scale assumed in most RCP 2.6 scenarios, substantial areas of land (several hundred million hectares), water (potentially doubling agricultural water demand) and fertilizer would be needed to sustain bioenergy crops. Limiting irrigation to reduce water use, or not replacing nutrients, would increase land requirements. Even under optimistic scenarios, less than half of the requirements for negative emissions could likely be met from abandoned agricultural land. Land use change envisaged in the central RCP 2.6 scenario would lead to large losses of terrestrial biodiversity.

7. **Ecosystem restoration including reforestation and appropriate afforestation can contribute to removing carbon dioxide and provide substantive biodiversity co-benefits. However, these activities on their own would be insufficient to remove carbon at the scale required in most current scenarios**. Avoiding deforestation, and the loss of other high-carbon natural vegetation, is more efficient than restoration or afforestation in contributing to climate mitigation and has greater biodiversity co-benefits. Afforestation of ecosystems currently under non-forest native vegetation would result in the loss of the biodiversity unique to such habitats, and from an ecological perspective, should be avoided[2]. Furthermore, the greenhouse effects of N_2O arising from nitrogen fertilizers may outweigh the CO_2 gains; afforestation of boreal areas and desert areas would increase global warming though albedo effects; and future climate change may jeopardize forest carbon sinks, through increased frequency of fire, pests and diseases and extreme weather events.

8. **Biochar may potentially contribute to carbon dioxide removal under certain circumstances, and the technique applied to agricultural soils may offer productivity co-benefits**. The application of biochar (charcoal)

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[2] The term "afforestation" under the UNFCC refers to the forestation of land that has not carried trees for at least 50 years. Thus, the term may include reforestation of some previously forested lands as well as afforestation of ecosystems under non-forest native vegetation.

to soils may have positive or negative impacts on soil biodiversity and productivity, but there is greater evidence of positive impacts, especially in acidic soils. In addition, biochar application to soils may also decrease soil carbon emissions. A quantitative understanding of the factors affecting the permanence of biochar carbon sequestration is being developed. However, until the use of coal and other high-emission fossil fuels are phased out, the alternative use of charcoal as fuel may have greater potential in climate mitigation. Assessments of the climatic benefits, co-benefits and costs of different biochar processes and products are needed to fully evaluate the potential of this technique. Current scenarios envisage the production of biochar from crop residues and food wastes. Nevertheless, deployment of this technique on a large scale would have significant direct and indirect impacts on the use of land, water and fertilizers to generate the biomass required.

9. The viability of alternative negative emission techniques such as direct air capture (DAC), enhanced weathering and ocean fertilization remains unproven. There has been significant research work since CBD (2012), yet conclusions remain broadly the same. Likely costs and energy requirements of DAC for CO_2 are still very high, albeit considerably lower than those reported in CBD (2012). Since there may be further potential for cost reductions, additional research on DAC techniques for CO_2, as well as methane, warrants attention. The potential contribution of enhanced weathering, on land or in the ocean, to negative emissions is unclear but logistical factors seem likely to limit deployment at large scales. Local marine application might be effective in slowing or reducing ocean acidification, with consequent benefits for marine biodiversity, though there might also be negative effects; e.g. from sedimentation. Enhancing ocean productivity, by stimulating phytoplankton growth in the open ocean and through nutrient addition ("ocean fertilization") or modification of upwelling, is only likely to sequester relatively modest amounts of CO_2, and the environmental risks and uncertainties associated with large-scale deployment remain high.

10. Carbon dioxide (or other greenhouse gases) captured from the atmosphere must be stored in some form. Options include vegetation, soils, charcoal, or carbon dioxide in geological formations. Vegetation, soils and charcoal demonstrate varying levels of (im)permanence. Technical considerations relating to safe carbon storage in geological formations, mostly expected to be beneath the seafloor, have recently been reviewed. The main effects of marine leakage would be local ocean acidification with experimental studies indicating that (at least for slow release rates) environmental impacts would be relatively localized. The extensive literature on ocean acidification, including the biodiversity changes observed at natural CO_2 vents, is relevant here. However, relatively few experimental studies on the impacts of high CO_2 on marine organisms cover the full range of values that might occur under leakage conditions. Other forms of storage in the ocean are considered to have unacceptable risks, and are not allowed under the London Convention/London Protocol.

Sunlight reflection methods / Solar radiation management

11. Recent studies and assessments have confirmed that SRM techniques, in theory, could slow, stop or reverse global temperature increases. Thus, if effective, they may reduce the impacts on biodiversity from warming, but there are high levels of uncertainty about the impacts of SRM techniques, which could present significant new risks to biodiversity. Modelling work consistently demonstrates that reduction in average global temperature (or prevention of further increase) and, to some extent, associated precipitation changes, would be possible, but would not fully restore future climatic conditions to their present day status. The regional distribution of temperature and precipitation effects are also different for different SRM techniques; these have been modelled, but many uncertainties remain. Even if, on average, the resulting disruptions to regional climates under SRM are less than those under climate change in the absence of SRM, this cannot be known with certainty: the possibility that some regions would benefit while others might suffer even greater losses, would have complex implications for governance. The implications for biodiversity have not been examined in most models. However, if SRM were to be started, but subsequently halted abruptly, termination effects (involving very rapid climate changes) would likely lead to serious losses of biodiversity. The use of CDR in addition to 'moderate' SRM could reduce such risks, and there is increasing emphasis in the scientific literature on the potential complementarity of the two approaches.

12. **Models suggest SRM could slow the loss of Arctic sea ice. However, preventing the loss of Arctic sea ice through SRM is unlikely to be achievable without unacceptable climatic impacts elsewhere.** Models suggest that even if SRM were globally deployed at a scale that returned average global temperatures to pre-industrial levels, Arctic sea ice loss would continue, albeit at a slower rate. Further loss of Arctic sea ice might be prevented by locally-strong SRM (using asymmetric application of stratospheric aerosols) but this would be associated with extremely negative impacts elsewhere due to major shifts in atmospheric and oceanic circulations. Cirrus cloud thinning may, in theory, be able to stabilize Arctic sea ice, but many uncertainties remain regarding that technique.

13. **SRM may benefit coral reefs by decreasing temperature-induced bleaching, but, under high CO_2 conditions, it may also increase, indirectly, the impacts of ocean acidification**. Notwithstanding uncertainties over regional distribution, lowered average global temperatures under SRM would be likely to reduce the future incidence of bleaching of warm-water corals (compared to RCP 4.5, 6.0 or 8.0 conditions). The interactions between ocean acidification, temperature and impacts on corals (and other marine organisms) are complex, and much will depend on the scale of additional measures taken to reduce the increase in atmospheric CO_2. If warming is prevented by SRM, there will be less additional CO_2 emissions from biogeochemical feedbacks; however, relative cooling would reduce carbonate saturation state, that may reduce calcification or even dissolve existing structures (for cold-water corals) if CO_2 emissions are not constrained.

14. **The use of sulphur aerosols for SRM would be associated with a risk of stratospheric ozone loss; there would also be more generic side effects involved in stratospheric aerosol injection (SAI)**. While ozone depletion effects may be avoidable if alternative aerosols are used, their suitability and safety have yet to be demonstrated. All SAI techniques would, if effective, change the quality and quantity of light reaching the Earth's surface; the net effects on productivity are expected to be small, but there could be impacts on biodiversity (community structure and composition).

15. **The climatic effectiveness of marine cloud brightening depends on assumptions made regarding micro-physics and cloud behaviour.** Many associated issues are still highly uncertain. The potential for regional-scale applications has been identified; their environmental implications, that include salt damage to terrestrial vegetation, have not been investigated in any detail.

16. **Large scale changes in land and ocean surface albedo do not seem to be viable or cost-effective.** It is very unlikely that crop albedo can be altered at a climatically-significant scale. Changing the albedo of grassland or desert over sufficiently large areas would be very resource-demanding, damaging to biodiversity and ecosystems, and likely cause regional-scale perturbations in temperature and precipitation. Changes in ocean albedo (through long-lasting foams) could, in theory, be climatically effective, but would be also accompanied by many biogeochemical and environmental changes, likely to have unacceptably large ecological and socioeconomic impacts.

Techniques aimed at increasing heat loss

17. **Cirrus cloud thinning may have potential to counteract climate change, but the feasibility and potential impacts of the technique have received little attention**. This technique would allow more heat (long-wave radiation) to leave the Earth, in contrast to SRM (which aims to reflect incoming short-wave energy).

Socioeconomic and cultural considerations

18. **Recent social science literature has focussed on framing, governance and ethical issues relating to atmospheric SRM.** Research has also covered international relations, national and international law, and economics, with most papers by US and European authors. While the socioeconomics of large-scale, land-based CO_2 removal techniques has, to some degree, been covered by discussion on biofuels and their implications for food security, there are major gaps regarding the commercial viability of CDR techniques, such as BECCS, their associated institutional frameworks relating to carbon trading or tax incentives, and evaluations of environmental impacts (in

context of ecosystem services) and implications for indigenous and local communities. For SRM, many different frames have been considered, with those based on 'climate emergencies' or 'tipping points' attracting particular interest and criticism. There is an increasing trend towards multidisciplinary and transdisciplinary programmes on climate geoengineering, and these are now beginning to deliver more integrated analyses, with a collaborative role for social scientists.

19. Where surveyed, the public acceptability of geoengineering is generally low, particularly for SRM. Nevertheless, studies in a range of countries have found broad approval for research into both CDR and SRM techniques, provided that the safety of such research can be demonstrated.

Regulatory framework

20. An amendment to the London Protocol to regulate the placement of matter for ocean fertilization and other marine geoengineering activities has been adopted by the Contracting Parties to the London Protocol. This relates to the 1996 Protocol to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, 1972 administered by the International Maritime Organization. The amendment, adopted in 2013, is structured to allow other marine geoengineering activities to be considered and listed in a new annex in the future if they fall within the scope of the Protocol and have the potential to harm the marine environment. The amendment will enter into force following ratification by two thirds of the Contracting Parties to the London Protocol. This amendment, once entered into force, will strengthen the regulatory framework for ocean fertilization activities and provide a framework for the further regulation of other marine geoengineering activities. The CBD COP, in decision XII/20, took note of Resolution LP.4(8) and invited parties to the London Protocol to ratify this amendment and other Governments to apply appropriate measures in line with this amendment, as appropriate.

21. The 2007 amendment to the OSPAR Convention which allows storage of carbon dioxide in geological formations under the seabed of the North-East Atlantic entered into force in July 2011 and is currently in force for 11 of the 16 OSPAR parties.

22. As noted in the original report**, the need for science-based global, transparent and effective control and regulatory mechanisms may be most relevant for those geoengineering techniques that have a potential to cause significant adverse transboundary effects, and those deployed in areas beyond national jurisdiction and in the atmosphere**. These would comprise a subset of the techniques included in the broad definition of climate geoengineering (para 1, above). Many ocean-based potential geoengineering approaches are already covered under the LC/LP, as noted above. However, the large-scale BECCS and afforestation proposed in many IPCC AR5 scenarios may raise new regulatory issues at the international level regarding the associated scale of land use change. The potential international governance implications of such large-scale BECCS have so far not been specifically addressed by the international regulatory framework or literature.

23. The lack of regulatory mechanisms for SRM remains a major gap. With regard to SRM, IPCC AR5 notes that "the governance implications...are particularly challenging", specifically in respect of the political implications of potential unilateral action. The spatial and temporal redistribution of risks raises additional issues of intra-generational and inter-generational justice, which has implications for the design of international regulatory and control mechanisms. The ethical and political questions raised by SRM would require public engagement and international cooperation in order to be addressed adequately. Other approaches that involve modifications to the atmospheric environment include cirrus cloud thinning are also not covered.

24. A recurring question is how research activities (as opposed to potential deployment) should and could be addressed by a regulatory framework. However, once the modelling and laboratory stage has been left behind, the distinction between research and development could become difficult to draw for regulatory purposes. It has been argued that governance can have an enabling function for "safe and useful" research; the London Protocol's concept of "legitimate scientific research" underlying the 2013 amendment can be seen in this context.

25. **These developments have not changed the validity of the key messages from Part II of the 2012 report**, including that "the current regulatory mechanisms that could apply to climate-related geoengineering relevant to the Convention do not constitute a framework for geoengineering as a whole that meets the criteria of being science-based, global, transparent and effective" and that "with the possible exceptions of ocean fertilization experiments and CO_2 storage in geological formations, the existing legal and regulatory framework is currently not commensurate with the potential scale and scope of climate related geoengineering, including transboundary effects."

Conclusions

26. **Biodiversity is affected by a number of drivers of change that will themselves be impacted by proposed CDR and SRM geoengineering techniques.** If effective, geoengineering would reduce the impacts of climate change on biodiversity at the global level. However, in the case of SRM under conditions of high CO_2 this would not necessarily be the case at local levels, due to an inherently unpredictable distribution of temperature and precipitation effects. On the other hand, the benefits for biodiversity of reducing climate change impacts through large-scale biomass-based CO_2 removal seem likely to be offset, at least in part, and possibly outweighed, by land use change. Changes in ocean productivity through large-scale fertilization would necessarily involve major changes to marine ecosystems, with associated risks to biodiversity. In general, technique-specific side effects that may be detrimental for biodiversity are not well understood.

27. **Assessment of the direct and indirect impacts (each of which may be positive or negative) of climate geoengineering is not straightforward.** Such considerations necessarily involve uncertainties regarding technical feasibility and effectiveness; scale dependencies; and complex comparisons with non-geoengineered conditions as well as value judgements and ethical considerations. Technique-specific considerations important for the evaluation of climate geoengineering techniques include effectiveness, safety and risks; co-benefits; readiness; governance and ethics; and cost and affordability. Many of these factors cannot yet be reliably quantified, and it is important that 'cost' includes both market and non-market values. Further research, with appropriate safeguards, could help to reduce some of these knowledge gaps and uncertainties.

CHAPTER 1

CONTEXT, MANDATE AND SCOPE OF WORK

1.1 INTRODUCTION

1. The most direct way of preventing dangerous, human-driven climate change is not in doubt: a rapid decrease in the global emissions of greenhouse gases. At the international level, measures and commitments to achieve that goal – primarily by phasing out the combustion of fossil fuels – are in negotiation under the auspices of the United Nations Framework Convention on Climate Change (UNFCCC)[3,4], with an ongoing process of Intended Nationally-Determined Contributions (INDCs)[5] to a new Climate Change Agreement. Recent progress at other levels and fora includes the G7 statement on decarbonizing the global economy by the end of the century[6], national policy proposals[7], and the call for action by major religious leaders[8,9]. Nevertheless, the profound societal and economic changes required to address the cause of the problem are such that many approaches to counter-act (i.e. potentially reverse) climate change, rather than just reducing emissions, have also been proposed. Climate scientists now consider that some of these interventions are very likely to be necessary as additional measures (rather than alternatives) to emission reductions if future increases in global temperature are to remain, with any confidence, within internationally-agreed limits. In particular, the oxymoronic concept of 'negative emissions', i.e. active removal of greenhouse gases from the atmosphere, is now built-in to almost all model scenarios that limit increases in mean global temperature to no more than 2°C higher than pre-industrial values. Another group of methods, involving reduction in solar energy received by the Earth, could also – in theory – be used to stabilize mean global temperature at a level closely similar to current conditions.

2. Proposed actions to counter-act climate change are widely known as climate geoengineering, climate engineering or geoengineering. The appropriateness of such terminology has been questioned[10], and the meaning of such terms is contested; nevertheless, geoengineering is used here to cover both greenhouse gas removal and sunlight reflection approaches. Such ideas have been developed on the conceptual basis that, although prevention is better than cure, cure becomes desirable if preventative measures are inadequate. Thus the two main groups of geoengineering methods share the same purpose: to remediate the climatic consequences of increasing levels of greenhouse gases in the atmosphere, and their adverse socioeconomic impacts. However, the two groups differ in several ways, and there has recently been increased emphasis on those differences.

3. An important feature of many negative emission techniques (almost exclusively focused on carbon dioxide, CO_2) is their similarity to other processes, both natural and managed, that can also result in either the long-term removal of carbon from global circulation or a reduction in its release. Such similarities to actions addressing the causes of climate change, and the broad range of techniques involved, make it difficult to unambiguously define climate geoengineering. There are also different technical uses of the term 'mitigation'. Both terms can either have narrow or broad meanings, see Figure 1.1. In this report a relatively broad definition for climate geoengineering

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[3] UNFCCC (United Nations Framework Convention on Climate Change) (2010)

[4] UNFCCC (United Nations Framework Convention on Climate Change) (2014)

[5] http://www4.unfccc.int/submissions/indc/Submission%20Pages/submissions.aspx

[6] Leaders' Declaration G7 Summit, 8 June 2015. https://www.g7germany.de/Content/DE/_Anlagen/G8_G20/2015-06-08-g7-abschluss-eng.html?nn=1281586

[7] For example, the US Clean Power Plan to limit CO2 emissions. https://www.whitehouse.gov/the-press-office/2015/08/03/fact-sheet-president-obama-announce-historic-carbon-pollution-standards

[8] Encyclical Letter Laudato Si of the Holy Father Francis on Care for Our Common Home. http://w2.vatican.va/content/francesco/en/encyclicals/documents/papa-francesco_20150524_enciclica-laudato-si.html

[9] Islamic Declaration on Climate Change. http://islamicclimatedeclaration.org/islamic-declaration-on-global-climate-change/

[10] NRC (National Research Council) (2015a)

is employed, considering it to be the same as climate engineering, and without prejudice to any definition that may be subsequently agreed under the Convention. Important distinctions between the two groups of geoengineering methods are recognized, as is the contested nature of the definition. For further discussion of such issues, see Section 1.4 and Annex 2.

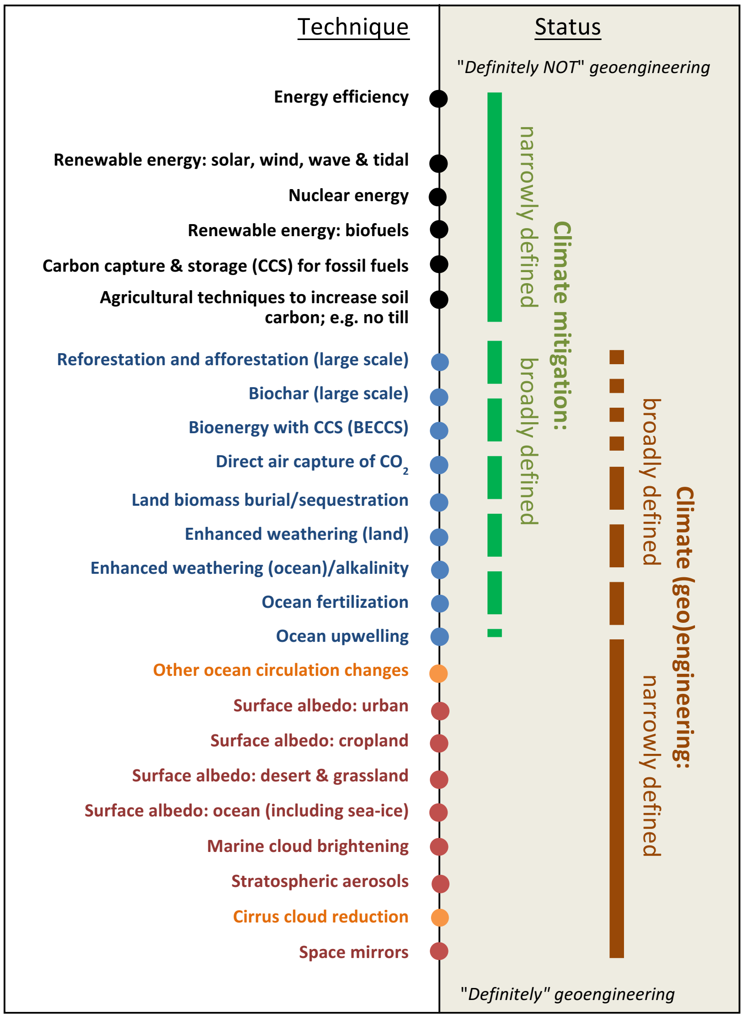

Figure 1.1 The spectrum of techniques that have been considered as either climate mitigation or climate geoengineering and their degree of overlap, depending on whether such terms are either narrowly or broadly defined. Colour coding for techniques: black, unambiguously climate mitigation ('conventional mitigation'); blue, negative emission techniques, based on carbon dioxide removal (CDR); purple, sunlight reflection methods, also known as solar radiation management (SRM); orange, other climate geoengineering techniques, based on enhanced heat storage or enhanced heat escape. The positioning of techniques along the spectrum from 'Definitely NOT' geoengineering to 'Definitely' geoengineering is illustrative rather than definitive, and the list of techniques is not intended to be comprehensive. Definition issues are discussed further in Section 1.4 and Annex 2.

4. The effectiveness of several carbon dioxide removal (CDR) techniques has been investigated at small-scale, and their deployment at the local level may be non-controversial, without adverse environmental impacts. Nevertheless, many problems and uncertainties arise relevant to CBD interests regarding their implementation at scales necessary to have the intended effects on global climate. Sunlight reflection methods (SRM) are inherently more speculative:

they can be considered as 'socio-technical imaginaries'[11,12], currently without proven efficacy in achieving desired results. The risks and uncertainties associated with both groups of geoengineering techniques do not mean that negative impacts on biodiversity would necessarily be greater than their positive impacts; it is plausible that there may be net benefits. Nevertheless, the risks and uncertainties relating to environmental consequences are not yet well understood. There are also other concerns (both generic and technique-specific) regarding feasibility, effectiveness, economic costs, governance, equity and ethics. Such issues would seem to provide a strong rationale for further research on climate geoengineering and its wider implications, covering both risks and benefits, in order to inform policy decisions relating to the very serious challenge of climate change. The opposite case can also be made: that, at least for some techniques, further research may itself be either dangerous or diversionary.

5. The main remit of this report is to provide "an update on the potential impacts of geoengineering techniques on biodiversity" together with an account of regulatory developments. The context of the update is the CBD Secretariat's previous (2012) report on this topic[13]. There have been very many scientific papers and reports relevant to climate geoengineering during the past three years, with ~500 such publications cited here. However, relatively little research has *directly* addressed the issue of 'impacts on biodiversity', nor even broader environmental implications: instead effort by natural scientists has mostly focussed on climatic (physico-chemical) or agricultural issues, while social scientists have addressed governance, framing and ethical considerations.

6. Although biodiversity is necessarily affected by climatic factors such as temperature and precipitation, there are many other ways in which natural ecosystems may be disadvantaged (or potentially benefit) from different geoengineering techniques. For agricultural systems, 'productivity' can be considered as a key indicator, with obvious socioeconomic benefits in its maintenance or enhancement; however, enhanced (plant) productivity is not necessarily advantageous for unexploited habitats and ecosystems, either terrestrial or marine. Furthermore, while decreased agricultural production in one geographic region may, to some degree, be offset by increased production elsewhere (with no net change in global yields), it is very much harder to achieve the same balance between biodiversity losses and gains, likely to operate on very different timescales.

7. Ecosystem integrity is therefore regarded as a key consideration for the future maintenance of species richness (i.e. avoiding biodiversity loss) and the continued provision of ecosystem services under conditions of climate change – and associated policy responses to such change, that may potentially include either CDR or SRM geoengineering. While climatic stability would be preferred, that option is no longer available: unequivocal warming has already occurred, and will continue for many decades even if all anthropogenic greenhouse gas emissions were to cease tomorrow[14]. Instead the internationally-agreed aim is that dangerous anthropogenic interference with the climate system should be achieved by stabilizing greenhouse gas concentrations "within a timeframe sufficient to allow ecosystems to adapt naturally"[15] . The environmental benefits of stabilizing greenhouse gases could, however, be jeopardized if the achievement of that goal were to involve additional adverse anthropogenic pressures on biodiversity, such as pollution, habitat loss/degradation and ocean acidification.

1.2 CLIMATE CHANGE, CLIMATE GEOENGINEERING AND THE CBD

8. The Convention on Biological Diversity (CBD) has long recognized the potentially-damaging impacts of climate change on biodiversity, at local to global levels. Decisions to explicitly address this issue were first made at the seventh meeting of the Conference of the Parties (COP-7, in 2004), covering the linkages between biological diversity and climate change, and advice on the integration of biodiversity considerations into the implementation of the UNFCCC's Kyoto Protocol (UNEP/CBD/SBSTTA/9/11), based on a report by the Ad Hoc Technical Expert

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[11] Jasanoff S (2015)

[12] Rayner S (2015)

[13] CBD (Secretariat of the Convention on Biological Diversity) (2012)

[14] IPCC (Intergovernmental Panel on Climate Change) (2013)

[15] UN Framework Convention on Climate Change, UNFCCC (Article 2).

Group on Biological Diversity and Climate Change (UNEP/CBD/SBSTTA/9/INF/12). COP-7 encouraged Parties *inter alia* "to take measures to manage ecosystems so as to maintain their resilience to extreme climate events and to help mitigate and adapt to climate change" (decision VII/15, paragraph 12). Further discussions and decisions on climate change have been made at subsequent CBD meetings.

9. These discussions have included consideration of the negative environmental impacts that can arise from some schemes that generate energy from renewable sources, and potentially also by techniques that aim to enhance carbon sinks. While 'conventional' climate change mitigation includes the protection and enhancement of natural carbon sinks (in addition to emission reduction), the UNFCCC Convention defines sinks in very broad terms, as "any process, activity or mechanism which removes a greenhouse gas, an aerosol or a precursor of a greenhouse gas from the atmosphere"[16]. Furthermore, a wide range of sink-enhancement processes are included in the definition of mitigation by the Intergovernmental Panel on Climate Change[17], overlapping with the IPCC's own definition of climate geoengineering (see Annex 2 of this report). Under such circumstances, careful consideration must be given to maximize the benefits while minimizing deleterious – and unintended – impacts. The ninth meeting of the Conference of Parties (COP-9, in 2008) considered the potential for environmental damage to arise from ocean fertilization (a proposed means to enhance the ocean carbon sink, through large-scale carbon dioxide removal). COP-9 requested Parties to ensure that such ocean fertilization activities did not take place until an 'adequate' scientific basis and regulatory framework was in place, including assessment of associated risks (decision IX/16 C). To assist in the scientific assessment of the impacts of ocean fertilization on marine biodiversity, the Secretariat prepared a synthesis report[18] on that topic, published in 2009.

10. A second report[19] of the CBD Ad Hoc Technical Expert Group on Biological Diversity and Climate Change, also published in 2009, was used by the Conference of Parties at its tenth meeting (COP-10, in 2010) to re-affirm the overall need for ecosystem-based mitigation and adaptation measures, and to reduce any negative impacts on biodiversity of climate change mitigation and adaptation measures. More specifically, COP-10 gave attention to the implications of other climate geoengineering techniques, in addition to ocean fertilization, inviting Parties to consider the following guidance [decision X/33 paragraph 8(w)]:

> "Ensure, in line and consistent with decision IX/16 C, on ocean fertilization and biodiversity and climate change, 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."

11. Climate geoengineering was then defined in a footnote as:

> "Without prejudice to future deliberations on the definition of geoengineering activities, understanding that any 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) should be considered as forms of geoengineering which are relevant to the Convention on Biological Diversity until a more precise definition can be developed. It is noted that solar insolation is defined as a measure of solar radiation

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[16] Definition 8 of Article 1 of UN Framework Convention on Climate Change

[17] IPCC (2014c) [Annex II, Glossary; KJ Mach, S Planton & C von Stechow (eds); p117-130]

[18] CBD (Secretariat of the Convention on Biological Diversity) (2009a)

[19] CBD (Secretariat of the Convention on Biological Diversity) (2009b)

energy received on a given surface area in a given hour and that carbon sequestration is defined as the process of increasing the carbon content of a reservoir/pool other than the atmosphere."

12. In subsequent paragraphs [9(l) and 9(m)] of decision X/33, the Conference of the Parties requested the Secretariat to compile and synthesize information on geoengineering relevant to the CBD. The outcome was CBD Technical Series No. 66 *Geoengineering in Relation to the Convention on Biological Diversity: Technical and Regulatory Matters* [hereafter CBD (2012)][20] that was available to inform discussions at the eleventh meeting of the Conference of the Parties (COP-11).

1.3 MANDATE

13. COP-11 adopted decision XI/20 on climate-related geoengineering. Because of the significance of decision XI/20 in relation to the current report, the relevant text is given in full in Box 1.1. In particular, the Conference of the Parties noted in paragraph 5 four definitions for geoengineering, while paragraph 16(a) provides the mandate for this report, through the request to the Executive Secretary to prepare an update on Technical Series No. 66 for a future meeting of the Subsidiary Body on Scientific, Technical and Technological Advice (SBSTTA).

14. In response to decision XI/20, an interim report on climate geoengineering was provided as an information document to the 18th meeting of the Subsidiary Body (UNEP/CBD/SBSTTA/18/INF/5), together with a compilation of information submissions related to measures undertaken in accordance with the guidance in paragraph 8(w) of decision X/33 (UNEP/CBD/SBSTTA/18/INF/14). The interim report comprised a bibliography of around 300 peer-reviewed scientific papers and other relevant reports published since the preparation of CBD (2012), together with a summary analysis of their key features. The most relevant excerpts of the Summaries for Policymakers of the reports of IPCC Working Groups I and III were included[21].

15. The interim report recognized that not all aspects of decision XI/20 paragraph 16 had been fulfilled, noting: "It is anticipated that a more comprehensive update will be prepared for a future meeting of the Subsidiary Body, when there will be the opportunity for detailed consideration to be given to all the IPCC AR5 reports and their geoengineering-relevant aspects".

16. SBSTTA-18 took note of the interim report, and adopted a recommendation to the Conference of the Parties relating to regulatory developments. That recommendation was adopted by the Conference of the Parties (COP-12) in decision XII/20 paragraph 1, in which the COP "takes note of Resolution LP.4(8) on the amendment to the London Protocol (1996) to regulate the placement of matter for ocean fertilization and other marine geoengineering activities, adopted in October 2013, and invites Parties to the London Protocol to ratify this amendment and other Governments to apply measures in line with this, as appropriate".

17. The current document expands on the interim update prepared for SBSTTA-18, with the inclusion of additional information from the Synthesis Report of the Fifth Assessment of the Intergovernmental Panel on Climate Change (IPCC), and other more recent publications. This report has been prepared by the CBD Secretariat with the assistance of the lead authors of Parts I and II of CBD (2012).

1.4 SCOPE

18. This report covers major developments since mid-2012 in the scientific understanding of proposed geoengineering techniques and their implications for biodiversity, with a closely similar scope and structure to CBD (2012). Regulatory issues are covered in Chapter 6. Definition issues are discussed further in Annex 2.

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[20] CBD (Secretariat of the Convention on Biological Diversity) (2012)

[21] Note that there was no mention of geoengineering in the IPCC AR5 WG II Summary for Policymakers. See Chapter 2 of this report for additional information on relevant IPCC text.

BOX 1.1 Decision relating to climate geoengineering made at the eleventh Conference of the Parties to the CBD, Hyderabad, India, October 2012 (decision XI/20, paragraphs 1-16). Cross-referencing to UNEP/CBD/SBSTTA/16/INF/28 and UNEP/CBD/SBSTTA/16/INF/29 corresponds to Parts 1 and 2 respectively of CBD Technical Series No.66 (CBD, 2012)[10], while UNEP/CBD/SBSTTA/16/10 provides the main messages given in that report.

The Conference of the Parties

1. *Reaffirms* paragraph 8, including its subparagraph (w), of decision X/33;

2. *Takes note* of the report on the impacts of climate-related geoengineering on biological diversity (UNEP/CBD/SBSTTA/16/INF/28), the study on the regulatory framework for climate-related geoengineering relevant to the Convention on Biological Diversity (UNEP/CBD/SBSTTA/16/INF/29) and the overview of the views and experiences of indigenous and local communities and stakeholders (UNEP/CBD/SBSTTA/16/INF/30);

3. *Also takes note* of the main messages presented in the note by the Executive Secretary on technical and regulatory matters on geoengineering in relation to the Convention on Biological Diversity (UNEP/CBD/SBSTTA/16/10);

4. *Emphasizes* that climate change should primarily be addressed by reducing anthropogenic emissions by sources and by increasing removals by sinks of greenhouse gases under the United Nations Framework Convention on Climate Change, noting also the relevance of the Convention on Biological Diversity and other instruments;

5. *Aware* of existing definitions and understandings, including those in annex I to document UNEP/CBD/SBSTTA/16/INF/28, and ongoing work in other forums, including the Intergovernmental Panel on Climate Change, *notes,* without prejudice to future deliberations on the definition of geoengineering activities, that climate-related geoengineering may include:

(a) Any technologies that deliberately reduce solar insolation or increase carbon sequestration from the atmosphere on a large scale and that may affect biodiversity (excluding carbon capture and storage from fossil fuels when it captures carbon dioxide before it is released into the atmosphere) (decision X/33 of the Conference of the Parties);

(b) Deliberate intervention in the planetary environment of a nature and scale intended to counteract anthropogenic climate change and/or its impacts (UNEP/CBD/SBSTTA/16/10); [*Footnote*: Excluding carbon capture and storage at source from fossil fuels where it captures carbon dioxide before it is released into the atmosphere, and also including forest-related activities]

(c) Deliberate large-scale manipulation of the planetary environment (32nd session of the Intergovernmental Panel on Climate Change);

(d) Technological efforts to stabilize the climate system by direct intervention in the energy balance of the Earth for reducing global warming (Fourth Assessment Report of the Intergovernmental Panel on Climate Change); [*Footnote*: Noting that this definition includes solar radiation management but does not encompass other geoengineering techniques]

6. *Notes* the findings contained in document UNEP/CBD/SBSTTA/16/INF/28, that there is no single geoengineering approach that currently meets basic criteria for effectiveness, safety and affordability, and that approaches may prove difficult to deploy or govern;

7. *Also notes* that there remain significant gaps in the understanding of the impacts of climate-related geoengineering on biodiversity, including:

(a) How biodiversity and ecosystem services are likely to be affected by and respond to geoengineering activities at different geographic scales;

(b) The intended and unintended effects of different possible geoengineering techniques on biodiversity;

(c) The socioeconomic, cultural and ethical issues associated with possible geoengineering techniques, including the unequal spatial and temporal distribution of impacts;

8. *Notes* the lack of science-based, global, transparent and effective control and regulatory mechanisms for climate-related geoengineering, the need for a precautionary approach, and that such mechanisms may be most necessary for those geoengineering activities that have a potential to cause significant adverse transboundary effects, and those deployed in areas beyond national jurisdiction and the atmosphere, noting that there is no common understanding on where such mechanisms would be best placed;

9. *Invites* Parties to address the gaps identified in paragraph 7 and to report on measures undertaken in accordance with paragraph 8(w) of decision X/33;

10. *Reaffirming* the precautionary approach, *notes* the relevant resolutions of the meeting of the Contracting Parties to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and other Matter, 1972 (the London Convention) and its 1996 Protocol, and *recalls* decision IX/16 C of the Conference of the Parties, on ocean fertilization, and also decisions IX/30 and X/33, and paragraph 167 of the outcome document of United Nations Conference on Sustainable Development (Rio+20, "The Future We Want"); [*Footnote*: Adopted in General Assembly resolution 66/288]

11. *Notes* that the application of the precautionary approach as well as customary international law, including the general obligations of States with regard to activities within their jurisdiction or control and with regard to possible consequences of those activities, and requirements with regard to environmental impact assessment, may be relevant for geoengineering activities but would still form an incomplete basis for global regulation;

12. *Further notes* the relevance of work done under the

BOX 1.1 (cont.)

auspices of existing treaties and organizations for the governance of potential geoengineering activities, including the United Nations Convention on the Law of the Sea, the London Convention and its Protocol, the United Nations Framework Convention on Climate Change and its Kyoto Protocol, the Vienna Convention for the Protection of the Ozone Layer and its Montreal Protocol, and regional conventions, as well as the United Nations General Assembly, the United Nations Environment Programme and the World Meteorological Organization;

13. *Requests* the Executive Secretary, subject to the availability of financial resources, to disseminate the reports referred to in paragraph 2 as widely as possible, including to the secretariats of the treaties and organizations referred to in paragraph 12, as well as the Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques, the Convention on Long-range Transboundary Air Pollution, the Outer Space Treaty, the Antarctic Treaty, the United Nations Human Rights Council and the Office of the High Commissioner for Human Rights, the United Nations Permanent Forum on Indigenous Issues, the Food and Agriculture Organization of the United Nations and its Committee on World Food Security for their information;

14. *Noting* that the Intergovernmental Panel on Climate Change, the purpose of which is to provide comprehensive assessments of scientific and technical evidence on issues relating to climate change and its impacts, considers, in its Fifth Assessment Report, different geoengineering options, their scientific bases and associated uncertainties, their potential impacts on human and natural systems, risks, research gaps, and the suitability of existing governance mechanisms, *requests* the Subsidiary Body on Scientific, Technical and Technological Advice to consider the Synthesis Report when it becomes available in September 2014 and report on implications for the Convention on Biological Diversity to the Conference of Parties;

15. *Also requests* the Executive Secretary, subject to the availability of financial resources, in collaboration with relevant organizations, to:

(a) Compile information reported by Parties as referred to in paragraph 9 above, and make it available through the clearing-house mechanism;

(b) Inform the national focal points of the Convention when the review procedures for the Fifth Assessment Report of the Intergovernmental Panel on Climate Change are initiated, so as to facilitate national cooperation in providing input, in particular as it relates to biodiversity considerations;

16. *Further requests* the Executive Secretary, subject to the availability of financial resources and at the appropriate time, to prepare, provide for peer review, and submit for consideration by a future meeting of the Subsidiary Body on Scientific, Technical and Technological Advice:

(a) An update on the potential impacts of geoengineering techniques on biodiversity, and on the regulatory framework of climate-related geoengineering relevant to the Convention on Biological Diversity, drawing upon all relevant scientific reports such as the Fifth Assessment Report of the Intergovernmental Panel on Climate Change and discussions under the Environment Management Group;

(b) An overview of the further views of Parties, other governments, indigenous and local communities and other stakeholders on the potential impacts of geoengineering on biodiversity, and associated social, economic and cultural impacts, taking into account gender considerations, and building on the overview of the views and experiences of indigenous and local communities contained in document UNEP/CBD/SBSTTA/16/INF/30.

19. Figure 1.2 provides a conceptual summary of the main climate geoengineering approaches, with a top-level grouping based on whether they either: i) increase the escape of heat (long-wave radiation) from the Earth system; or ii) re-distribute heat within the system (by increasing ocean heat uptake); or iii) decrease the amount of energy entering the system, by reflecting sunlight (short-wave radiation), i.e. albedo enhancement or brightening, either at the surface, or in the atmosphere, or in space. More conventional grouping is at the technique level, with most proposals in category (i) involving greenhouse gas removal (GGR) or negative emission techniques (NETs), specifically carbon dioxide removal (CDR). In category (ii), techniques are known as solar radiation management or sunlight reflection methods (SRM). As noted in Table 1 of CBD (2012), the concept of deliberate climate modification is not new[22]; however, it is only in the past 10-15 years that such ideas have been given serious policy attention.

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[22] Fleming JR (2010)

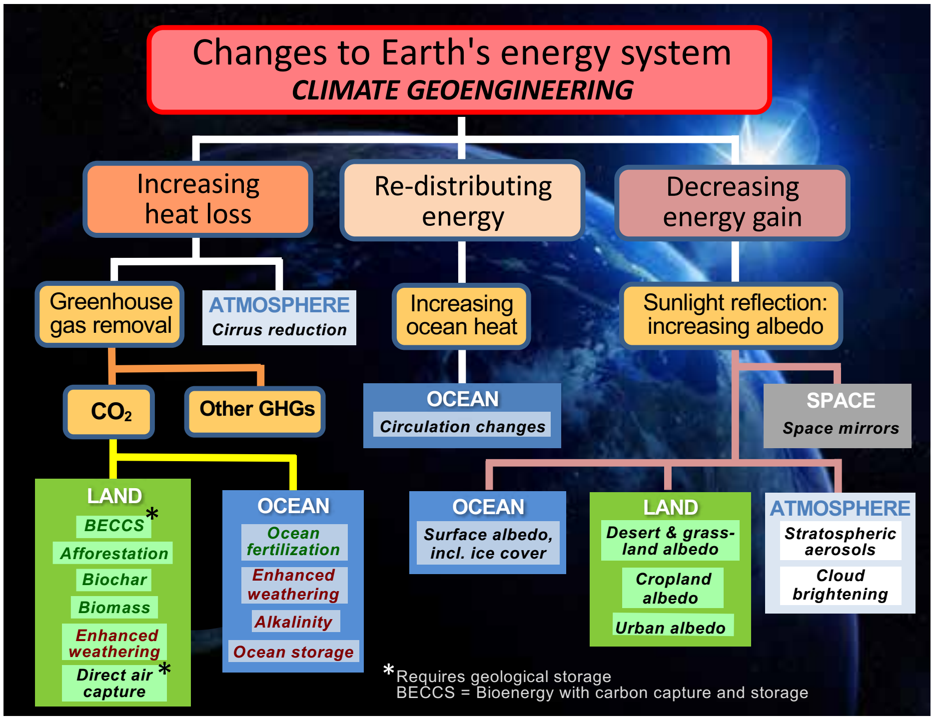

Figure 1.2 Main climate geoengineering techniques based on typology presented in CBD (2012) [Part 1, Annex II; Table1]. Greenhouse gas removal (GGR) techniques indicated by yellow/orange branching; carbon dioxide removal (CDR) by yellow branching; sunlight reflection methods (SRM) by pink branching. GHGs, greenhouse gases; BECCS, bioenergy with carbon capture and storage. Green, dark red and black text for specific techniques (in italics) indicate whether the climatic effects are mainly achieved through biological, (geo)chemical or physically-based processes. Note that some land-based CDR techniques, e.g. enhanced weathering may also affect the ocean.

20. In this report, the definition of climate geoengineering developed in CBD (2012)[23] is used, i.e. "*The deliberate intervention in the planetary environment of a nature and scale intended to counteract anthropogenic climate change and/or its impacts*". The inclusion of 'counteract' in this definition is intended to emphasize that geoengineering is able to reverse, not just slow, climate change. Climate geoengineering is therefore remedial, rather than preventative. Although the above definition is relatively broad, it is considered consistent with wider usage, clarity, purpose, brevity and etymology. It is also sufficiently similar to IPCC definitions (and others) not to cause practical problems.

21. The definition adopted here is without prejudice to any future CBD decision on such issues. As discussed in Chapter 6, greater exactness, e.g. at the technique-specific level, is likely to be necessary for regulatory purposes, with focus on those techniques that have significant potential for adverse transboundary impacts[24,25]. The need for international regulation of climate geoengineering (at least for deployment, if not also for research), has been identified by CBD, other international bodies, non governmental organizations, and the academic community[26,27,28];

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[23] CBD (Secretariat of the Convention on Biological Diversity) (2012)

[24] Boucher O, Forster PM, Gruber N, Ha-Duaong M et al. (2014)

[25] Saxler B, Siegfried J & Proelss (2015)

[26] Parson EA & Ernst LN (2013)

[27] Bodle R, Oberthuer S, Donat L, Homann G et al. (2014)

[28] Dilling L & Hauser R (2013)

however, it is not universally accepted[29]. Additional definition-related issues are considered in Annex 2 of this report, including the definition options noted in CBD decision XI/20 (Box 1.1).

22. In common with wider usage and several other definitions of climate geoengineering [CBD (2012); Part I, Annex 1], the definition used here excludes actions taken to directly decrease emissions of greenhouse gases from fossil fuel combustion and other anthropogenic activities, e.g. by carbon capture and storage, CCS, at power stations using fossil fuel; or by changing to renewable or nuclear energy generation. Such emission reductions are conventionally regarded as 'mitigation' in the context of climate change (Figure 1.1). Nevertheless, some geoengineering techniques also involve chemically-engineered CO_2 capture and its managed, longterm storage and therefore have much in common with fossil fuel CCS; in particular, direct air capture (DAC) and bioenergy with carbon capture and storage (BECCS). For the latter, it is the combination of bioenergy and CCS, with the intention of reducing atmospheric CO_2, that justifies such a technique being considered as geoengineering – recognising that bioenergy alone, or conventional CCS alone, would not be similarly regarded.

1.5 ALTERNATIVE FUTURES FOR CLIMATE CHANGE AND BIODIVERSITY

23. CBD (2012) provided an overview of climate change and the associated impacts of ocean acidification. The wider context of ongoing and projected changes in climate-related conditions (temperature, rainfall and other hydrological processes, sea level, ocean acidity and extreme events) and their impacts on terrestrial and marine biodiversity[30,31], species' distributions[32], ecosystems[33], and societal vulnerability[34] remains crucial to the assessment of the potential effects of climate geoengineering. There is also need for awareness of the impacts of many other environmental pressures, mostly human-driven, that include land use changes, species introductions, pollution, and unsustainable harvesting of natural resources. Many of these changes are linked to projected human population increase, of around 40% by 2050, and growth in the global economy, expected to triple in size over that time period[35] – with associated societal needs for increased food and water, and other environmental goods and services.

24. Attention frequently focusses on the potential for negative impacts of geoengineering on biodiversity, occurring as undesirable side-effects; nevertheless, impacts can also be positive. In particular, there are expected to be environmental benefits arising from the intended stabilizing of climate, atmospheric CO_2 and ocean pH, also more directly; e.g. mixed-species afforestation for the purpose of enhancing carbon sinks. But the balance between the negative and positive impacts of geoengineering is uncertain and may be very difficult to determine, even on a technique-specific basis. That is because, as identified in CBD (2012):

i) Assessment of the net balance between costs and benefits involves trade-offs, value judgements and ethical considerations that are highly contested[36,37,38,39,40, 41], particularly for SRM.

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[29] Reynolds J (2015)

[30] Warren R, VanDerWal J, Price J, Walbergen JA et al. (2013)

[31] Moritz C & Agudo R (2013)

[32] Burrows MT, Schoeman DS, Richardson AJ, Molinos JG et al. (2014)

[33] Bopp L, Resplandy L, Orr JC, Doney SC et al. (2013)

[34] Thornton PK, Ericksen PJ, Herrero M & Challinor AJ (2014)

[35] OECD (Organisation for Economic Co-operation and Development) (2014)

[36] Klepper G (2012)

[37] Preston CJ (2013a)

[38] Keith D (2013)

[39] Morrow DR (2014)

[40] Gardiner SM (2013a)

[41] Hamilton C (2013c)

ii) Many impacts are highly scale-dependent[42,43,44], spatially and temporally – particularly for CDR, varying with the intensity of the intervention and also between short-term and long-term.

iii) The climatic benefits are crucially linked to the technical feasibility and potential effectiveness of the geoengineering technique, aspects that may be highly uncertain and difficult to quantify in advance of large-scale testing or actual implementation[45,46].

iv) Assessment of impacts requires comparison with alternative, non-impacted conditions, as a 'control'. However, except for small-scale, short-term experiments, such comparisons may not be achievable except through model simulations – when the control may involve future, scenario-based conditions that are themselves far from certain.

25. General aspects relevant to issues (i) - (iii) above are considered further in section 1.6 below; technique-specific aspects are discussed in Chapters 3 and 4. Here, issue (iv), the need for valid comparisons, is given further attention.

26. Present-day conditions are only of limited value as a control or baseline for considering the impacts of either CDR or SRM geoengineering. Climate change and its associated environmental impacts are already underway, interacting with other human-driven global changes[47]: thus future conditions will inevitably be different – and the hypothesized geoengineering action needs to be considered in the context of those other changes. Mathematical models provide the tools to make projections of scenarios and 'counterfactuals': what has not happened, but could, would or might. Yet such maybe-modelling inevitably introduces additional uncertainties, not only due to the relatively arbitrary nature of some underlying assumptions (arising from limitations of our understanding of natural processes and their interactions), but also due to the inherent unpredictability of climatic variability (including the occurrence of extreme events) and societal behaviour.

27. Examples of possible future climate scenarios are provided by IPCC Representative Concentration Pathways[48,49] (RCPs; Table 1.1), based on assumptions regarding future forcings by greenhouse gas emissions. Three of these (RCP 4.5, 6.0 and 8.5) result in global mean temperatures exceeding the UNFCCC 2°C limit for 'dangerous' climate change, providing the main comparators against which the effects of geoengineering can be assessed. It should be noted that RCP 2.6 – involving very strong and rapid emission reductions as well as carbon dioxide removal (negative emissions) in most scenarios, see below – is not necessarily 'safe', since it only provides a probabilistic likelihood of avoiding +2°C. Furthermore, the appropriateness of the 2°C limit is much debated by the scientific community[50], not least because many deleterious climate impacts occur at lower temperature increases[51,52].

28. More generally, it should be noted that emission pathways can be achieved in a variety of different ways, since there are many processes and factors linking human activities with the release of greenhouse gases. Integrated

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[42] McLaren D (2012)

[43] Jones C, Williamson P, Haywood J, Lowe J et al. (2013)

[44] Hill S & Ming Y (2012)

[45] MacMynowski DG, Keith D, Caldeira K & Shin HJ (2011)

[46] Seidel DJ, Feingold G, Jacobson AR & Loeb N (2014)

[47] Steffen W, Richardson K, Rockström J, Cornell SE et al. (2015)

[48] Van Vuuren DP, Edmonds J, Kainuma M, Riahi K et al. (2011)

[49] IPCC scenarios have not been accepted by the Plurinational State of Bolivia, on the basis that they "favour, by political and not scientific decision, the inclusion of technologies such as Carbon Capture and Storage (CCS) and Bioenergy with Carbon Capture and Storage (BECCS) among others, technologies that have important environmental and biodiversity impacts, with high economic, social and health costs" (comments on consultation draft of this report). Also see www.cbd.int/climate/doc/Bolivia-notif-2015-016-geoengineering-es.pdf

[50] Knopf B, Kowarsch M, Flachsland C & Edenhofer O (2012)

[51] UNFCCC (United Nations Framework Convention on Climate Change) (2015)

[52] Gattuso J-P, Magnan A, Billé R, Cheung WWL et al. (2015)

assessment models (IAMs) are used to simulate the main socioeconomic, ecological and physical processes involved (Figure 1.3). For RCP 2.6, most (~90%) IAM scenarios assume that negative emissions (i.e. CDR) will be achievable after 2050, and the 'central' RCP 2.6 pathway is based on that assumption (Figure 1.4). An alternative approach, based on Earth System Models, has also recently been used[53]: that also found that large-scale carbon removal (of 0.5 - 3.0 Gt C yr^{-1}) was necessary to keep global warming below 2˚C, even in conjunction with the most optimistic scenario for reducing emissions.

Table 1.1. Main scenarios developed for use in the IPCC 5th Assessment Report. Representative Concentration Pathways (RCPs) relate to the increase in radiative forcing at the Earth's surface by 2100, e.g. RCP 4.5 = increase of 4.5 W m^{-2} relative to pre-industrial conditions. Note that i) anthropogenic forcing of ~2.0 W m^{-2} has already occurred (by 2000); ii) temperature increases in polar regions are expected to be much higher, up to ~10°C in the Arctic by 2100; iii) temperature increases would continue after 2100 for RCPs 4.5, 6.0 and 8.5; and iv) a complete cessation of anthropogenic greenhouse gas emissions within the next decade would not halt future climate change. Thus a further increase of ~0.6°C in global mean surface temperature is considered inevitable, due to slow-acting climate responses. From Moss et al (2010)[54] and IPCC WG I AR5 report[55]

RCP	Greenhouse gas emissions	Atmospheric CO_2 concentrations by 2100	Mean and likely range for increase in global mean surface temperature by 2081- 2100, °C		Increase in mean surface ocean acidity 2000-2100 (pH decrease)
			Relative to 1986-2005	Relative to 1850-1900	
2.6	Lowest; most models include negative emissions	~420 ppm (after peaking at ~445 ppm in 2050)	1.0 (0.3 – 1.7)	1.6 (0.9 – 2.6)	-0.065
4.5	Low	~540 ppm	1.8 (1.1 – 2.6)	2.4 (1.7 – 3.2)	-0.150
6.0	Moderate	~670 ppm	2.2 (1.4 – 3.1)	2.8 (3.0 -3.7)	-0.225
8.5	High; current trajectory	~940 ppm	3.7 (2.6 – 4.8)	4.3 (2.6 – 4.8)	-0.350

29. Although not explicitly covered by IPCC RCPs or UNFCCC agreements, more exacting targets for limiting future greenhouse gas emissions and associated warming could – if achievable[56] – greatly reduce environmental damage[57] and the risk of long-term socioeconomic costs (including sea level rise after 2100). *Note that this text was written before the negotiation of the Paris Agreement, with the international commitment to hold the global temperature increase to well below 2°C above industrial levels and to pursue efforts to limit the temperature increase to 1.5°C.* For example, by re-defining the temperature threshold distinguishing 'safe' from 'dangerous' to ~1.5°C, as promoted by many UNFCCC Parties[58] and tentatively proposed in the Final Report of the UNFCCC Structured Expert Dialogue[59]:

> "The guardrail concept, in which up to 2°C of warming is considered safe, is inadequate and would therefore be better seen as an upper limit, a defence line that needs to be stringently defended, while less warming would be preferable" (Message 5)
>
> "Whilst science on the 1.5°C warming limit is less robust, efforts should be made to push the defence line as low as possible… limiting global warming to below 1.5°C would come with several advantages in terms of coming closer to a safer 'guardrail'. It would avoid or reduce the risks, for example, to food production or unique and threatened systems such as coral reefs or many parts of the cryosphere, including the risk of sea level rise" (Message 10).

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[53] Gasser T, Guivarch C, Tachiiri K, Jones CD & Ciais P (2015)

[54] Moss RH, Edmonds JA, Hibbard KA, Manning MR et al. (2010)

[55] IPCC (Intergovernmental Panel on Climate Change) (2013)

[56] PwC (PricewaterhouseCoopers) (2014)

[57] Steinacher M, Joos F & Stocker TF (2013)

[58] Tschakert P (2015)

[59] UNFCCC (United Nations Framework Convention on Climate Change) (2015)

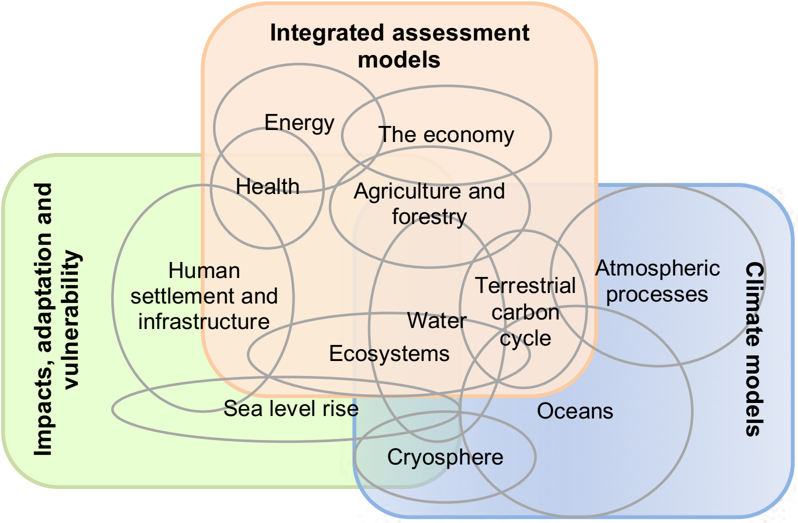

Figure 1.3 Simplified conceptual representation of the overlapping and interacting components of integrated assessment models, climate system models, and factors relating to impacts, adaptation and vulnerability. Geoengineering actions (not explicitly included) would have either direct or indirect effects on all these components. Reprinted by permission from Nature Publishing Group (MacMillan Publishers Ltd); Moss et al. (2010) *Nature* 463, 747-756.

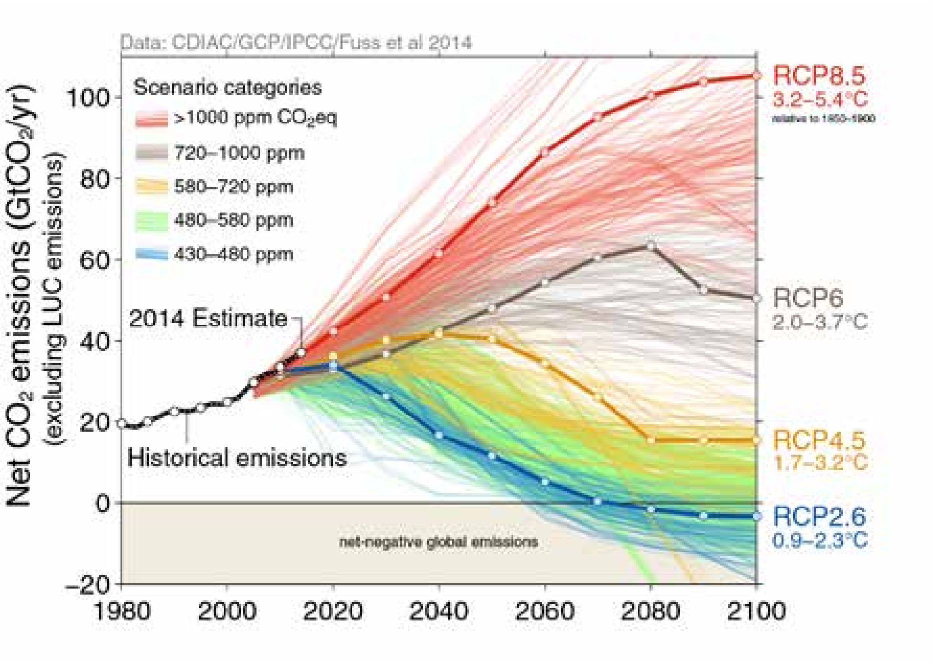

Figure 1.4. Historical (1980-2014) and projected (2005 – 2100) net anthropogenic emissions of carbon dioxide (excluding land-use change, LUC, but including future carbon dioxide removal by BECCS), with 1089 scenarios for projected net emissions shown in comparison to the four IPCC Representative Concentration Pathways. Data from IPCC AR5 database, Global Carbon Project and Carbon Dioxide Information Analysis Centre. Reprinted by permission from Nature Publishing Group (MacMillan Publishers Ltd); Fuss et al (2014) *Nature Climate Change* 4, 850-853.

30. For CDR geoengineering, comparisons are usually based on assumptions regarding the amount of carbon or carbon dioxide that might be removed (as Gt or Pg, of either C or CO_2)[60]. Hence the climatic consequences are assumed to be similar to reducing emissions by the same amount. However, the match is not exact, since the climatic effectiveness of CDR will depend on background level of CO_2 and other greenhouse gases, and there may also be significant feedbacks via the global carbon cycle. Such issues are discussed in greater detail in Chapter 3. For SRM geoengineering, climatic effects are more usually estimated in terms of radiative forcing (W m^{-2})[61], while recognizing that there may also be consequences for the carbon cycle. The main uncertainties in such estimates of climatic effectiveness then relate to the skill of the climate model, particularly at the regional level, affected by the validity of its assumptions.

31. There are also many model-based future climate scenarios that involve emission pathways that are intermediate between the RCPs (Figure 1.4), involving different permutations of mitigation actions. Geoengineering-relevant aspects of these scenarios are discussed in the IPCC AR5 reports (particularly in the WG III report[62]), reviewed here in Chapter 2.

32. It is possible to directly explore the climatic consequences (in terms of temperature increase, precipitation changes and ocean acidification) of factors affecting greenhouse gas emissions by an online Global Calculator[63], allowing 44 metrics (covering lifestyle, technology and fuels, land and food, and demographics) to be manipulated, each at four different levels. Results from the Calculator show that there are several possible pathways that avoid exceeding the 2°C warming threshold while not compromising living standards, nor "relying on futuristic technologies to solve the climate problem". Nevertheless, consistent with IPCC AR5 (see Chapter 2), the combination of rapid phasing-out of fossil fuels and greatly increased bioenergy with carbon capture and storage (i.e. BECCS) seems to be a feature of nearly all pathways that limit cumulative emissions to 3010 Gt CO_2e by 2100, and therefore have a 50% chance of constraining global mean temperature increase to 2°C.

33. Any single future-world scenario can be considered illustrative, as a projection not a prediction. Within IPCC AR5, no attempt was made to pre-judge the probability of different RCPs, since the actual outcome will depend on political decisions that have yet to be made. While noting that recent global emissions[64] still closely follow (or exceed) the highest assumptions used in IPCC RCP 8.5, preparatory discussions[65] and commitments[66] under the UNFCCC indicate that global energy policy is changing from 'business as usual'.

34. As discussed in greater detail in Chapter 3, the different RCP trajectories involve different land use changes as well as climatic changes. As a result, there is not a simple relationship that lower-value RCP scenarios are necessarily less damaging for (terrestrial) ecosystems. Although RCP 8.5 is the worst outcome from the effects of land use change with regard to projected net change in local species richness in 2100, the second worst is RCP 2.6[67]; see Figure 1.5. Another study also found that land-use changes associated with biofuel-based CDR could have greater negative impacts on terrestrial biodiversity loss than the positive effect of reducing climate change[68], although that did not use the full range of IPCC scenarios. These issues are discussed in greater detail in Chapter 3.

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[60] Pg, petagram; Gt, gigaton. 1PgC = 1 GtC = 3.664 Gt CO2

[61] Ideally, the radiative forcing of SRM (reducing heat input) should cancel the greenhouse radiative forcing (reducing heat escape), not just globally but for all locations on Earth. Because the two processes are inherently different, that is almost certainly unachievable – and the Earth's regional climate patterns under SRM with high greenhouse gases will therefore not be the same as the climate patterns without SRM and with lower greenhouse gases.

[62] IPCC (Intergovernmental Panel on Climate Change) (2014b)

[63] DECC (UK Department of Energy & Climate Change) and partners (2015)

[64] le Quéré C, Moriarty R, Andrew RM, Peters GP et al. (2015)

[65] UNFCCC Subsidiary Body for Scientific and Technological Advice (SBSTA) (2015)

[66] http://www4.unfccc.int/submissions/indc/Submission%20Pages/submissions.aspx

[67] Newbold T, Hudson LN, Hill SLL, Contu S et al. (2015)

[68] Powell TWR & Lenton TM (2013)

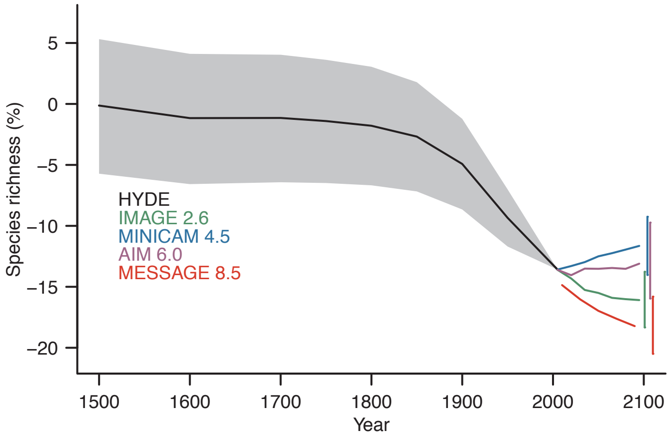

Figure 1.5 Hindcast and projected change in terrestrial local species richness 1500-2000 and 2000-2100, with the latter four pathways based on IPCC RCP 2.6, 4.5, 6.0 and 8.5. Reprinted by permission from Nature Publishing Group (MacMillan Publishers Ltd); Newbold et al. (2014) *Nature* 520, 45-50.

1.6 EVALUATING GEOENGINEERING TECHNIQUES IN CBD CONTEXT

35. In the same way that there is no fully-objective evaluation process to determine what constitutes 'dangerous' climate change, there are no fully-objective criteria for deciding which might be the 'best' (or least worst) geoengineering technique(s) to provide, if necessary, an additional means of counter-acting climate change – or for deciding 'none of the above'. While from the CBD perspective, impacts (positive or negative) on biodiversity, ecosystems and indigenous communities are of greatest concern and interest, a wide range of other factors and considerations are relevant to deciding whether serious policy attention ought to be given to specific geoengineering approaches.

36. In the 2009 Royal Society report on geoengineering[69], four criteria were assessed with semi-quantitative scoring (scale of 1-5): effectiveness, costs/affordability, timeliness, and safety. Aspects of these factors, and others, are considered in Table 1.2 below, taking account of a critique[70] of visual representations of such evaluations, and a recent, more comprehensive treatment of appraisal criteria[71] Many uncertainties currently preclude a well-informed comparison based on these factors for the majority of proposed geoengineering techniques. Even for those that are relatively well-characterized, the question of weighting arises: are some factors more important than others? Politically, economic issues (cost/affordability)[72] and response times[73] can be crucial, and when such factors are simulated in integrated assessment models, future discounting may also be applied – giving potential benefits in temporal decoupling of emissions and remedial action[74]. Much less attention has been given to assessing non-monetized environmental costs.

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[69] Royal Society (2009)

[70] Kruger T (2015)

[71] Bellamy R (2015)

[72] Edenhofer O, Carraro C & Hourcade J-C (2012)

[73] van Vuuren DP & Stehfest E (2013)

[74] Kriegler E, Edenhofer O, Reuster L, Luderer G & Klein D (2013)

Table 1.2 Main factors and additional issues that might be used to evaluate scientific and societal suitability of climate geoengineering techniques, developed from Royal Society (2009), Kruger (2015) and Bellamy (2015)

Main factors that warrant consideration	**Components and additional related issues**
Effectiveness: *Does the technique work?*	• Conceptual (technical) efficacy: magnitude of theoretical potential for intended effects over specified timescale • Pragmatic efficacy: magnitude of realistic achievability of intended effects over specified timescale • Climate change impacts reduction is main performance indicator, not just temperature • Need to take account of regional variability in intended responses (particularly with regard to changes in hydrological processes)
Feasibility/readiness *How easily can it be developed, applied and benefits obtained?*	• Technological readiness; time required for research and development • Time required for full scale-up and/or for climatic benefits to be unambiguously demonstrated (response time) • Resource requirements affecting scalability
Safety/risks: *What could go wrong?*	• Likelihood of adverse impacts to biodiversity, environmental services, food/water security and human health. Some of those impacts may be relatively predictable, and/or assessed in monetary terms; others highly uncertain, and/or difficult to value. • Temporal controllability/reversibility: can deployment be quickly discontinued without additional adverse consequences if problems were to arise? • Spatial controllability: what would be the scale (local, regional or global) of any problems that might arise? • Strategy to avoid/minimize termination effects for SRM • Future proofing: could risks and uncertainties increase over time? (e.g. for CDR, increased likelihood of re-release of stored carbon; for SRM, increased severity of termination effects unless CDR also deployed)
Co-benefits:	• Potential for added value (e.g. biochar increasing soil fertility) • Opportunities for commercial exploitation
Governance and ethics: *who decides?*	• Legality and agreement at international and national levels • Risk of conflict arising from uncoordinated actions • Social licence to operate; appropriate consultation procedures and approval procedures for all those that might be affected • Ethics of inter-regional and intergenerational equity • Liability for any adverse transboundary consequences • Verification (that may need to be on decadal-century scale) to show that intended benefits have been delivered (e.g. for carbon trading)
Cost/affordability: *How much does it cost?*	• Direct cost for deployment and operation (including verification) in terms of intended effect over specified time period. For CDR, costs are usually estimated as $ per GtC; for SRM, $ per W m^{-2}: how can these two scalings best be compared? • Direct costs of damage through undesirable effects (linked to 'safety/risks' above) • Non-monetizable, indirect costs, particularly in relation to environmental damage • Costs of additional supporting actions that may be necessary • International agreement on cost-sharing • Opportunity costs: diversion from other actions that may be more effective

CHAPTER 2

RELEVANT INTERNATIONAL AND NATIONAL SYNTHESES, ASSESSMENTS AND REVIEWS

2.1 INTRODUCTION

37. The mandate for the current report explicitly requested that it should draw upon "all relevant scientific reports such as the Fifth Assessment Report of the Intergovernmental Panel on Climate Change" (decision XI/20; paragraph 16(a); Box 1.1). Sections 2.2.1 – 2.2.5 below provides extracts and summaries of the text and conclusions relating to climate geoengineering from the three IPCC AR5 Working Group reports[75,76,77], also relevant text from the Synthesis report[78]. The report of the IPCC Expert Meeting on Geoengineering[79] was available to CBD (2012); information from that was subsequently included in the AR5 WG reports. In addition, other overview reports on both CDR and SRM geoengineering research are briefly considered here, excluding those that are concerned with only one of those main approaches (covered instead in Chapters 3 and 4).

38. The main content of the IPCC AR5 reports provides a wealth of information on changes to the climate system and its feedbacks with the biosphere and human society. As already noted (section 1.5), there is no attempt here to review our understanding of climate change nor its implications for biodiversity. Attention is, however, drawn to four publications that synthesize relevant climate change research since the cut-off dates (March, August and October 2013) for literature to be considered for inclusion in the three AR5 Working Group reports. As follows:

- The report on the Structured Expert Dialogue process under the UNFCCC, post AR5[80]
- A post-AR5 literature review on observed and predicted impacts of climate change on ocean processes[81]
- A review of recent research on climate instabilities[82]
- A review of recent research on climate impacts[83].

39. The current update focuses on scientific information published in the three years since CBD's previous report on climate geoengineering (CBD, 2012). It therefore takes account of relevant literature that was not available to the IPCC Working Groups, estimated at ~200 peer-reviewed papers, reports and other publications (~40% of the total considered here; excluding those included in the additional socioeconomic bibliography, Annex 1). Relevant post-IPCC AR5 literature includes three CBD publications:

- Global Biodiversity Outlook 4, an overview of biodiversity status and pressures[84]
- CBD Technical Series No. 78, on progress towards the Aichi Biodiversity Targets[85]
- CBD Technical Series No. 75, on the impacts of ocean acidification on marine biodiversity[86].

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[75] IPCC (Intergovernmental Panel on Climate Change) (2013)

[76] IPCC (Intergovernmental Panel on Climate Change) (2014a)

[77] IPCC (Intergovernmental Panel on Climate Change) (2014b)

[78] IPCC (Intergovernmental Panel on Climate Change) (2014c)

[79] IPCC (Intergovernmental Panel on Climate Change) (2012)

[80] UNFCCC (United Nations Framework Convention on Climate Change) (2015)

[81] Howes EL, Joos F, Eakin CM & Gattuso J-P (2015)

[82] Good P, Lowe J, Ridley J, Bamber J et al. (2014)

[83] Warren R, Arnell N, Brown S, Kjellstrom T et al. (2014)

[84] CBD (Secretariat of the Convention on Biological Diversity) (2014a)

[85] CBD (Secretariat of the Convention on Biological Diversity) (2014b)

[86] CBD (Secretariat of the Convention on Biological Diversity) (2014c)

40. One important post-IPCC AR5 scientific development relating to climate change is that an apparent pause or hiatus in increasing surface temperatures[87,88] seems to have ended, with indications that 2015 will globally be the warmest year on record[89]. Furthermore, there was no slowing in the observed incidence of hot temperature extremes during the past decade[90].

41. An additional UN review process for the marine environment has been established: the Regular Process for Global Reporting and Assessment of the State of the Marine Environment, including Socioeconomic Aspects (‘Regular Process’). The summary of the First Global Integrated Marine Assessment, the first outcome of the Regular Process, was published[91] in September 2015; it considers the effects of climate change on the ocean including sea level rise, ocean acidification, circulation changes and deoxygenation.

2.2 FIFTH ASSESSMENT REPORT OF THE INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE

2.2.1 Overview of geoengineering in IPCC AR5

42. Geoengineering (both CDR and SRM) features in all four volumes of the IPCC Fifth Assessment Report, totalling ~5000 pages and comprising reports from Working Group I (Physical Sciences), Working Group II (Impacts, Adaptation and Vulnerability, Parts A and B), and Working Group III (Mitigation of Climate Change), together with a Synthesis Report. While text on geoengineering is widely scattered, effort is made below to identify all significant comments and conclusions, re-presenting key statements from the Summaries for Policymakers, Technical Summaries and the main body of the each report. The wider context of other material in the reports is, of course, also relevant.

43. An overall conclusion that may be drawn from the AR5 reports is that deployment of negative emission techniques, i.e. active removal of greenhouse gases from the atmosphere (hereafter CDR unless other greenhouse gases are also under consideration) is now regarded as an important component of mitigation, in addition to direct emission reductions, in order to keep within global temperature limits agreed under the UNFCCC, as exemplified by RCP 2.6. Bioenergy with carbon capture and storage (BECCS) is identified as the main CDR approach to assist with emission reductions in RCP 2.6 scenarios.

44. The WG III Report and Synthesis Report both recognize that there are major uncertainties relating to the large-scale use of BECCS (for all components), and that it is likely to have serious implications for land use and biodiversity. However, environmental issues were not assessed in any detail. For example, although relevant references were cited, there did not seem to be any quantitative information presented on the different model assumptions regarding the total area of land, nor for associated land-use changes, that would be required for bioenergy crops; furthermore, quantitative estimates of projected effects on food production, water availability and loss of natural habitat also seemed absent.

45. The re-presentations of IPCC text extracts below are relatively lengthy. Nevertheless, it is considered important to have as comprehensive view as possible of the most relevant IPCC AR5 comments and conclusions, particularly since geoengineering was not given significant attention in previous IPCC assessments.

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[87] Trenberth KE (2015)

[88] Rajaratnam B, Romano J, Tsiang M & Diffenbaugh NS (2015)

[89] NOAA/NCEI Global Summary Information, August 2015. http://www.ncdc.noaa.gov/sotc/summary-info/global/201508

[90] Seneviratne SI, Donat MG, Mueller B & Alexander LV (2014)

[91] http://www.un.org/ga/search/view_doc.asp?symbol=A/70/112

2.2.2 Working Group I: Physical Science

46. The **Summary for policymakers** in the IPCC WG I Report[92] includes the following overview paragraph on climate geoengineering, highlighting limitations and uncertainties (from Section E.8, Climate Stabilization, Climate Change Commitment and Irreversibility, p 29):

> "Methods that aim to deliberately alter the climate system to counter climate change, termed geoengineering, have been proposed. Limited evidence precludes a comprehensive quantitative assessment of both Solar Radiation Management (SRM) and Carbon Dioxide Removal (CDR) and their impact on the climate system. CDR methods have biogeochemical and technological limitations to their potential on a global scale. There is insufficient knowledge to quantify how much CO_2 emissions could be partially offset by CDR on a century timescale. Modelling indicates that SRM methods, if realizable, have the potential to substantially offset a global temperature rise, but they would also modify the global water cycle, and would not reduce ocean acidification. If SRM were terminated for any reason, there is high confidence that global surface temperatures would rise very rapidly to values consistent with the greenhouse gas forcing. CDR and SRM methods carry side effects and long-term consequences on a global scale."

47. The WG1 **Technical Summary** includes Box TS.7, Climate Geoengineering Methods (p.98), that provides a definition of geoengineering, and summary descriptions of the main approaches:

> "Geoengineering is defined as the deliberate large-scale intervention in the Earth system to counter undesirable impacts of climate change on the planet. Carbon Dioxide Reduction (CDR) aims to slow or perhaps reverse projected increases in the future atmospheric CO_2 concentrations, accelerating the natural removal of atmospheric CO_2 and increasing the storage of carbon in land, ocean and geological reservoirs. Solar Radiation Management (SRM) aims to counter the warming associated with increasing GHG [greenhouse gas] concentrations by reducing the amount of sunlight absorbed by the climate system. A related technique seeks to deliberately decrease the greenhouse effect in the climate system by altering high-level cloudiness."

48. Note that the above definition/description differs slightly from that given in the WGI, WGIII and Synthesis Report glossaries (see below). Box TS.7 also states that: CDR would *likely* need to be deployed at large scale and over at least one century to be able to significantly reduce CO_2 concentrations; it is *virtually certain* that CO_2 removals from the atmosphere by CDR would be partially offset by outgassing of CO_2 previously stored in ocean and terrestrial carbon reservoirs; there is *low confidence* on the effectiveness of CDR methods and their side effects on carbon and other biogeochemical cycles; there is *medium confidence* that SRM through stratospheric aerosol injection is scalable to counter the radiative forcing and some of the climate effects expected from a doubling of atmospheric CO_2 concentration; and there is *high confidence* that if SRM were to be terminated, surface temperatures would increase within a decade or two to values consistent with the greenhouse gas forcing.

49. Information on the IPCC confidence and likelihood terminology used above and subsequently (in italics) is given here as Table 2.1. Details from those parts of the WG1 chapters that consider geoengineering are provided below, but are almost certainly not fully comprehensive.

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[92] IPCC (Intergovernmental Panel on Climate Change) (2013)

Table 2.1 Uncertainty treatment from text and tables in IPCC AR5 (WG I)[93]. 'Confidence' is distinct from statistical confidence, and calibrates IPCC Working Group judgement at five levels according to combinations of evidence and agreement. 'Likelihood' is a probabilistic estimate of the occurrence of a particular outcome.

Confidence		Likelihood	
Very high	High agreement, robust evidence	Virtually certain	99-100% probability
High	High agreement, medium evidence, *or* medium agreement, robust evidence	Very likely	90-100% probability
		Likely	66-100% probability
Medium	High agreement, limited evidence, *or* low agreement, robust evidence, *or* medium agreement, medium evidence	About as likely as not	33-66% probability
		Unlikely	10-33% probability
Low	Medium agreement, limited evidence, *or* low agreement, medium evidence	Very unlikely	1-10% probability
Very low	Low agreement, limited evidence	Exceptionally unlikely	0-1% probability

50. **Chapter 6**, Carbon and other Biogeochemical Cycles, in the WG I Report includes two paragraphs in its Executive Summary on Geoengineering Methods and the Carbon Cycle (p 469) and additional detail, mostly on CDR, in section 6.5, Potential effects of Carbon Dioxide Removal Methods and Solar Radiation Management on the Carbon Cycle (p 546-552). The Executive Summary paragraphs closely match the information in the Summary for Policymakers, already given above. Other issues of relevance to CBD interests in Chapter 6 include the following considerations:

- The permanence (or non-permanence) of carbon storage for CDR is a key consideration[94,95]. Some methods, particularly biological ones, only achieve temporary sequestration, re-releasing CO_2 to the atmosphere – although they may still have value in slowing temperature increase[96].
- The removal of (say) 100 Gt CO_2 from the atmosphere does not necessarily reduce the atmospheric total by that amount, since there will be compensatory releases from natural reservoirs. Equivalent processes operate in the opposite direction on anthropogenic emissions (only ~45% of released CO_2 remains in the atmosphere).
- Widespread implementation of CDR is already in-built within models that achieve RCP 2.6; furthermore, "RCP 4.5 also assumes some use of BECCS to stabilize CO_2 concentrations by 2100". Thus CDR "cannot be seen as additional potential for CO_2 removal from the low RCPs as this is already included in those scenarios".
- As a consequence of thermal inertia, climate warming will continue for several decades after CDR is applied. If a reduction in atmospheric CO_2 is achieved (as envisaged in RCP 2.6), "the global hydrological cycle could intensify in response"[97,98] [*The papers cited indicate that the climate system would show hysteresis – non-exact reversibility – if CO_2 reduction were to occur, due to heat previously accumulated in the ocean. While the models indicate an increase in mean global rainfall under such conditions, high spatial variability is likely. In particular, drying is projected for some tropical and sub-tropical regions*][99].

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93 IPCC (Intergovernmental Panel on Climate Change) (2013)

94 Kirschbaum MUF (2003)

95 Herzog`H, Caldeira K & Reilly J (2003)

96 Dornburg V & Marland G (2008)

97 Wu PL, Wood R, Ridley J & Lowe J (2010)

98 Cao L, Bala G, & Caldeira K (2011)

99 Text here in brackets/italics is additional information from IPCC-cited references; it may not necessarily be directly stated in the IPCC Report.

- SRM could affect the carbon cycle by reducing the effects of temperature increase on carbon sinks [*reducing biospheric feedbacks that release further greenhouse gases in a warmer world*].

51. Technique-specific aspects of CDR methods are also discussed in WG I Chapter 6, and estimates of the maximum (idealized) potential for CO_2 removal are summarized in Table 6.15 of that report. However, it is noted in para 6.5.5 that "unrealistic assumptions about the scale of deployment are used… and hence large potentials are simulated".

52. **Chapter 7**, Clouds and Aerosols, in the WG I Report includes two paragraphs in its Executive Summary on Geoengineering Using Solar Radiation Management Methods and the Carbon Cycle (p 574-575) and additional detail in section 7.7, Solar Radiation Management and Related Methods (p 627- 635), including FAQ 7.3: Could Geoengineering Counteract Climate Change and What Side Effects Might Occur? (p 632-634; covers both CDR and SRM). The Executive Summary paragraphs closely match the information in the Summary for policymakers, already given above. Other issues of relevance to CBD interests within Chapter 7 include the following:

- The radiative forcing (RF) from stratospheric aerosols that might be used for SRM is a function of many factors, including chemical species, and location, rate and frequency of injection. Models that fully account for aerosol processes produce less RF per unit mass[100], also more rapid sedimentation.
- Evidence on the effectiveness of cloud brightening methods is ambiguous, subject to many of the uncertainties affecting aerosol-cloud interactions more broadly.
- SRM would provide an inexact compensation for the effects of greenhouse gases, both spatially and temporally; for example, it will only change heating rates during daytime, while greenhouse gases cause warming both day and night. Hydrological responses may show significant regional variability.
- SRM would have to be maintained for very long periods (potentially thousands of years) if atmospheric CO_2 levels are not also constrained or actively decreased; if it were to be discontinued, very rapid warming would result.
- Models consistently suggest that SRM would generally reduce climate differences compared to a world with elevated greenhouse gas concentrations and no SRM; however, there would also be residual regional differences in climate when compared to a climate without high greenhouse gases.

2.2.3 Working Group II: Impacts, Adaptation and Vulnerability

53. There is no mention of geoengineering in the Summary for Policymakers of the IPCC WG II Report[101]. However the WG II **Technical Summary** includes a paragraph on the topic in sub-section C-2, Climate Resilient Pathways and Transformation, of Section C, Managing Future Risks (p 91):

> "Geoengineering approaches involving manipulation of the ocean to ameliorate climate change (such as nutrient fertilization, binding of CO_2 by enhanced alkalinity, or direct CO_2 injection into the deep ocean) have very large environmental and associated socioeconomic consequences (*high confidence*). Alternative methods focusing on solar radiation management (SRM) leave ocean acidification unabated as they cannot mitigate rising atmospheric CO_2 emissions".

54. **Chapter 6** of the WG II Report, Ocean Systems, considers the impacts and effectiveness of ocean fertilization and other ocean-based CDR geoengineering methods under the heading 6.4.2.2, Geoengineering Approaches (p. 454) within the section and sub-section headings of Human Activities in Marine Ecosystems: Adaptation Benefits and Threats, and Management-related Adaptations and Risks. The following assessments are made:

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[100] English JT, Toon OB & Mills MJ (2012)

[101] IPCC (Intergovernmental Panel on Climate Change) (2014a)

- Any regional increase in organic material (through fertilization or intentional storage of biomass) would cause enhanced O_2 demand and deep-water O_2 depletion, increasing the level and extent of hypoxia and associated impacts on marine ecosystems. The synergistic effects of CO_2-induced acidification will exacerbate the biological impacts (*high confidence*).

- Direct injection of CO_2 or its localized disposal in the ocean (e.g., as a lake in a deep-sea valley) causes locally highly increased CO_2 and acidification effects on deep sea organisms (*high confidence*). In contrast to long-term ocean fertilization or storage of biomass, this technique leaves the oxygen inventory of the deep ocean untouched (*limited evidence*, *medium agreement*).

- The knowledge base on the implementation of SRM and CDR techniques and associated risks is presently insufficient. Comparative assessments suggest that the main ocean-related geoengineering approaches are very costly and have large environmental footprints (*high confidence).*

55. **Chapter 19** of the WG II Report, Emergent Risks and Key Vulnerabilities, includes sub-section 19.5.4, Risks from Geoengineering (Solar Radiation Management) (p. 1065) under the section on Newly Assessed Risks. It notes that current knowledge on SRM is limited and our confidence in related conclusions is therefore *low.* Governance-related issues are also discussed:

> "There is also a risk of "moral hazard"; if society thinks geoengineering will solve the global warming problem, there may be less attention given to mitigation[102]. In addition, without global agreements on how and how much geoengineering to use, SRM presents a risk for international conflict[103]. Because the direct costs of stratospheric SRM have been estimated to be in the tens of billions of U.S. dollars per year[104,105], it could be undertaken by non-state actors or by small states acting on their own[106], potentially contributing to global or regional conflict[107,108]. Based on magnitude of consequences and exposure of societies with limited ability to cope, geoengineering poses a potential key risk".

2.2.4 Working Group III: Mitigation of Climate Change

56. The **Summary for Policymakers** of the IPCC WG III Report[109] discusses bioenergy with carbon capture and storage (BECCS) and/or CDR geoengineering in five paragraphs in section SPM 4, Mitigation Pathways and Measures in the Context of Sustainable Development. Two relevant paragraphs are in sub-section SPM 4.1, Long-term Mitigation Pathways (p 10-12):

> "**Scenarios reaching atmospheric concentration levels of about 450 ppm CO_2eq by 2100 (consistent with a *likely* chance to keep temperature change below 2°C relative to pre-industrial levels) include substantial cuts in anthropogenic GHG** [greenhouse gas] **emissions by mid-century through large-scale changes in energy systems and potentially land use** (*high confidence*). Scenarios reaching these concentrations by 2100 are characterized by lower global GHG emissions in 2050 than in 2010, 40% to 70% lower globally, and emissions levels near zero $GtCO_2$eq or below in 2100. In scenarios reaching 500 ppm CO_2eq by 2100, 2050 emissions levels are 25% to 55% lower than in 2010 globally. In scenarios reaching 550 ppm CO_2eq, emissions in 2050 are from 5% above 2010 levels to 45% below 2010 levels globally (Table SPM.1). At the global level, scenarios reaching 450 ppm CO_2eq are also characterized by

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[102] Lin A (2013)

[103] BrzoskaM, Link PM, Maas A &. Scheffran J (2012)

[104] Robock A, Marquardt A, Kravitz B & Stenchikov G (2009)

[105] McClellan J, Keith DW & Apt J (2012)

[106] Lloyd ID & Oppenheimer M (2014)

[107] Robock A (2008a)

[108] Robock A (2008b)

[109] IPCC (Intergovernmental Panel on Climate Change) (2014b)

> more rapid improvements of energy efficiency, a tripling to nearly a quadrupling of the share of zero- and low-carbon energy supply from renewables, nuclear energy and fossil energy with carbon dioxide capture and storage (CCS), or bioenergy with CCS (BECCS) by the year 2050 (Figure SPM.4, lower panel). These scenarios describe a wide range of changes in land use, reflecting different assumptions about the scale of bioenergy production, afforestation, and reduced deforestation. All of these emissions, energy, and land-use changes vary across regions. Scenarios reaching higher concentrations include similar changes, but on a slower timescale. On the other hand, scenarios reaching lower concentrations require these changes on a faster timescale."
>
> **"Mitigation scenarios reaching about 450 ppm CO_2eq in 2100 typically involve temporary overshoot of atmospheric concentrations, as do many scenarios reaching about 500 ppm to 550 ppm CO_2eq in 2100. Depending on the level of the overshoot, overshoot scenarios typically rely on the availability and widespread deployment of BECCS and afforestation in the second half of the century. The availability and scale of these and other Carbon Dioxide Removal (CDR) technologies and methods are uncertain and CDR technologies and methods are, to varying degrees, associated with challenges and risks (see Section SPM 4.2)** (*high confidence*)**.** CDR is also prevalent in many scenarios without overshoot to compensate for residual emissions from sectors where mitigation is more expensive. There is only *limited evidence* on the potential for large-scale deployment of BECCS, large-scale afforestation, and other CDR technologies and methods."

57. SPM sub-section 4.2, Sectoral and Cross-sectoral Mitigation Pathways and Measures, includes the following three paragraphs under headings 4.2.1, Cross-sectoral Mitigation Pathways and Measures (p 18); 4.2.2, Energy Supply (p.21); and 4.2.4, Agriculture, Forestry and other Land Use (AFOLU) (p 25):

> **"There are strong interdependencies in mitigation scenarios between the pace of introducing mitigation measures in energy supply and energy end-use and developments in the AFOLU** [agriculture, forestry and other land use] **sector** (*high confidence*)**.** The distribution of the mitigation effort across sectors is strongly influenced by the availability and performance of BECCS and large scale afforestation (Figure SPM.7). This is particularly the case in scenarios reaching CO_2eq concentrations of about 450 ppm by 2100. Well-designed systemic and cross-sectoral mitigation strategies are more cost-effective in cutting emissions than a focus on individual technologies and sectors. At the energy system level these include reductions in the GHG emission intensity of the energy supply sector, a switch to low-carbon energy carriers (including low-carbon electricity) and reductions in energy demand in the end-use sectors without compromising development (Figure SPM.8)."
>
> **"Combining bioenergy with CCS (BECCS) offers the prospect of energy supply with large-scale net negative emissions which plays an important role in many low-stabilization scenarios, while it entails challenges and risks** (*limited evidence, medium agreement*)**.** These challenges and risks include those associated with the upstream large-scale provision of the biomass that is used in the CCS facility as well as those associated with the CCS technology itself."
>
> **"Bioenergy can play a critical role for mitigation, but there are issues to consider, such as the sustainability of practices and the efficiency of bioenergy systems** (*robust evidence, medium agreement*)**.** Barriers to large-scale deployment of bioenergy include concerns about GHG emissions from land, food security, water resources, biodiversity conservation and livelihoods. The scientific debate about the overall climate impact related to land-use competition effects of specific bioenergy pathways remains unresolved (*robust evidence, high agreement*). Bioenergy technologies are diverse and span a wide range of options and technology pathways. Evidence suggests that options with low lifecycle emissions (e. g., sugar cane, fast growing tree species, and sustainable use of biomass residues), some already available, can reduce GHG emissions; outcomes are site-specific and rely on efficient integrated 'biomass-to-bioenergy systems', and sustainable land-use management and governance. In some regions, specific bioenergy options, such as improved cook-stoves, and small-scale biogas and biopower production, could reduce

> GHG emissions and improve livelihoods and health in the context of sustainable development (*medium evidence, medium agreement*)."

58. The **Technical Summary** of the IPCC WG III Report discusses geoengineering and/or BECCS in two paragraphs under headings TS 3.1, Mitigation Pathways, and TS 3.1.3, Costs, Investment and Burden Sharing (p 60-61); also in one paragraph of headings TS 3.2, Sectoral and Cross-Sectoral Mitigation Measures, and TS 3.2.2, Energy Supply (p 69). As follows:

> **"Geoengineering denotes two clusters of technologies that are quite distinct: carbon dioxide removal (CDR) and solar radiation management (SRM). Mitigation scenarios assessed in AR5 do not assume any geoengineering options beyond large-scale CDR due to afforestation and BECCS.** CDR techniques include afforestation, using bioenergy along with CCS (BECCS), and enhancing uptake of CO_2 by the oceans through iron fertilization or increasing alkalinity. Most terrestrial CDR techniques would require large-scale land-use changes and could involve local and regional risks, while maritime CDR may involve significant transboundary risks for ocean ecosystems, so that its deployment could pose additional challenges for cooperation between countries. With currently known technologies, CDR could not be deployed quickly on a large scale. SRM includes various technologies to offset crudely some of the climatic effects of the build-up of GHGs in the atmosphere. It works by adjusting the planet's heat balance through a small increase in the reflection of incoming sunlight such as by injecting particles or aerosol precursors in the upper atmosphere. SRM has attracted considerable attention, mainly because of the potential for rapid deployment in case of climate emergency. The suggestion that deployment costs for individual technologies could potentially be low could result in new challenges for international cooperation because nations may be tempted to prematurely deploy unilaterally systems that are perceived to be inexpensive. Consequently, SRM technologies raise questions about costs, risks, governance, and ethical implications of developing and deploying SRM, with special challenges emerging for international institutions, norms and other mechanisms that could coordinate research and restrain testing and deployment."

> **"Knowledge about the possible beneficial or harmful effects of SRM is highly preliminary.** SRM would have varying impacts on regional climate variables such as temperature and precipitation, and might result in substantial changes in the global hydrological cycle with uncertain regional effects, for example on monsoon precipitation. Non-climate effects could include possible depletion of stratospheric ozone by stratospheric aerosol injections. A few studies have begun to examine climate and non-climate impacts of SRM, but there is very little agreement in the scientific community on the results or on whether the lack of knowledge requires additional research or eventually field testing of SRM-related technologies."

> **"Combining bioenergy with CCS (BECCS) offers the prospect of energy supply with large-scale net negative emissions, which plays an important role in many low-stabilization scenarios, while it entails challenges and risks** (*limited evidence, medium agreement*). Until 2050, bottom-up studies estimate the economic potential to be between 2 – 10 $GtCO_2$ per year. Some mitigation scenarios show higher deployment of BECCS towards the end of the century. Technological challenges and risks include those associated with the upstream provision of the biomass that is used in the CCS facility, as well as those associated with the CCS technology itself. Currently, no large-scale projects have been financed."

59. Elsewhere in the WG III Technical Summary there is discussion of the value judgements involved in mitigation decisions (Boxes TS.1 and TS.5), and mitigation costs and benefits (Boxes TS.2 and TS.11). Biodiversity gets a mention in Box TS.11 (p 64):

> "Mitigation can have many potential co-benefits and adverse side-effects, which makes comprehensive analysis difficult. The direct benefits of climate policy include, for example, intended effects on global mean surface temperature, sea level rise, agricultural productivity, biodiversity, and health effects of global warming [WGII TS]. The co-benefits and adverse side-effects of climate policy could include effects on a partly overlapping set of objectives such as local air pollutant emissions reductions and related health

> and ecosystem impacts, biodiversity conservation, water availability, energy and food security, energy access, income distribution, efficiency of the taxation system, labour supply and employment, urban sprawl, and the sustainability of the growth of developing countries."

60. **Chapter 6** of the WG III Report, Assessing Transformation Pathways, discusses effects of mitigation on biodiversity under headings 6.6.2, Transformation Pathway Studies with Links to other Policy Objectives, and 6.6.2.5, Biodiversity Conservation (p 476), noting that:

> "The primary biodiversity-related side-effects from mitigation involve the potentially large role of reforestation and afforestation efforts and of bioenergy production. These elements of mitigation strategy could either impose risks or lead to co-benefits, depending on where and how they are implemented. The integrated modelling literature does not at this time provide an explicit enough treatment of these issues to effectively capture the range of transformation pathways. One study[110] suggests that it is possible to stabilize average global biodiversity at the 2020 - 2030 level by 2050 even if land-use mitigation measures are deployed. Such an achievement represents more than a halving of all biodiversity loss projected to occur by mid-century in the baseline scenario and is interpreted to be in accordance with the Aichi Biodiversity Targets[111] (CBD, 2010). Of critical importance in this regard are favourable institutional and policy mechanisms for reforestation / afforestation and bioenergy that complement mitigation actions."

61. Aspects of both CDR and SRM are covered in section 6.9, Carbon and Radiation Management and other Geo-engineering Options including Environmental Risks (p 484-489). While many issues have already been covered above, the following specific information and conclusions are noteworthy:

- Estimates of the global CDR potential for BECCS vary from 3 to > 10 $GtCO_2$ /yr[112,113,114], with initial cost estimates also varying greatly, from 60 - 250 USD/tCO_2[115]. Important limiting factors for BECCS include land availability, a sustainable supply of biomass, and storage capacity[116].
- Carbon dioxide captured through CCS, BECCS, and DAC [direct air capture] are all intended to use the same storage reservoirs (in particular deep geologic reservoirs), potentially limiting their combined use under a transition pathway.
- Few papers have assessed the role of DAC in mitigation scenarios[117,118,119]. These studies show that the contribution of DAC critically depends on the stringency of the concentration goal, the costs relative to other mitigation technologies, time discounting, and assumptions about scalability. In modelling studies to date, the influence of DAC on the mitigation pathways is similar to that of BECCS (assuming similar costs): thus it leads to a delay in short-term emission reduction in favour of further reductions later in the century. Other techniques are even less mature and currently not evaluated in integrated models.
- The potentials for BECCS, afforestation, and DAC are constrained on the basis of available land and/ or safe geologic storage potential for CO_2. Both the potential for sustainable bio-energy use (including competition with other demands, e. g., food, fibre, and fuel production) and the potential to store >100 GtC of CO_2 per decade for many decades are very uncertain and raise important societal concerns.

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[110] PBL (Netherlands Environmental Assessment Agency) (2012)

[111] CBD (Convention on Biological Diversity (2010)

[112] Koornneef J et al. (2012)

[113] McLaren D (2012)

[114] Van Vuuren DP, Deetman S, van Vliet J, van den Berg M et al (2013)

[115] McGlashan N, Shah N, Caldecott B & Workman M (2012)

[116] Gough C & Upham P (2011)

[117] Pielke Jr RA (2009)

[118] Nemet GF & Brandt A R (2012)

[119] Chen C & Tavoni M (2013)

- Pathways that assume future large-scale availability of CDR shift the mitigation burden in time, and could therefore exacerbate inter-generational impacts.

62. WG III **Chapter 11** covers Agriculture, Forestry and Other Land Use (AFOLU). The mitigation potential of biochar is summarized in Box 11.3 (p 833) and that of bioenergy in Box 11.5 (p 835). The latter includes the following text on constraints, including land availability and implications for biodiversity:

> "Land demand and livelihoods are often affected by bioenergy deployment. Land demand for bioenergy depends on (1) the share of bioenergy derived from wastes and residues; (2) the extent to which bioenergy production can be integrated with food and fibre production, and conservation to minimize land-use competition; (3) the extent to which bioenergy can be grown on areas with little current production; and (4) the quantity of dedicated energy crops and their yields. Considerations of trade-offs with water, land, and biodiversity are crucial to avoid adverse effects. The total impact on livelihood and distributional consequences depends on global market factors, impacting income and income-related food security, and site-specific factors such as land tenure and social dimensions. The often site-specific effects of bioenergy deployment on livelihoods have not yet been comprehensively evaluated."

63. Further discussion of bioenergy is given in section 11.13, an Appendix on Bioenergy: Climate Effects, Mitigation Options, Potential and Sustainability Implications. Sub-section 11.13.7, Tradeoffs and Synergies with Land, Water Food and Biodiversity, includes the text:

> "A model comparison study with five global economic models shows that the aggregate food price effect of large-scale lignocellulosic bioenergy deployment (100 EJ globally by the year 2050) is significantly lower (+5% on average across models) than the potential price effects induced by climate impacts on crop yields (+25% on average across models[120]. Possibly hence, ambitious climate change mitigation need not drive up global food prices much, if the extra land required for bioenergy production is accessible or if the feedstock, e.g., from forests, does not directly compete for agricultural land. Effective land-use planning and strict adherence to sustainability criteria need to be integrated into large-scale bioenergy projects to minimize competitions for water (for example, by excluding the establishment of biofuel projects in irrigated areas). If bioenergy is not managed properly, additional land demand and associated LUC [land use change] may put pressures on biodiversity[121]. However, implementing appropriate management, such as establishing bioenergy crops in degraded areas represents an opportunity where bioenergy can be used to achieve positive environmental outcomes[122]."

2.2.5 Synthesis Report

64. The **Summary for Policymakers** of the AR5 Synthesis Report[123] does not specifically mention geoengineering. However, following extensive discussion of the need for mitigation, it is made clear in section SPM 3.4, Characteristics of Mitigation Pathways, that CDR is very likely to be necessary to meet agreed upper limits for climate change, either in terms of atmospheric CO_2 or global mean temperature rise.

65. The 'main message' from SPM 3.4 states:

> "There are multiple mitigation pathways that are likely to limit warming to below 2°C relative to pre-industrial levels. These pathways would require substantial emissions reductions over the next few decades and near zero emissions of CO_2 and other long-lived greenhouse gases by the end of the century. Implementing such reductions poses substantial technological, economic, social and institutional

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[120] Lotze-Campen H, von Lamp M, Kyle P, Fujimori S et al. (2013)

[121] Groom M, Gray E & Townsend P (2008)

[122] Nijsen M, Smeets E, Stehfest E & Vuuren DP (2012)

[123] IPCC (Intergovernmental Panel on Climate Change) (2014c)

> challenges, which increase with delays in additional mitigation and if key technologies are not available. Limiting warming to lower or higher levels involves similar challenges but on different timescales." [p 20]

66. Subsequent text includes:

> "Mitigation scenarios reaching about 450 ppm CO_2-eq in 2100 (consistent with a likely chance to keep warming below 2°C relative to pre-industrial levels) typically involve temporary overshoot* of atmospheric concentrations, as do many scenarios reaching about 500 ppm CO_2-eq to about 550 ppm CO_2-eq in 2100 (Table SPM.1). Depending on the level of overshoot, overshoot scenarios typically rely on the availability and widespread deployment of bioenergy with carbon dioxide capture and storage (BECCS) and afforestation in the second half of the century. The availability and scale of these and other CDR technologies and methods are uncertain and CDR technologies are, to varying degrees, associated with challenges and risks**. CDR is also prevalent in many scenarios without overshoot to compensate for residual emissions from sectors where mitigation is more expensive (*high confidence*)." [p 23]
>
> * In concentration 'overshoot' scenarios, concentrations peak during the century and then decline.
>
> ** CDR methods have biogeochemical and technological limitations to their potential on the global scale. There is insufficient knowledge to quantify how much CO_2 emissions could be partially offset by CDR on a century timescale. CDR methods may carry side effects and long-term consequences on a global scale.
>
> "In the absence or under limited availability of mitigation technologies (such as bioenergy, CCS and their combination BECCS, nuclear, wind/solar), mitigation costs can increase substantially depending on the technology considered. Delaying additional mitigation increases mitigation costs in the medium to long term. Many models could not limit likely warming to below 2°C over the 21st century relative to pre-industrial levels if additional mitigation is considerably delayed. Many models could not limit likely warming to below 2°C if bioenergy, CCS and their combination (BECCS) are limited (*high confidence*) [Table SPM.2]." [p 24].

67. Similar statements regarding the need for BECCS are made in section SPM 4.3, Response Options for Mitigation, that includes the following text:

> "In the majority of low-concentration stabilization scenarios (about 450 to about 500 ppm CO_2-eq, at least about as likely as not to limit warming to 2°C above pre-industrial levels), the share of low-carbon electricity supply (comprising renewable energy (RE), nuclear and carbon dioxide capture and storage (CCS) including bioenergy with carbon dioxide capture and storage (BECCS)) increases from the current share of approximately 30% to more than 80% by 2050, and fossil fuel power generation without CCS is phased out almost entirely by 2100."

The above conclusion is re-iterated in the legend to Figure SPM.14.

68. The **main text of the Synthesis Report** includes Box 3.3, Carbon Dioxide Removal and Solar Radiation Management Geoengineering Technologies – Possible Roles, Options, Risks and Status (p 89). The main messages (bold text) in Box 3.3 are as follows:

- CDR plays a major role in many mitigation scenarios
- Several CDR techniques could potentially reduce atmospheric greenhouse gas (GHG) levels. However, there are biogeochemical, technical and societal limitations that to, varying degrees, make it difficult to provide quantitative estimates of the potential for CDR
- SRM is untested, and is not included in any of the mitigation scenarios, but, if realizable, could to some degree offset global temperature rise and some of its effects. It could possibly provide rapid cooling in comparison to CO_2 mitigation.
- If it were deployed, SRM would entail numerous uncertainties, side effects, risks and shortcomings.

- SRM technologies raise questions about costs, risks, governance and ethical implications of development and deployment. There are special challenges emerging for international institutions and mechanisms that could coordinate research and possibly restrain testing and deployment.

69. In addition, the main text of the Synthesis Report includes the following comments and conclusions that would seem relevant:

- Effective mitigation will not be achieved if individual agents advance their own interests independently: outcomes seen as equitable can lead to more effective cooperation. [Section 3.1; Foundations of Decision Making about Climate Change]
- Mitigation involves some level of co-benefits and risks, but these risks do not involve the same possibility of severe, widespread and irreversible impacts as risks from climate change (*high confidence*). [Section 3.2; Climate Change Risks reduced by Adaptive Mitigation]
- Increasing efforts to mitigate and adapt to climate change imply an increasing complexity of interactions, encompassing connections among human health, water, energy, land use and biodiversity (*very high confidence*). [Section 4.5; Trade-offs, Synergies and Integrated Response]
- Explicit consideration of interactions among water, food, energy and biological carbon sequestration plays an important role in supporting effective decisions for climate resilient pathways (*medium evidence, high agreement*). [Section 4.5; Trade-offs, Synergies and Integrated Response].

2.3 REPORTS BY US NATIONAL ACADEMY OF SCIENCES/NATIONAL RESEARCH COUNCIL

2.3.1 Overview of NAS/NRC reports

70. Two closely-linked US reports on climate geoengineering were published[124,125] in early 2015, authored by a study panel of the National Research Council. Since many of the issues raised regarding technique-specific considerations are discussed in Chapters 3 and 4 of this report, attention here is focused on key points from the Summary section (shared by both NAS/NRC reports) and also the report-specific recommendations.

71. As already noted (Section 1.3), the NAS/NRC reports use the term ‘climate interventions’ rather than geoengineering. They also: i) consider ‘CDR with reliable sequestration’ to be the greenhouse gas removal approach, preferring ‘sequestration’ to ‘storage’; ii) use ‘albedo modification’ and ‘sunlight reflection’ as the preferred terms for solar radiation management; and iii) seem to limit ‘mitigation’ to emission reductions, rather than extending its meaning to CDR (in contrast to IPCC).

72. The Summary to the NAS/NRC reports includes a comparison between CDR and SRM approaches, emphasizing their differences, and re-presented here as Table 2.1. Although generally helpful, there are over-simplifications involved, as recognized in the table legend.

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[124] NRC (National Research Council) (2015a)

[125] NRC (National Research Council) (2015b)

Table 2.1. Overview of differences between carbon dioxide removal (CDR) and albedo modification proposals, as included in both NAS/NRC reports[126,127]. GHG, greenhouse gases (of natural or anthropogenic origin). Original table legend included the proviso: "each statement may not be true of some proposals within each category".

Carbon Dioxide Removal proposals…	**Albedo Modification proposals…**
… address the cause of human-induced climate change (high atmospheric GHG concentrations)	… do not address cause of human-induced climate change (high atmospheric GHG concentrations)
… do not introduce novel risks	… introduce novel risks
… are currently expensive (or comparable to the cost of emission reduction)	… are inexpensive to deploy (relative to cost of emission reduction)
… may produce only modest climate effects within decades	… can produce substantial climate effects within years
… raise fewer and less difficult issues with respect to global governance	… raise difficult issue with respect to global governance
… will be judged largely on issues relating to cost	… will be judged largely on questions related to risk
… may be implemented incrementally with limited effects as society becomes more serious about reducing GHG concentrations or slowing their growth	… could be implemented suddenly, with large-scale impacts before enough research is available to understand their risks relative to inaction
… require cooperation by major carbon emitters to have a significant effect	… could be done unilaterally
… for likely future emission scenarios, abrupt termination would have limited consequences	… for likely emissions scenarios, abrupt termination would produce significant consequences

73. While the reports consider CDR approaches to be less problematic than SRM, they also make clear that more conventional means of addressing climate change (i.e. emission reduction) are preferred. Thus it is less risky environmentally to avoid a given CO_2 emission than to expect that it will be purposefully removed, or otherwise counter-acted, at a later time. That view is formally stated in ***NAS/NRC Recommendation 1:*** *Efforts to address climate change should continue to focus most heavily on mitigating*[128] *greenhouse gas emissions in combination with adapting to the impacts of climate change because these approaches do not present poorly defined and poorly quantified risks and are at a greater state of technological readiness*.

2.3.2 NAS/NRC report on Carbon Dioxide Removal and Reliable Sequestration

74. The introductory text of this report points out that natural processes (photosynthesis on land and in the upper ocean) are already carrying out CDR on a global scale, although with relatively little[129] long-term sequestration. Thus there is an annual cycle in most parts of the world that involves a summertime decrease of ~5 ppm in atmospheric CO_2 in the northern hemisphere, seasonally over-riding anthropogenic emissions. That decrease is subsequently exceeded by a wintertime increase, due to the combined effects of natural processes (decomposition) and human activities. To reduce atmospheric levels by 100 ppm would require the long-term removal of ~1800 Gt CO_2, much the same as has been added by human activities from 1750 to 2000. In Table 2.2 of the NAS/NRC CDR report, limitations of different CDR techniques are identified. For bioenergy with carbon capture and storage, a key issue is that sequestration of 18 Gt CO_2/yr (i.e. annual reduction of ~1 ppm in atmospheric CO_2) is estimated to require

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[126] NRC (National Research Council) (2015a)

[127] NRC (National Research Council) (2015b)

[128] This Recommendation is ambiguous as to whether 'mitigating' includes negative emissions/CDR. Although not explicitly defined, other text in the report indicates that conventional mitigation, i.e. direct emission reduction, is intended.

[129] 'relatively little' relates to the scale of the natural uptake and release processes. Under stable climatic conditions, CO2 uptake and release would balance; however, there is currently net uptake due to the anthropogenic perturbation, and there are many geological precedents for uptake exceeding release or vice versa; e.g. during the Earth's natural ice age cycle of the past ~3 million years.

up to 1,000 million acres of arable land, compared to an estimated total of 1,500 million acres currently available. Such issues are discussed here in greater detail in Chapter 3.

75. Within the body of the NAS/NRC report, the following CDR techniques are considered:

- Land management
    - Afforestation and reforestation
    - Carbon sequestration on agricultural lands

  [Biochar: summary discussion only (Box 3.1), not considered in the NAC/NRC report as a CDR technique]
- Accelerated weathering methods and mineral carbonation
- Ocean fertilization
- Bioenergy with carbon capture and sequestration
- Direct air capture and sequestration

[Also discussion of potential for seawater CO_2 capture (Box 3.3)]

76. Summary tables are provided giving Committee evaluations (with high/ medium/low confidence) for four groupings of the above techniques (direct air capture; biological land-based; biological ocean-based; accelerated weathering land-based; accelerated weathering ocean-based) and a comparison with point-source capture with regard to the following 10 considerations, each on a high/medium/low scale:

- Technological readiness, speed to deployment, technical risk
- Time required to scale to maximum deployment with major effort (to capture ~ 1 Gt CO_2/yr)
- Effect per unit cost for pilot scale with currently available technology
- Maximum feasible deployment capture rate
- Verifiability: ability to confirm/quantify CO_2 capture
- Negative environmental consequences
- Environmental co-benefits
- Socio-political risks (including national security)
- Governance challenges for deployment at scale
- Risk of detrimental deployment from unilateral and uncoordinated actors.

77. A comparison of sequestration (carbon storage) approaches is also given, for 10 considerations. Concluding chapters cover Social Context and Way Forward, with the latter commenting that CDR deployment would be necessary to achieve climatic stability for IPCC scenarios that involve a 'temporary overshoot' in atmospheric CO_2 concentrations. Furthermore: "it is almost inevitable that some CDR will be needed long term to deal with residual emissions by non-participatory nations, or by sectors for which fossil fuel substitutes prove difficult to implement (e.g. aviation)[130]."

78. The need for further scientific study of CDR is strongly argued, with an associated action, as follows. ***NAS/ NRC recommendation 2:*** *The Committee recommends research and development investment to improve methods of carbon dioxide and removal at scales that matter, in particular to minimize energy and materials consumption, identify and quantify risks, lower costs, and develop reliable sequestration and monitoring.*

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[130] NRC (National Research Council) (2011)

2.3.2 NAS/NRC report on Reflecting Sunlight to Cool Earth

79. A short précis of this report is provided by an early section heading, "Albedo modification presents poorly understood risks"; the first sentence of that section: "Proposed albedo modification approaches introduce environmental, ethical, social, political, economic, and legal risks associated with intended and unintended consequences"; and the first recommendation (numbered in sequence with those in the CDR report): ***NAS/NRC recommendation 3:*** *Albedo modification at scales sufficient to alter climate should not be deployed at this time.*

80. Subsequent recommendations, and the main text, reflect that emphasis on risks and uncertainties. Nevertheless, they also consider that research is needed to improve knowledge that would be useful under several circumstances that are hypothetical but plausible. For example:

- A situation where, despite mitigation and adaptation, the impacts of climate change became intolerable (e.g. massive crop failures)
- A gradual phase-in might be internationally considered to a level expected to create detectable effects, to gain experience that might be considered necessary in response to potential scaling-up in a future climate emergency [*but see Sillmann et al (2015)*[131]*, here discussed further in Chapter 5*]
- If unsanctioned albedo modification were to occur, scientific research would be needed to understand how best to detect and quantify the act and its consequences and impacts.

81. Furthermore, scientific knowledge of the processes involved in albedo modification provides wider understanding of the climate system, and can therefore be considered as 'multiple benefit' research.

82. Two albedo modification strategies, both atmospheric-based, are considered in detail (stratospheric aerosols and marine cloud brightening); relatively little attention is given to 'other methods' (space-based methods, surface albedo, and cirrus cloud modification).

83. Governance and socio-political considerations are discussed in both a US and international context. The latter includes specific consideration of the role of the CBD, with the comment that "due to its hortatory language, Decision X/33 is generally not considered to be legally binding on Parties to the CBD". Other international agreements and bodies that are noted as relevant or potentially relevant include the United Nations Framework Convention on Climate Change (UNFCCC), the Vienna Convention, the Montreal Protocol, the Convention on Long-Range Transboundary Air Pollution (CLRTAP), the Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques (ENMOD), and the Outer Space Treaty.

84. The report recognized the need for a governance mechanism appropriate for research on some types of albedo modification techniques. Such a mechanism would need to be transparent, involve input from a broad range of stakeholders, and ensure that all dimensions are appropriately considered. The goal of the governance would be to ensure that the research helps society to understand the challenges and impacts of albedo modification while minimizing the risks associated with the research. Governance in this context is not considered synonymous with regulation.

85. Arising from the above considerations, three concluding recommendations are made:

> ***NAS/NRC recommendation 4:*** *The Committee recommends an albedo modification research programme be developed and implemented that emphasizes multiple benefit research that also furthers basic understanding of the climate system and its human dimensions.* Five specific areas for further attention are identified [Box 5.1, p 151 of the report. Specific areas include 'small field studies' to explore poorly-understood issues that affect the viability of candidate albedo modification strategies. These might include controlled emissions to the atmosphere].

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[131] Sillman J, Lenton TM, Levermann A, Ott K et al. (2015)

NAS/NRC recommendation 5: *The Committee recommends that the United States improve its capacity to detect and measure changes in radiative forcing and associated changes in climate.*

NAS/NRC recommendation 6: *The Committee recommends the initiative of a serious deliberative process to examine: (a) what types of research governance, beyond those that already exist, may be needed for albedo modification research, and (b) the types of research that would require such governance, potentially based on the magnitude of their expected impact on radiative forcing, their potential for detrimental direct and indirect effects, and other considerations.*

86. Three appendices to the report on albedo modification provide additional insights and information:

Planned Weather Modification (Appendix C). This text distinguishes the time scale, spatial scale and purpose of weather modification (including cloud seeding and reducing hurricane intensity) from climate intervention/geoengineering. US activities in the former area, their regulation, and their generally inconclusive results, are described.

Volcanic Eruptions as Analogues for Albedo Modification (Appendix D). While similar aspects of atmospheric chemistry and physics are involved, 'one off' volcanic eruptions are inexact analogies for engineered stratospheric aerosol injection, that would need to be maintained for decades to counteract global warming. Key differences include the mix of materials injected by volcanoes, and the short-term nature of their effects. Thus volcanic cooling of a year or two has much greater effect on land surface temperatures than those of the ocean; over longer time periods, that response would change, with implications for weather systems (e.g. monsoons) driven by land-sea thermal contrasts.

Discussion of Feasibility of Albedo Modification Technologies (Appendix E). Conceptual (or scientific feasibility) is distinguished from practical feasibility, although both aspects are important. A stepwise sequence for improving feasibility estimates is described.

2.4 OTHER RECENT RELEVANT REPORTS AND OVERVIEWS

2.4.1 UNEP Emissions Gap Report 2014

87. The 5th report in the "emissions gap" series was published[132] by the United Nations Environment Programme in November 2014. It gives particular attention to the constraints on future CO_2 emissions if global temperature increase is to stay within the 2°C limit, estimating that the maximum total CO_2 release from 2012 onwards is ~1000 Gt. On that basis, global carbon neutrality will need to be achieved between 2055 and 2070, and total global greenhouse gas emissions (including gases other than CO_2) need to shrink to net zero between 2080 and 2100. The role for CDR, considered as negative emissions, is discussed, noting that: i) there are many associated uncertainties and barriers to viability; and ii) the greater the delay in initially reducing emissions, the greater the subsequent dependence on negative emissions. However, scenarios were identified that showed[133,134] that it may be possible to meet internationally-agreed climate commitments (limiting temperature increase to +2°C) without BECCS, provided that all global regions participate in strong emissions reductions. [The 6th UNEP Emissions Gap report was published in November 2015. It is not considered here]

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[132] UNEP (United Nations Environment Programme) (2014)

[133] Riahi K, Dentener F, Gielen D, Grubler A et al. (2012)

[134] Edmonds J, Luckow P, Calvin K Wise M et al. (2013)

Box 2.1 Suggested rationale for, and concerns with, geoengineering research. Summary of Section 5.2 from EuTRACE report·

Rationale for research	Concerns
• **Information requirements for policy**. Research on geoengineering provides the specific information needed for sound climate change policy at national and international levels • **Knowledge provision**. Broader scientific knowledge is required for process-based understanding and wider discussions • **Deployment readiness**. If future environmental conditions dramatically worsen, then it would be advantageous to have one or more techniques that were near to 'deployment ready' • **Avoid premature implementation**. Research would reduce the likelihood that a technique might be deployed before its effects and side-effects were properly known. • **Proposals elimination.** Research would focus attention on the most effective and least-damaging techniques • **National preparedness**. States need to know what side-effects might arise from the actions of other nations • **Scientific freedom/curiosity.** Geoengineering research is scientifically challenging, and provides wider insights and intellectual rewards.	• '**Moral hazard' argument.** Research on geoengineering should not weaken policy resolve for emission reductions • **Allocation of resources**. Research on geoengineering should not divert funding from energy efficiency, renewable energy and broader climate change science • **Slippery slope.** A clear break is needed between research and deployment, with no assumptions regarding linkage. It may however difficult to decide the boundary between large-scale, long-term testing and pilot deployment. • **Concerns regarding large-scale field tests**. For stratospheric aerosol injection, it would be difficult to develop tests that would demonstrate effectiveness without risk of climatic disruption. This criteria may preclude SAI from further study. • **Backlash against research.** Research benefits and rationale (and regulatory safeguards) need to be transparently demonstrated to avoid adverse responses, that might have implications for other unrelated studies

2.4.2 Final Report of the European Transdisciplinary Assessment of Climate Engineering (EuTRACE)

88. The EuTRACE project was funded by the European Commission, 2012 -2015, and supported 14 partner organizations in 5 countries. Its aims were to: i) bring together European expertise to develop a next-generation assessment of the potential, uncertainties, risks and implications of various options for climate engineering [the favoured descriptor; considered to be the same as (climate) geoengineering as used here]; ii) **actively engage in dialogue** with policy makers, the public and other stakeholders to disseminate information about climate engineering in response to their concerns and perspectives, and incorporate these into the assessment; iii) **outline policy options and pathways** for the EU and its partners to address the challenges posed by climate engineering; and iv) **identify the most important gaps in current understanding** of climate engineering.

89. The EuTRACE final report[135], published in July 2015, reviewed a range of climate engineering techniques, with focus on bioenergy with carbon capture and storage (BECCS), ocean iron fertilization, and stratospheric aerosol injection. It concluded that climate engineering is not an option for near-term climate policy. Nevertheless, "it is sensible to continue to investigate climate engineering techniques to understand their potential in the second half of this century and beyond".

90. The main challenges relating to greenhouse gas removal (GGR/CDR) techniques were considered to be:

- Determining whether the techniques could be scaled up from current prototypes, and what their costs might be
- Determining the constraints imposed by various technique-dependent factors, such as available biomass
- Developing the very large-scale infrastructures and energy inputs, along with the accompanying financial and legal structures, that most of the proposed techniques would require.

91. For sunlight reflection techniques, major problems affecting their scientific and technical feasibility were identified, including the need (for atmospheric-based methods) for a much deeper understanding of the underlying

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[135] Schäfer S, Lawrence M, Stelzer H, Born W et al. (2015)

physical processes, such as the microphysics of particles and clouds, as well as how modification of these would affect the climate on a global and regional basis.

92. Box 2.1 summarizes the research issues relevant to both CDR and SRM that were identified in the EuTRACE report as being important for further consideration.

93. The EuTRACE assessment highlighted the possible effects of various climate interventions on human security, conflict risks and societal stability. At present, no existing international treaty body is in a position to broadly regulate greenhouse gas removal, albedo modification, or climate engineering in its entirety. The assessment stressed the value of public engagement in the discussion, and suggested that EU member states might seek a common position on climate engineering issues, with such an agreement consistent with the high degree of importance that EU primary law places on environmental protection.

94. The EuTRACE report also discussed the governance and regulation of climate engineering, and proposed greater integration of the activities of the UNFCCC (with its emphasis on context), the LC/LP (with emphasis on activities), and the CBD (with emphasis on effects). Also see Chapter 6 of this report.

2.4.3 LWEC Geoengineering Report: A Forward Look for UK Research on Climate Impacts of Geoengineering

95. The UK Living with Environmental Change (LWEC) partnership promotes collaborative, coordinated and co-funded UK research initiatives relevant to climate change, involving both funding agencies and government departments. Its report on climate geoengineering[136] reviewed ongoing research in a UK, European and international context, and identified 10 research gaps. These were in four main groups: quantifying potential effectiveness (intended impacts); unintended impacts (side effects); synergies and interactions; and governance and monitoring/attribution. A more general research gap was also identified, relating to innovative – but not unrealistic – ideas. While the focus of the report was on natural science linkages between geoengineering and climate change, the fundamental importance of interdisciplinarity and socioeconomic considerations was emphasized.

96. No new UK research programmes have yet directly arisen as a consequence of the LWEC report. Nevertheless, it has informed an ongoing planning process for a possible multi-agency research initiative on greenhouse gas removal.

2.4.4 Bibliometric analyses of climate geoengineering

97. Three recent analyses[137,138,139] provide information on the development of geoengineering research from a bibliometric perspective. A common feature is the near-exponential increase in total number of scientific publications in the topic (using a wide range of search terms to cover different nomenclatures) since ~2000; see Figure 2.1.

98. During the period 1990-2013, it has been estimated[140] that there were at least 825 climate geoengineering publications by 1961 authors, with involvement of 667 organizations in 67 countries. Researchers from the US and Europe predominated. Related patent activity was also quantified and trends discussed. Such bibliometric monitoring of research and patenting activity provides insights into the level of scientific interest in different topic areas; it can also contribute to the "anticipatory governance of geoengineering… by making visible the often-hidden networks of collaboration, funding and problem-definition involved in emerging areas of science and technology, and to provide a transparent evidence base that can inform assessment and democratic deliberation".

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[136] Jones C, Williamson P, Haywood J, Lowe J et al (2013)

[137] Belter CW & Seidel DJ (2013)

[138] Oldham P, Szerszynski B, Stilgoe J, Brown C et al. (2014)

[139] Linnér B-O & Wibeck V (2015)

[140] Oldham P, Szerszynski B, Stilgoe J, Brown C et al. (2014)

While networks of research collaboration occur in all scientific fields, they are of particular interest in rapidly-developing subject areas with policy implications, and where public engagement, understanding and acceptability are important considerations[141].

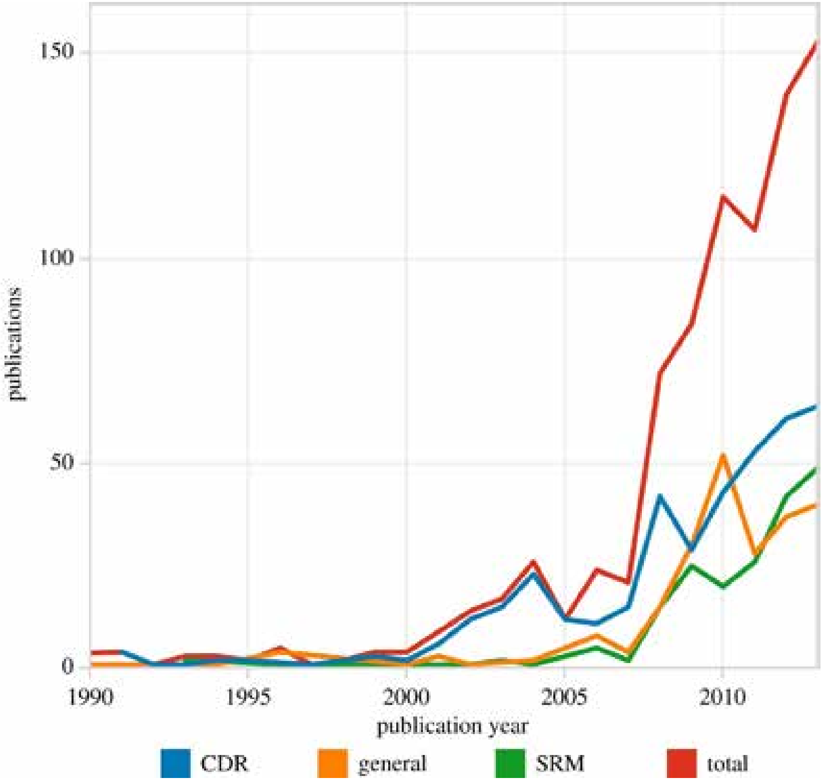

Figure 2.1. The growth of publications in carbon dioxide removal (CDR), sunlight reflection methods (SRM), general climate geoengineering and their total, 1990-2013. From Oldham et al (2014), reprinted with permission

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[141] Oldham P, Hall S &Burton G (2012)

CHAPTER 3

POTENTIAL IMPACTS ON BIODIVERSITY OF CLIMATE GEOENGINEERING ACHIEVED BY REMOVAL OF CARBON DIOXIDE OR OTHER GREENHOUSE GASES

3.1 INTRODUCTION AND GENERAL CONSIDERATIONS

99. This chapter focuses on recent advances in knowledge and understanding of techniques to remove carbon dioxide, and potentially other greenhouse gases, from the atmosphere. There are close similarities between 'negative emissions' achieved through many carbon dioxide removal (CDR) techniques and conventional mitigation strategies, with both affecting the Earth's heat budget through the same processes. For that reason, there remains debate as to whether all the techniques considered here should be regarded as geoengineering. Attention is directed at new literature and aspects not previously considered by Technical Series No. 66 (CBD, 2012)[142], noting that there have been high-profile calls to prioritize CDR research[143,144]. In view of the importance of bioenergy with carbon capture and storage in IPCC AR5 (scenario RCP 2.6, see Chapter 2 here), issues relating to that technique are explored in some depth.

100. Despite the abundance of recent literature on CDR, relatively little research has been specifically directed at impacts on ecosystems and biodiversity. Environmental consequences are therefore mostly discussed in terms of climatic effectiveness, agricultural impacts, land use change or other indirect impacts; e.g. fertilizer application or water extraction. It is important to note that both decreased and increased productivity are generally undesirable from a natural ecosystem perspective (for both terrestrial and marine environments), although increased productivity is agriculturally beneficial. Enhancement of soil carbon is not considered as a climate geoengineering technique (except via biochar and land-based enhanced weathering), since its climatic benefits could be transient, and unlikely to be at the scale required.

101. In addition to the assessments and reports discussed in Chapter 2 and other recent reviews and briefing papers[145,146,147,148,149,150], the journals *Process Safety and Environmental Protection* and *Climatic Change* published special issues on CDR/negative emission techniques, in 2012 and 2013 respectively. These special issues included a total of 16 papers, most of which are individually cited here. The introductory paper[151] in the Climatic Change special issue emphasized that CDR necessarily involves two components – carbon capture and carbon storage – both of which can be achieved by a variety of processes, with different implications. Thus capture processes can be either biological or geochemical, and storage processes can either be biogeochemical (directly in soil or ocean) or geological (deep below the land or seafloor surface). A summary of the different combinations of these processes, that may be either land- or ocean-based, is given in Table 3.1.

102. The removal-storage paradigm can, however, be considered as conceptually over-simplistic, since, 'storage' may involve additional transformations or uses of CO_2; it may also involve additional environmental risks. Increasing

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[142] CBD (Secretariat of the Convention on Biological Diversity) (2012)

[143] National Academy of Sciences (2015a)

[144] Lomax G, Lenton TM, Adeosun A & Workman M (2015)

[145] Ryaboshapko AG & Revokatova AP (2015)

[146] Erbach G (2015)

[147] McGlashan NR, Workman MHW, Caldecott B & Shah N (2012)

[148] Caldecott B, Lomax G & Workman M (2015)

[149] McLaren D (2011)

[150] Boucher O, de Guillebon B, Abbadie L, Barré P et al. (2014)

[151] Tavoni M & Socolow R (2013)

attention is being given to possibilities for industrial use of captured CO_2, as a feedstock for other products[152,153]; however, in the context of stabilizing climate, such products must not only keep the carbon out of circulation on a long-term basis, but they must also be capable of scaling-up to gigaton quantities. The main current commercial use of CO_2 is for enhanced oil recovery: while long-term storage of injected CO_2 would then be achieved, the climatic benefits of its removal are likely to be negated through further fossil fuel combustion and CO_2 release.

Table 3.1 Main categories of CDR based on capture and storage processes. BECCS, bioenergy with carbon capture and storage.

		CARBON CAPTURE			
		Biological processes		**Geochemical processes**	
CARBON STORAGE	**Biogeochemical storage (soil or ocean)**	*Land removal & land storage* • **Afforestation** • **Biochar**	*Land removal & ocean storage* • **Ocean biomass storage**	*Land removal & land storage* • **Enhanced weathering**	*Land removal & ocean storage* • **Enhanced weathering** (ocean storage occurs via river run-off)
		(Ocean removal & land storage)	*Ocean removal & ocean storage* • **Ocean fertilization**	*(Ocean removal & land storage)*	*Ocean removal & ocean storage* • **Enhanced weathering** • **Enhanced alkalinity**
	Geological storage (deep reservoirs)	*Land removal & land storage* • **BECCS** (with land sub-surface storage)	*Land removal & ocean storage* • **BECCS** (with sub-seafloor storage)	*Land removal & land storage* • **Direct air capture** (with land sub-surface storage)	*Land removal & ocean storage* • **Direct air capture** (with sub-seafloor storage)
		Ocean removal & land storage • **'Ocean afforestation'** (with land sub-surface storage)	*Ocean removal & ocean storage* • **'Ocean afforestation'** (with sub-seafloor storage)	*(Ocean removal & land storage)*	*Ocean removal & ocean storage* • **Ocean CO_2 capture** (with sub-seafloor storage)

103. Where geological 'CO_2 storage' involves geochemical transformation (carbonation), reservoir leakage is very unlikely to be a problem[154,155]. A pilot-scale study of that technique has recently been completed[156,157]. In other cases, leakage risks are expected to be low[158], yet the scale of the projected future CCS requirements[159,160,161] does require consideration of the consequences of potential reservoir failures.

104. Technical considerations relating to **safe carbon storage** were considered in some detail in the NAS/NRC report on CO_2 removal and sequestration[162], and relevant environmental issues have recently been reviewed[163]. The main effects of marine leakage would be local ocean acidification[164,165], with experimental studies indicating that (at least for slow release rates) environmental impacts would be relatively localized[166]. The extensive literature on ocean acidification, including the biodiversity changes observed at natural CO_2 vents, is relevant here, as reviewed

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[152] Aresta M (ed) (2010)

[153] Armstrong K & Styring P (2015)

[154] Kelemen PB, Matter J, Strelt EE, Rudge JF et al. (2011)

[155] Matter JM, Stute M, Hall J, Mesfin K et al. (2014)

[156] Matter JM, Broecker WS, Stute M, Gislason SR et al. (2009)

[157] Final report on the CarbFix project available at: http://cordis.europa.eu/project/rcn/100456_en.html

[158] Ha-Duong M & Loisel R (2009)

[159] Herzog HJ (2011)

[160] Maddali V, Tularam GA & Glynn P (2015)

[161] Gasser T, Guivarch C, Tachiiri K, Jones CD & Ciais P (2015)

[162] National Academy of Sciences (2015a)

[163] Jones DG, Beaubien SE, Blackford JC, Foekema EM et al. (2015)

[164] Widdicombe S, Blackford JC & Speirs JI (eds) (2013)

[165] Dewar M, Wei W, McNeil D & Chen B (2013)

[166] Blackford J, Stahl H, Bull JM, Bergès BJP et al (2014)

in a recent CBD report[167]. However, relatively few experimental studies on the impacts of high CO_2 on marine organisms cover the full range of values that might occur under leakage conditions[168].

105. Most of the studies of the impacts of CO_2 leaks from terrestrial storage sites have focussed on impacts on agricultural crops[169,170,171]. Such work has shown adverse impacts on plant growth and yield at high soil CO_2 levels, also the potential for using remote-sensed data (leaf spectra index).[172,173,174] and molecular techniques[175] for leak detection. Studies at terrestrial natural CO_2 vents indicate local adaptation by plant and microbial communities to long-term exposure[176].

106. As noted in Chapter 2, the IPCC WG I report identified the importance of **carbon cycle dynamics** when assessing the effectiveness of negative emission approaches. In much the same way that CO_2 emissions to the atmosphere cause increased uptake by natural sinks, CO_2 removal will be partly offset by outgassing from natural sources[177,178]. This effect would become most apparent if CDR is used to reduce atmospheric levels of CO_2, rather than just slowing their increase. The quantity to be removed to correct for any 'overshoot' in atmospheric CO_2 (as in most RCP 2.6 scenarios) or, more ambitiously, to return to pre-industrial levels[179], cannot therefore be directly calculated from the difference in atmospheric concentrations; it is, however, closely similar to the amount of CO_2 that was anthropogenically added since the lower, target level of atmospheric CO_2 was previously experienced.

107. An additional complexity is that different climate processes respond at different rates to CO_2-driven changes in radiative forcing, causing changes in re-adjustment rates to other Earth system components (e.g. sea ice[180], sea level[181] and ocean pH[182]). The climatic conditions that occur for a given level of atmospheric CO_2 therefore depend on the historical context, on a decadal-to-century timescale[183]. Thus mean global temperatures and rainfall, and their regional variability, under (say) 450 ppm CO_2 in 2100 will depend on whether ~ 50 years earlier it was 425 ppm, 450 ppm, or 475 ppm, (assuming that a reduction from 475 ppm to 450 ppm can be achieved by CDR).

108. As a result of the above effects, the stabilization of concentrations of atmospheric greenhouse gases does not necessarily result in stability for all climate system components. Any overshoot is therefore likely to have additional environmental consequences that may not be reversible on decadal to centennial timescales – and, if species extinctions are involved, irreversibility is absolute. Climatic processes affecting sea level (the heat content of the deep ocean, and the stability of land ice) are of particular concern, since important natural drivers of such changes operate on millennial time scales. Ocean acidification is another slow-response process. For RCP 2.6, restoration of pre-industrial pH values in the surface ocean would take ~700 years; to achieve the same target on the same timescale via CDR for RCP 8.5 (hence with much larger overshoot), an unfeasibly high rate of CO_2 removal of 25 Gt yr^{-1} would be required[184]. In both cases, significant pH anomalies for the ocean interior would remain for very much longer.

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[167] CBD (Secretariat of the Convention on Biological Diversity) (2014b)

[168] de Vries P, Tamis JE, Foekema EM, Klok C & Murk AJ (2013)

[169] Patil RH (2012)

[170] Al-Traboulsi M, Sjögersten S, Colls J, M Steven & Black C (2013)

[171] Al-Traboulsi M, Sjögersten S, Colls J, M Steven et al. (2012)

[172] Jiang J, Michael DS, Cai Q, He R et al (2014)

[173] Jiang J, Michael D, He R, Cai Q et al (2013)

[174] Jiang J, Michael DS & Chen Y (2012)

[175] Noble RRP, Stalker L, Wakelin SA, Pejcic B et al. (2012)

[176] Ziogou F, Gemeni V, Koukouzas N, de Angelis D et al. (2013)

[177] Boucher O, Halloran P, Burke E, Doutriaux-Boucher M et al. (2012)

[178] Vichi M, Navarra A & Fogli PG (2013)

[179] MacDougall AH (2013)

[180] Ridley JK, Lowe JA & Hewitt HT (2012)

[181] Bouttes N, Gregory JM & Lowe JA (2013)

[182] Mathesius S, Hofman M, Caldeira K & Schellnhuber HJ (2015)

[183] Wu P, Ridley J, Pardaens A, Levine R & Lowe J (2015)

[184] Mathesius S, Hofmann M, Caldeira K & Schellnhuber HJ (2015)

109. Summarising the above, the net environmental effect of adding 1 Gt CO_2 and then subtracting 1 Gt CO_2 only equals zero when there is no substantive de-coupling in space or time between the addition and subtraction processes. If there are decadal-scale delays, significant and potentially irreversible climatic and environmental consequences may occur. For those reasons, an important consideration in evaluating the potential role of CDR techniques is their effectiveness in achieving sufficiently rapid reductions of net emissions so that overshoot issues can be avoided.

110. CDR techniques discussed here are grouped under seven headings: bioenergy with carbon capture and storage; afforestation and reforestation; soil carbon and biochar; enhancement of ocean productivity; enhanced weathering and ocean alkalinization; direct air capture; and removal of greenhouse gases other than CO_2.

Table 3.2. Main conclusions from CBD (2012) relating to greenhouse gas removal (primarily CDR), with some additional information (in italics) on subsequent developments. Full text of 2012 key messages is given in Annex 3.

Key message text originally in bold relating to CDR chapter; re-numbered
1. Carbon dioxide removal techniques, if effective and feasible, would be expected to reduce the negative impacts on biodiversity of climate change and, in most cases, of ocean acidification. *Confirmed importance of scalability in determining effectiveness - and other impacts.*
2. Individual CDR techniques may have significant unintended impacts on terrestrial, and/or ocean ecosystems, depending on the nature, scale and location of carbon capture and storage.
3. Ocean fertilization involves increased biological primary production with associated changes in phytoplankton community structure and species diversity, and implications for the wider food web. *Unregulated iron addition carried out in NE Pacific in 2012*
4. Enhanced weathering would involve large-scale mining and transport of carbonate and silicate rocks, and the spreading of solid or liquid materials on land or sea. The scale of impacts (that may be positive as well as negative) on terrestrial and coastal ecosystems will depend on the method and scale of implementation.
5. The impacts on biodiversity of ecosystem carbon storage through afforestation, reforestation, or the enhancement of soil and wetland carbon depend on the method and scale of implementation.
6. Production of biomass for carbon sequestration on a scale large enough to be climatically significant is likely to either compete for land with food and other crops or involve large-scale land-use change, with impacts on biodiversity as well as greenhouse gas emissions that may partially offset (or even exceed) the carbon sequestered as biomass. *Greatly increased interest in such approaches due to inclusion of bioenergy with carbon capture and storage (BECCS) in IPCC scenarios.*
7. The impacts of long-term storage of biochar (charcoal) in different soil types and under different environmental conditions are not well understood. *Additional research in this topic area, with identification of factors affecting biochar persistence and performance variability*
8. Ocean storage of terrestrial biomass (e.g., crop residues) is expected to have a negative impact on biodiversity.
9. Chemical capture of CO_2 from ambient air would require a large amount of energy. Some proposed processes may also have high demand for freshwater, and potential risk of chemical pollution from sorbent manufacture; otherwise they would have relatively small direct impacts on biodiversity.
10. Ocean CO_2 storage will necessarily alter the local chemical environment, with a high likelihood of biological effects
11. Leakage from CO_2 stored in sub-seafloor geological reservoirs, though considered unlikely if sites are well selected, would have biodiversity implications for benthic fauna on a local scale. *Additional studies on potential impacts of leakage from marine and terrestrial storage.*

111. The eleven key messages relating to CDR in CBD (2012) are re-presented in Table 3.2. These summary statements are all still considered valid; for some statements, comments are also given relating to significant subsequent developments.

3.2 BIOENERGY WITH CARBON CAPTURE AND STORAGE (BECCS)[185]

3.2.1 The role of BECCS in climate policy

112. There is an extensive literature on the opportunities and risks of greatly expanding the use of terrestrial biomass as an energy source, and issues of particular relevance to biodiversity have been relatively recently reviewed by the CBD[186]. Such bioenergy offers an alternative to fossil fuels and a potential mechanism for net carbon removal when linked to CCS. Bioenergy with carbon capture and storage (BECCS) meets both these needs: it has therefore been given scientific and policy attention[187,188,189] as an approach to help address climate change, particularly within integrated assessment models (IAMs) that are structured to deliver cost-minimizing scenarios.

113. A recent major review has expressed confidence that bioenergy can greatly increase its contribution to global energy needs[190], at the scale required for BECCS. However, other analyses and reviews have been more cautious[191,192,193], giving greater emphasis to environmental and ecological constraints[194,195,196,197,198] and socioeconomic considerations[199,200,201,202]. A bibliographic review[203] of >1600 peer-reviewed articles on biofuel-related topics concluded that biodiversity was not well-represented in the literature. Gaps were especially striking in the Southern hemisphere, where the greatest socioeconomic benefits, as well as economic damages, may co-occur.

114. The range of perspectives on bioenergy is exemplified by the lack of consensus on the carbon accounting method that should be used to quantitatively assess climatic benefits, regardless of whether or not CCS is also involved. There is also no consensus on the scale of yields that might be sustainably achieved by bioenergy, both in total and from each its three main future sources: second generation energy crops; residues from agriculture, forestry and waste; and directly from forestry. Currently there is around an order of magnitude difference in each of those estimates[204], with lack of clarity in distinguishing *theoretical* potential, constrained by biophysical conditions; *technical* potential, taking greater account of practicalities (e.g. existing land uses, development of operational CCS); and *economic* potential, affected by costs and policies.

115. Such variation in estimating the potential for intended effects in a comparable way is not unique to BECCS, but applies to all other CDR techniques – as noted by IPPC AR5 WG I and the NAS/NRC report, and highlighted by many

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[185] This section acknowledges the contributions of Naomi Vaughan (University of East Anglia) and Clair Gough (University of Manchester)

[186] CBD (Secretariat of the Convention on Biological Diversity) (2012b)

[187] Edenhofer O, Carraro C & Hourcade J-C (2012)

[188] van Vuuren DP, Deetman S, van Vliet J, van der Berg M et al. (2013)

[189] Kriegler E, Edenhofer O, Reuster L, Luderer G & Klein D (2013) .

[190] Souza GM, Victoria R, Joly C & Verdade L (eds) (2015)

[191] Creutzig F, Ravindranath NH, Berndes G, Bolwig S et al. (2015)

[192] Searchinger T & Heinlich (2015)

[193] DeCicco JM (2013)

[194] Havlik P, Schneider UA, Schmid E, Böttcher H et al. (2011)

[195] Smith LJ & Torn MS (2013)

[196] Immerzeel DJ, Verweij PA, van der Hilst F & Faaji ACP (2014)

[197] Creutzig F (2016)

[198] Powell TWR & Lenton TM (2013)

[199] Powell TWR & Lenton TM (2012)

[200] Hunsberger C, Bolwig S, Corbera & Creutzig F (2014)

[201] Reilly J, Melillo J, Cai Y, Kicklighter D et al. (2012)

[202] Gomiero T (2015)

[203] Ridley CE, Clark CM, LeDuc SD, Bierwagen BG et al. (2012)

[204] Slade R, Bauen A & Gross R (2014)

other multi-technique reviews[205,206,207,208]. Nevertheless, 87% (101 out of 116) of scenarios in the IPCC database that are consistent with RCP 2.6 currently include BECCS in order to achieve zero, near-zero or net negative emissions by 2100[209]. To meet the less stringent requirements of RCP 4.5 and RCP 6.0, 36% (235 of 653) of model scenarios in those groups also include BECCS. For RCP 2.6 scenarios and similar, BECCS is expected to remove from the atmosphere, and safely store, up to 10 Gt CO_2 per year by 2050, delivering a median cumulative total of 608 Gt CO_2 (and, in some scenarios, up to 1,000 Gt CO_2) by 2100 – when it is expected to meet 10-40% of primary energy needs (Figure 3.1).

116. The feasibility of BECCS at that scale is, however, highly uncertain – and the scaling-up would itself be challenging. Only around 4.0 EJ (exajoules = 10^{18} joules) of the total energy currently obtained from biomass is suitable for use in a BECCS system: that would need to be increased 40-50 fold[210] by 2050 to reach the value of ~200 EJ commonly assumed in RCP 2.6 scenarios[211]. Within the next 35 years, the tonnage of CO_2 involved in the carbon capture and storage part of BECCS would need to be similar to that of the current global coal industry (~7.8 Gt per year) and iron ore industry (~2.8 Gt per year) combined, and also directly comparable to the current natural global sinks of CO_2 in the ocean and on land, both at around 9 -10 $GtCO_2$ per year (~1.5 Gt C). Other issues relating to the practicality and impacts of large-scale BECCS are discussed below.

3.2.2 Impacts, assumptions and uncertainties relating to BECCS

117. Integrated assessment models (IAMs) make many assumptions regarding BECCS and the wider impacts of its large-scale deployment. While some assumptions may be explicit and well-founded, others are implicit and/or highly uncertain[212,213]. A summary of the main environmental, scientific, economic, political, social and individual consequences is given in Figure 3.2, with associated main assumptions and uncertainties identified in Table 3.3. Biodiversity-related considerations are discussed in greater detail in subsequent text.

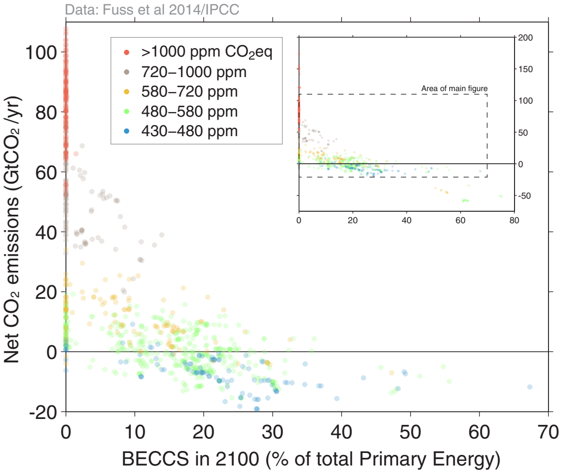

Figure 3.1. The importance of BECCS in limiting net CO_2 emissions and atmospheric CO_2eq concentrations in climate change scenarios. Data from IPCC AR5 database, Global Carbon Project and Carbon Dioxide Information Analysis Centre. Reprinted by permission from Nature Publishing Group (MacMillan Publishers Ltd); Fuss et al (2014) *Nature Climate Change* 4, 850-853,

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[205] Keller DP, Feng EY & Oschlies A (2014)

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[212] Creutzig F, Ravindranath NH, Berndes G, Bolwig S et al. (2015)

[213] Searchinger T, Edwards R, Mullinger D, Heimlich R & Plevin R (2015)

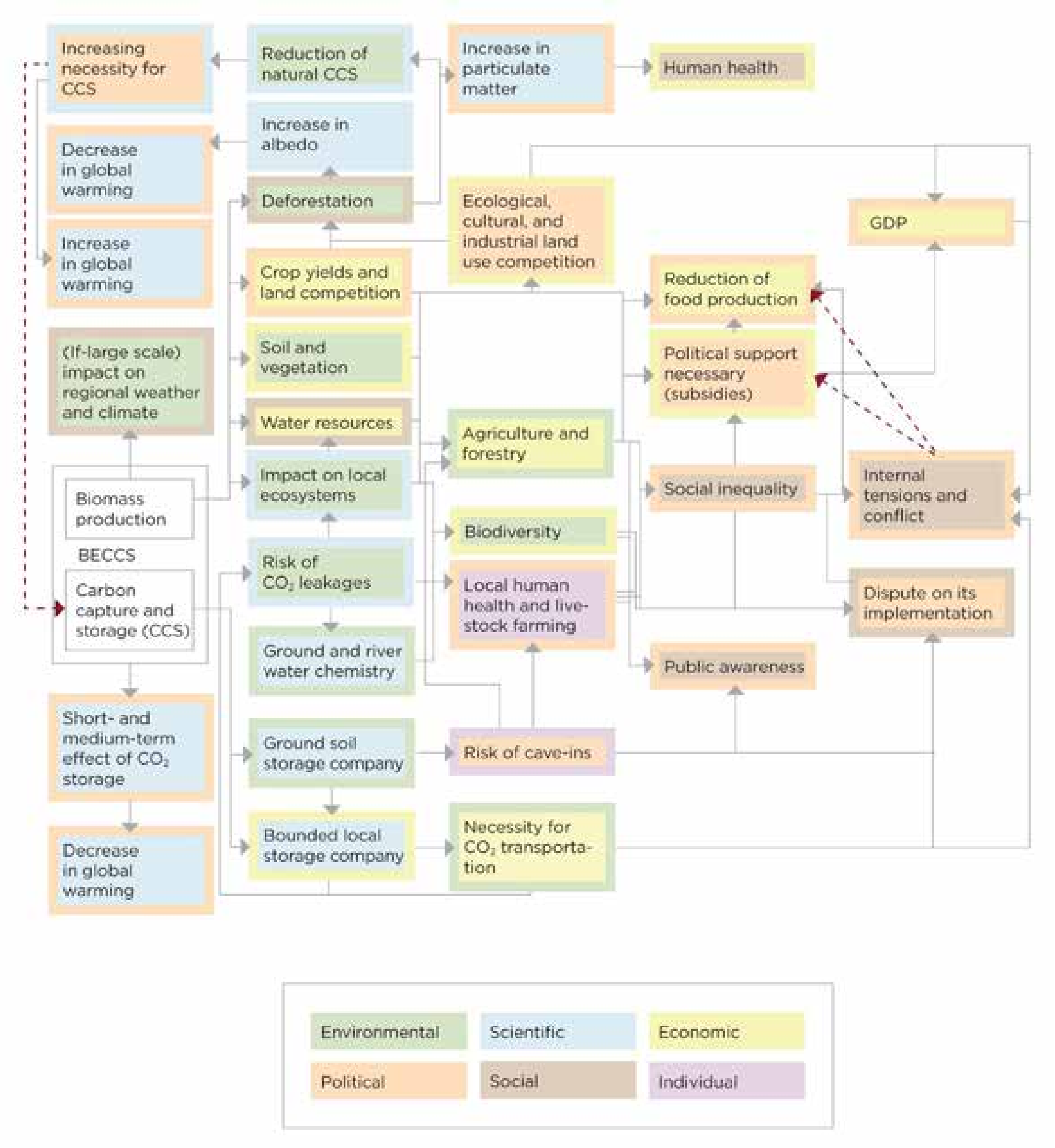

Figure 3.2 Schematic overview of possible consequences of large-scale BECCS deployment. Grey arrows, plausible consequences; red arrows, feedbacks. Colour coding key relates to main (in box) and secondary (surrounding border) nature of consequences. Source: JSA Link & J Scheffran; ref[214], reprinted with permission.

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214 Schäfer S, Lawrence M, Stelzer H, Born W et al.(2015)

Table 3.3 Summary of BECCS-related assumptions and uncertainties. Many aspects are closely linked, requiring consequential (rather than attributional) life cycle assessments[215] to evaluate their implications for BECCS effectiveness as a CDR technique. Based on ref[216].

Assumption	Detail
1. Bioenergy technical potential	
1.1 Land area required/available for BECCS	BECCS necessarily displaces an existing land use/land cover, with more land needed if its productivity is inherently poor. The scale and nature of the changes needed for climatically-significant BECCS implementation are crucial considerations (see main text for referenced discussion). *Uncertainties:* Implications of land use/land cover change for integrity of natural carbon sinks, biodiversity, food security, water security and nutrient dynamics.
1.2 Agricultural efficiency gains	Assumptions made regarding continued improvements in agricultural efficiency will affect the land available for future bioenergy crops. *Uncertainties:* Future impacts of climate change; likelihood of future nutrient limitation; scope for genetic modification
1.3 Yields of bioenergy crops	Scenarios have differing water and fertilizer assumptions, affecting land area requirements. *Uncertainties:* Future impacts of climate change; likelihood of future nutrient limitation; scope for genetic modification
1.4 Residue availability	Many scenarios include use of biomass residues (from crops and managed forests) as well as dedicated bioenergy crops. *Uncertainty:* Scale and location of residue availability, with transport implications.
2. Processing and storage capabilities	
2.1 Infrastructure	Requirement for biomass transport infrastructure and biomass energy generation plants with carbon capture (more efficient at larger size). Requirement for CO_2 transport to storage site *Uncertainties:* Capital and recurrent costs; technology innovation rates; carbon capture rates; life-cycle efficiencies for carbon removal.
2.2. CO_2 storage	Assumed availability of safe storage in appropriate geological formations. *Uncertainties:* Current storage capacity is not well-characterized; potential for regional mismatch between CO_2 production via BECCS and storage capabilities.
3. Political and socioeconomic	
3.1 Population, lifestyle & diets	Assumptions on these factors affect agricultural assumptions (hence bioenergy potential). *Uncertainties:* Peak population estimates vary between 9 -12 billion; behavioural projections are also uncertain.
3.2 Acceptability over range of scales and societal levels	Societal acceptability for BECCS is assumed for all actors, over full range of supply chain (land use/land cover changes, bioenergy power generation/carbon capture and CO_2 storage), in order to deliver deployment at climatically-significant scale. *Uncertainties*: Only limited public engagement to date; land-based carbon storage may be problematic in some countries.
3.3 Governance	Most scenarios assume participation of all global regions in BECCS, with requirement for national and international institutional frameworks in order to i) enable BECCS to become commercially viable; and ii) verify that intended scale of carbon removal has been achieved. *Uncertainty:* Global agreement on such issues not straightforward, since complex financial and political considerations are involved.
3.4 Cost (carbon price/ carbon tax)	Effective carbon pricing mechanism necessary to deliver intended benefits without compromising sustainable development goals. *Uncertainty:* Global agreement on such issues not straightforward; risk that economic drivers will cause deforestation and other adverse environmental consequences.

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[215] Plevin RJ, Delucchi MA & Creutzig F (2013)

[216] Gough C & Vaughan N (2015)

118. The scale of BECCS impacts is necessarily linked with the area of land used for bioenergy crops and the previous status of that land[217]. Within IPCC AR5 IAMs, the amount of land expected to be used varies from 50-700 Mha. For comparison, the current global cover of arable land is ~1400 Mha, permanent crops ~15 Mha, and permanent pasture ~3360 Mha[218]. The US total land area is 915 Mha. To obtain the land area needed for upper estimates of bioenergy development, there is risk of near-total loss of primary, unmanaged forest and ~90% loss of unmanaged pasture by 2100 unless appropriate environmental safeguards are in place[219]. Most IAMs are ecologically more benign, limiting BECCS to abandoned agricultural land and unmanaged pasture, e.g. the IMAGE RCP 2.6 projection, that assumes 430-580 Mha is used for bioenergy crops. However, as already shown (Figure 1.5), the land use changes assumed in the IMAGE RCP 2.6 scenario have serious implications for terrestrial species richness, with effects this century expected to be greater than the climatic impacts occurring in either RCP 4.5 or 6.0[220].

119. Scenarios where bioenergy crops require less land-use change than the IMAGE pathway are also possible, but would significant transformations in food systems to make available existing farmland. For example, by dietary shifts, reducing food waste and technological improvements to agriculture[221,222,223].

120. Other key considerations relating to land use/land cover change and bioenergy technical potential include:

- The loss of soil carbon (with associated greenhouse gas emissions) when abandoned land and 'marginal land'[224] is returned to, or brought into, cultivation[225]. In one scenario, the expected BECCS benefit of a global temperature reduction of 1.34°C by 2100 was reduced to 0.15°C when this factor was taken into account[226].
- The trade-off between using a smaller area of more productive land (with higher bioenergy yields per hectare), or a larger area of less productive land (with lower yields)
- Many aspects of future yield assumptions seem speculative and may be over-optimistic[227]. In practice, actual yields may be ~50% of those that are theoretically plausible. The higher yields would require tangible benefits from genetic modification, and/or high fertilizer applications. The latter would have environmental consequences not only via greenhouse gas emissions but also through nitrogen pollution of groundwater, with increased risk of freshwater and coastal eutrophication. Future bioenergy crop yields are likely (at best) to grow linearly rather than exponentially. They could also level off, due to biophysical limits, or decline, due to the effects of climate change (including increased risk of extreme weather events, even under RCP 2.6 scenarios) in the period 2050-2100.
- Similar linkages and constraints apply to water use[228], noting that i) some BECCS scenarios could double agricultural water withdrawals if no explicit water protection policies are implemented; ii) if those water protection measures are introduced (i.e. no irrigation) for bioenergy crops, then the area of land required for them may need to increase by ~40%, increasing pressure on other habitats, e.g. pasture land and tropical forests; iii) there is likely to be additional water demand (of ~0.6m^3 kg^{-1} feedstock) for biofuel

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[218] FAO (Food & Agriculture Organization) (2013)

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[226] Wiltshire A & Davies-Bernard T (2015)

[227] Creutzig F (2016)

[228] Bonsch M, Humpenöder F, Popp A, Bodirsky B et al. (2014)

powerplant and CCS processes[229]; and iv) future nutrient constraints are likely to limit CO_2 fertilization effects, for both managed and unmanaged terrestrial vegetation[230].

- Even if there is no direct competition between bioenergy crops and those for food/feed production (as usually assumed within IAMs), indirect interactions are likely[231]. As an example, large-scale planting of poplar (*Populus* spp) as a biofuel crop in Europe could significantly increase ground level ozone (through the production of volatile organic compounds)[232], decreasing wheat and maize yields by up to ~9 Mt yr^{-1}.
- Changes in albedo is likely to occur when land is used for bioenergy production[233]. If the conversion is from forest, albedo-induced cooling effects may (depending on the bioenergy crop, and the timescale under consideration) provide greater climatic benefits than those obtained from BECCS[234]. However, such land use change also involves high greenhouse gas emissions, with net negative effects on climate – as well as direct impacts on biodiversity.
- All stages in the BECCS process potentially involve undesirable greenhouse gas emissions, reducing overall effectiveness. A life cycle assessment of production, processing and CCS for the temperate switchgrass *Panicum virgatum* has shown that the final sequestering of 1 Gt carbon is likely to require 2.11 Gt of carbon in switchgrass biomass, i.e. an overall efficiency of 47%[235]. Although most losses occurred in the CCS process (with scope for technical improvements), there were also emissions embedded at the farm, bailing losses, losses during gasification and conditioning, and in CO_2 transport and injection. A life cycle assessment[236] for using North American woody biomass as a biofuel in the UK (without CCS) has shown the importance of different biomass sources, and the inefficiencies associated with its long-distance transport.

121. In a recent modelling analysis taking account of many of the above factors[237], the maximum negative emissions that could be achieved by BECCS was estimated to be 130 GtC (476 $GtCO_2$) over the 21st century. Values did, however, depend on assumptions regarding climate forcing and land use: the BECCS scenario providing least benefit resulted in increased emissions, by 100 GtC (366 $GtCO_2$) by 2100. Those values compare with the median BECCS removal requirement of 166 GtC (608 $GtCO_2$) compatible with a 2°C climate target in IPCC model scenarios. While large uncertainties in the recent model estimates are acknowledged, they strongly imply that further measures (in addition to large-scale BECCS deployment, and substantial, rapid emission reductions) would be needed to meet the 2°C target.

122. Most of the issues above are relevant to large-scale bioenergy development, without CCS, as a lower-carbon alternative to fossil fuels (hence enabling their phase-out). However, that would not provide net CO_2 removal. Direct linkage with CCS is therefore a crucial component regarding feasibility of BECCS as a CDR technique. While there are less biodiversity implications for the CCS component, overall viability does require the commercial development of large-scale operational CCS infrastructure, that may not be straightforward[238]. The CCS component also requires appropriate institutional and policy frameworks, relating to incentivization, carbon pricing, accounting and verification at the international scale; these societal structures are currently poorly developed[239].

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[229] Smith LJ & Torn MS (2013)
[230] Wieder WR, Cleveland CC, Smith WK & Todd-Brown K (2015)
[231] Searchinger T, Edwards R, Mulligan D, Heimlich R & Plevin R (2015)
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[238] Maddali V, Tularam GA & Glynn P (2015)
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3.3 AFFORESTATION AND REFORESTATION

123. Afforestation (on land that has not been forested for > 50 yr) and reforestation are not always regarded as geoengineering; however, they do provide a mechanism for managed carbon dioxide removal, and are considered as a negative emission technique in IPCC AR5 and elsewhere, e.g. the NAC/NRC report[240]. The biodiversity implications of "reducing emissions from deforestation and forest degradation, conservation of forest carbon stocks, sustainable management of forests and enhancement of forest carbon stocks in developing countries" (REDD-plus) have been separately reviewed under the CBD[241], and are subject to ongoing discussions under the UNFCCC as well as at CBD SBSTTAs and COPs.

124. Land use emissions (primarily by deforestation) since 1750 have totalled ~660 Gt CO_2, providing an approximate upper limit to the physical potential for reforestation to remove carbon dioxide[242]. Since such emissions have only been ~10% of those from fossil fuels and cement production, and complete reforestation is unrealistic (competing for crop production and biofuels in the context of an increasing population), afforestation/reforestation on its own cannot be relied on to achieve climatic stability. Nevertheless, its contribution could be significant, estimated by IPCC AR5 to be in the range 1.5 - 14 Gt CO_2eq yr^{-1} (Table 11.8, WG III Report).

125. In a specific scenario[243], tropical afforestation at the rate of 7 Mha yr^{-1} could remove 3.7 Gt CO_2 yr^{-1}, while requiring 0.07 Mt yr^{-1} of nitrogen and 0.2 Mt yr^{-1} of phosphorus. There are, however, several provisos to consider:

- Use of nitrogen fertilizer at that scale is likely to increase N_2O release (a greenhouse gas, with century-scale global warming potential 298 times greater than CO_2)[244] reducing or over-riding the benefits of CO_2 drawdown. Other environmental impacts relevant to biodiversity could include increased risk of freshwater and coastal eutrophication. Global supplies of phosphate rock, the source of phosphorus fertilizer, are likely to be exhausted sometime between 2050-2100[245].
- The effectiveness of CO_2 removal decreases as a forest system matures, generally approaching net balance in 50-100 years[246]. While old-growth forests and their soils can also be net carbon sinks[247], there is evidence (at least for the Amazon basin) of a decline in net carbon uptake over the past 30 years[248].
- Future climate change will jeopardize *in situ* carbon sequestration by terrestrial biomass, through increased frequency of fire, pests and disease, and extreme weather. These effects need to be taken into account, but are difficult to reliably quantify for 2050-2100.
- While it is likely that increased atmospheric CO_2 has to date enhanced total terrestrial productivity, tropical tree growth does not seem to have responded in that way[249], and future increases may anyway be constrained by nutrient limitation[250].
- Changes in albedo and evapotranspiration resulting from large-scale afforestation are complex[251,252,253]

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[240] National Academy of Sciences (2015a)
[241] CBD (Secretariat of Convention on Biological Diversity) (2011)
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[243] Smith LJ & Torn MS (2013)
[244] IPCC (Intergovernmental Panel on Climate Change) (2013) [Table 8.7]
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[251] Arora VK & Montenegro A (2010)
[252] Anderson RG, Canadell JG, Randerson JT, Jackson RB et al. (2011)
[253] Bonan GB (2008)

involving both surface cooling, effects on cloud cover, and other atmospheric changes. Mid-latitude and boreal afforestation, as advocated by some for greenhouse gas offsetting[254], may counter-intuitively have a net warming effect, over-riding the benefits of increased carbon storage[255]. Such afforestation is not only likely to reduce albedo (particularly during seasonal snow cover) but may also significantly increase atmospheric water vapour (a greenhouse gas, although not usually considered as such).[256,257]. The net climatic effect will change with time, and will depend on the nature of the land-use change (the species involved), soil conditions and other land management practices[258].

126. A modelling study[259] of (hypothetical) afforestation of all North African and Australian deserts, using unspecified irrigation processes, also found the effect identified in the last bullet above – with such interventions increasing global mean temperature by 0.12°C by 2100, primarily due to albedo change. That study also noted that afforestation of desert regions might also reduce the productivity of adjacent oceans, by reducing, windblown desert dust (with ocean-fertilizing role); however, such effects were not simulated.

127. CBD (2012) emphasized the importance of maximising the biodiversity benefits of managed forests by (re-) planting assemblages of native trees rather than exotic monocultures, and that conclusion[260] is re-iterated here. From a climatic perspective, the benefits of reducing deforestation seem much greater, and more certain, than afforestation/reforestation – while recognizing the complexities of the many interactions, trade-offs and stakeholder interests in forestry management[261,262].

3.4 SOIL CARBON – WITH FOCUS ON BIOCHAR

128. This section focuses on biochar. No specific attention is given to increasing soil carbon, other than by biochar and enhanced weathering, since soil management techniques that are already used in agriculture (excluding the potential for peat management[263]) are not generally considered to be geoengineering. While that is mostly due to the relative lability of soil organic carbon[264], and the complexity of processes affecting its turnover[265], there are also many uncertainties regarding the scale of additional carbon sequestration that may be achievable[266,267]. Even when soil carbon storage is enhanced, through no-till agriculture and other techniques, its climatic benefits may be partly or fully offset by increased N_2O emissions[268]. Nevertheless, the avoidance of further CO_2 emissions from soil and other land carbon sinks, and the re-filling of depleted stocks, is widely considered to be an important component of climate-change mitigation[269], thereby reducing the need for other, more radical, negative emission technologies.

129. CDR based on biochar involves the partial combustion (pyrolysis) or gasification of terrestrial biomass, mostly crop residues, at low oxygen levels and subsequently adding the black carbon (charcoal) product to soil to achieve

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storage. There is an extensive literature on the topic, primarily because biochar is increasingly being used for soil improvement[270,271], particularly for degraded or acidic soils. The partial combustion process also provides energy (directly and/or indirectly through fuel gases), although less than for complete oxygenation.

130. The effectiveness of biochar for long-term CO_2 removal is, however, controversial. An upper total of 476 Gt CO_2 (130 Gt C) for century-scale removal has been estimated "without endangering food security, habitat or soil conservation"[272]. That value was cited in the IPCC AR5 WG I report (Table 6.15)[273], and is greater than than the equivalent BECCS estimate of 458 Gt CO_2 (125 Gt C), given in the same table. In contrast, the potential for biochar as a climate intervention technique was only briefly considered in the NAC/NRC report[274], since it was "not classified… as a CDR technology" (although included in concluding comparative evaluations). The most recent of the three biochar references cited there was a review[275], based on literature up to 2011, that emphasized uncertainties regarding biochar's effectiveness in achieving long-term carbon removal. CBD (2012) also expressed concerns regarding the environmental consequences, and potential agricultural benefits, of large-scale biochar development.

131. In the CBD interim report on climate geoengineering (UNEP/CBD/SBSTTA/18/INF/5), 34 additional peer-reviewed papers on biochar were identified to mid-2014, and there have been more than 50 other significant new publications. The consensus from that recent literature, that includes meta-analyses[276,277,278,279],books[280,281,282] and reviews[283,284], is that biochar does have potential as a CDR technique – while recognizing that its contribution may not be as great as has been claimed, and that the term biochar covers many products, with different properties. Thus there can be many equally valid values for biochars' lability/recalcitrance in soil[285], covering the range from tens to hundreds to thousands of years. That trait is determined by four main factors:

- The nature of the biomass feedstock (e.g. straw, corn stalks, woody materials, sawdust, rice husks, palm kernel shells, dried sewage sludge etc), particularly its carbon content
- Pyrolysis temperature and other processing conditions
- The chemistry and mineralogy of the soils to which the biochar is added
- Subsequent environmental conditions (primarily temperature and soil moisture).

132. Standard methods and metrics to obtain a process-based understanding of the effects of these factors on biochar persistence have recently been developed[286,287,288,289]. Multi-year experiments under a range of field conditions are

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now underway to test these methods on different biochars, to enable projections on 50-100 year timescales to be made – while recognizing the complexities of *in situ* decomposition rates[290].

133. Short-term studies have shown large variability regarding the more easily measured effects of biochar – on crop yields/productivity, water retention (in sandy soils), and drainage (in clay soils). Crop yield changes from -16% to +100% have been reported within a single study[291], with up to 4-fold increase in some circumstances[292]. Overall, a meta-analysis[293] has indicated a mean yield increase of 14% in acidic soils, and an overall mean of 10% in all soil types. Agronomic benefits usually relate to the first year of treatment, and may subsequently show a marked decline[294].

134. The addition of biochar can enhance soil carbon by more than the amount added. Thus a hardwood biochar added to a *Miscanthus* crop suppressed soil CO_2 emissions by 33% over a two year trial[295]. Significant reductions in the soil emissions of other greenhouse gases, specifically methane (CH_4)[296,297] and nitrous oxide (N_2O)[298,299,300], and both[301,302], have been also been reported – with the scale of the response dependent on biochar properties and other treatment conditions.

135. Treatment conditions also, not surprisingly, strongly influence the impacts of biochar on soil biology. Microbial activity is generally enhanced[303,304], and there can be both positive and negative effects on soil fauna[305,306]. Further study would seem necessary: a recent review of this topic[307] concluded that "Elucidating the impacts of soil fauna directly and indirectly on biochar stability is a top research priority". Other important treatment-related knowledge gaps relate to:

- The interactions of biochar with other crop treatments and pollutants; for example, biochar might reduce the effectiveness of pre-emergent herbicides[308]; introduce phytotoxic organic compounds[309] or metal contamination (from timber treatment)[310,311]; affect heavy metal bioavailability[312]; or remediate the impacts of other toxic pollutants[313,314]. Many uncertainties remain regarding the underlying processes and long-term implications[315] of these effects

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- Possible effects on plant vulnerability to pests and diseases, due to down-regulation of defence genes accompanying growth enhancement[316]

- The consequences of loss of applied biochar through erosion and run-off[317,318], with implications for air and water quality, and wider environmental impacts.

136. Large-scale deployment of biochar could result in important and climatically-undesirable albedo impacts[319,320], through air-borne particles or at the soil surface. The latter effect could offset biochar's climatic benefits by up to ~30%[321]. Nevertheless, spring soil-warming is likely to be agriculturally advantageous for most crops in temperate regions. For tropical soils, such albedo effects could potentially be reduced by mixing the applied biochar with high reflectance minerals – possibly olivine, combining two CDR techniques.

137. The global availability of biomass feedstock for biochar has been estimated[322] at ~2.3 Gt C yr^{-1} (around a quarter of fossil fuel emissions), with potential[323] for net carbon removal of ~1.8 Gt C yr^{-1}. The focus is usually expected to be on crop residues and other biowaste; however, biomass crops and agroforestry contribute around half that total, requiring 100% use of abandoned, degraded cropland that is not in other use, and 170 Mha of tropical grass pasture converted to silvopasture. Land-use changes at that scale would therefore involve similar environmental issues as identified above for BECCS. The removal of crop residues also could be problematic with regard to soil carbon and nutrients[324,325] unless the biochar is returned to the same soils.

138. As already noted for BECCS, life cycle assessments are also a valuable tool for evaluating overall effectiveness – providing there is awareness of their uncertainties[326]. For biochar, quantitative consideration must be given not only to the production process[327,328], but also to the persistence of biochar in soil, the timeframe under consideration, and whether there may be an upper limit for soil storage capacity (i.e. for cumulative biochar additions to the same land, noting that only a proportion of arable land is likely to be available for biochar treatment, and that proportion will vary regionally and nationally).

139. A life cycle assessment has been carried out for straw-based biochar, in comparison to using the straw for building purposes[329]. The latter was found to be more environmentally advantageous, with net impacts for 1 t of straw estimated to be -0.93 t CO_2eq for biochar and -3.3 t CO_2eq for straw-bale construction. These results were considered indicative rather than absolute, since they were strongly affected by assumptions relating to energy efficiency of the building (in Finland). Scalability issues and long-term considerations could also be important; e.g. upper limits on demand for use of straw-based building materials. The removed straw contained 0.5% nitrogen and 0.1% phosphorus; for sustainable building use, these nutrients would need to be replaced, by fertilizer or (for nitrogen) by nitrogen-fixing cover crops. For biochar, the need for fertilizer could be less if the biochar is used where the straw was sourced.

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319 Meyer S, Bright RM, Fischer D. et al. (2012)
320 Verheijen F.G.A., Jeffery S., van der Velde M. et al. (2013)
321 Bozzi E, Genesio L, Toscano P, Pieri M & Miglietta F (2015)
322 Woolf D, Amonette JE, Street-Perrott FA, Lehmann J & Joseph S (2010)
323 Woolf D, Amonette JE, Street-Perrott FA, Lehmann J & Joseph S (2010)
324 Liska AJ, Yang H, Milner M. Goddard S et al. (2014)
325 Raffa DW, Bogdanski A & Tittonell P (2015)
326 Plevin RJ, Delucchi MA & Creutzig F (2013)
327 Roberts KG, Gloiy BA, Joseph S, Scott NR & Lehmann J (2010)
328 Gaunt JL & Lehmann J (2008)
329 Mattila T, Grönroos J, Judl J & Korhonen M-J (2012)

3.5 OCEAN FERTILIZATION AND OTHER PROCESSES TO ENHANCE OCEAN PRODUCTIVITY

140. Most proposed methods for enhancing ocean productivity involve the stimulation of phytoplankton growth in the open ocean – in order to achieve biological removal of dissolved carbon from surface waters and its transfer to greater depths, and hence drawdown of atmospheric CO_2. Such ocean fertilization can be achieved either by the addition of nutrients from external sources (principally iron) or physical changes to increase natural nutrient supply (artificial upwelling). In addition, the large-scale cultivation of macro-algae (seaweed) has also been recently proposed, and is briefly considered below.

141. Two recent reviews of research on ocean fertilization[330,331] covered much the same literature as CBD (2012), and reached similar conclusions: that there is limited scope for enhanced ocean productivity based on nutrient additions to be developed as a CDR technique, due to i) the biological and physico-chemical constraints on the overall effectiveness of the approach; ii) the inherent difficulties in verifying carbon sequestration and in monitoring secondary impacts (both over large ocean areas and on long time scales), and iii) the contested governance issues relating to those parts of the global ocean where iron-based ocean fertilization is likely to be most effective (Southern Ocean). The NAS/NRC[332] and EuTRACE[333] reports were also unenthusiastic, with the former concluding that "the risks and costs currently outweigh the benefits" and that ocean fertilization was therefore "an immature CDR technology with high technical and environmental risk".

142. Recent topic-specific studies on enhanced ocean productivity have provided valuable additional detail, but do not seem to have contradicted the above assessments, that are consistent with the relevant key messages from CBD (2012). The new research is summarized below under eight topic headings: characterization of natural iron fertilization; modelling studies of ocean iron fertilization; the LOHAFEX iron fertilization experiment; unregulated ocean iron addition; effectiveness of iron delivery to the upper ocean; ocean fertilization using macro-nutrients; ocean macro-algal afforestation; and artificial upwelling to stimulate ocean productivity. Legal developments relating to the regulation of ocean fertilization are covered in Chapter 6 of this report; they are also discussed in a recent review[334].

143. **Characterization of natural iron fertilization** and its impacts has been greatly improved, relating to the supply of iron from seafloor sediments around islands[335,336], from wind-blown dust[337,338], and from volcanic eruptions on land[339,340,341,342,343] and undersea[344]. In the Southern Ocean, the export of particulate organic carbon is generally ~3 times higher under conditions of natural iron fertilization[345]; however, effects on CO_2 drawdown depend on the

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330 Williamson P, Wallace DWR, Law CS, Boyd PW et al. (2012)
331 Boyd PW (2013)
332 NRC (National Research Council) (2015a)
333 Schäfer S, Lawrence M, Stelzer H, Born W et al. (2015)
334 Branson MC (2014)
335 Quéroué F, Sarthou G, Planquette HF, Bucciarelli E et al. (2015)
336 Tremblay L, Caparros J, Lreblanc K & Obernosterer I (2015)
337 Winton VHL, Dunbar GB, Bertler NAN, Millet M-A et al. (2014)
338 Martínez-Garcia A, Sigman DM, Ren H, Anderson RF et al. (2014)
339 Achterberg EP, Moore CM, Henson SA, Steigenberger S et al (2013)
340 Olgun N, Duggen S, Langmann B, Hort M et al. (2013)
341 Kearney KA, Tommasi D & Stock C (2015)
342 Lindenthal A, Langmann B, Pätsch J, Lorkowski I & Hort M (2013)
343 Mélançon J, Levasseur M, Lizotte M, Delmelle P et al. (2014)
344 Santana-Casiano JM, González-Dávila M, Fraile-Nuez E, de Armas D et al. (2013)
345 Morris PJ & Charette MA (2013)

ratio of organic/inorganic carbon in sinking particles[346]. Light levels (determined by mixing depth) can also be important in determining the effectiveness of natural iron fertilization[347].

144. Additional **modelling studies of ocean iron fertilization** have been carried out at global, regional and local scales. A global study[348] assumed complete elimination of iron limitation in the Southern Ocean, and showed that could decrease atmospheric carbon by ~90 Gt by 2100 (in comparison to scenario RCP 8.5), with a global surface air temperature reduction of 0.15°C. Marine productivity, acidification and de-oxygenation would all increase south of 40°S, but decrease to the north. A Southern Ocean modelling study[349] examined in greater detail the effect of initial sequestration depth, and found that 66% of carbon sequestered to 1000m is likely to be re-exposed to the atmosphere within 100 years, with an average of 38 years. A patch-scale modelling study showed that the availability of nutrients other than iron would become increasingly important as treatment area increases[350]. This effect means that direct scaling-up from iron fertilization experiments to operational CDR deployment is likely to over-estimate sequestration rates and efficiencies.

145. A further analysis of the 2009 **LOHAFEX ocean iron fertilization experiment** in the Sub-Antarctic Atlantic Ocean showed that, in that study, stimulation of primary production did not result in additional downward carbon flux[351]. A database for all iron fertilization studies has been compiled[352]

146. A private sector, **unregulated ocean iron addition** was carried out in July 2012 in the north east Pacific, for the purpose of gaining carbon credits and fishery enhancement[353]. This project attracted considerable interest[354,355] by the media and NGOs. Although initially seeming to have support from local indigenous peoples, such linkages were later repudiated (statement by Council of the Haida Nation, 18 October 2012). There were no established protocols for research associated with the deployment, nor peer review of the design of the activity, and it had not been authorized by the Government of Canada. The scientific analyses of this project have been limited; nevertheless, a satellite-based study[356] and plankton surveys[357] indicated that phytoplankton and subsequently zooplankton abundances may have been enhanced. Effects on carbon drawdown are uncertain. Although the intended benefits for the salmon fishery have been claimed[358], their scientific linkage has not been established. The apparent effects of natural ocean fertilization (by the Kasatochi volcano) on the abundances of spawning salmon a few years earlier[359] do seem to have a causal link[360] , and have not been replicated in a recent modelling study[361].

147. To enhance the **effectiveness of iron delivery to the upper ocean**, a method has been proposed using rice-husks coated with slow release minerals[362]. A floating lifetime of one year is envisaged for the flakes, but that has yet to be tested. At sea, the flakes are likely to be attractive to small fish and seabirds; the potential toxicity of mineral treatments could therefore be of concern.

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[346] Salter I, Schiebel R, Ziveri P, Movellan A et al. (2014)

[347] Selph KE, Apprill, Measures CI, Hatta M et al. (2013)

[348] Keller DP, Feng EY & Oschlies (2014)

[349] Robinson J, Popova EE, Yool A, Srokosz et al. (2014)

[350] Ianson D, Völker C, Denman K, Kunze E & Steiner N (2012)

[351] Martin P, van der Loeff MR, Cassar N, Vandromme P et al (2013)

[352] Boyd PW, Bakker DCE & Chandler C (2012)

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[357] Batten SD & Gower JFR (2014)

[358] http://www.nationalreview.com/article/376258/pacifics-salmon-are-back-thank-human-ingenuity-robert-zubrin

[359] Parsons T & Whitney F (2012)

[360] McKinnell S (2013)

[361] Kearney KA, Tommasi D & Stock C (2015)

[362] Clarke WS (2015)

148. The assumption is usually made that fertilization by iron, as a micro-nutrient, would be much more effective, and therefore cheaper, than **ocean fertilization using macro-nutrients**, e.g. N and/or P. That assumption is challenged by a modelling study of nutrient uptake rates[363], and contrasting cost estimates of US$ 457 per tonne CO_2 removed by iron fertilization[364] and US$ 20 per tonne CO_2 removed by adding nitrogen (as ammonium hydroxide)[365]. However, these estimates may not be directly comparable, and are likely to be sensitive to many aspects that are currently uncertain; e.g. cost of any negative impacts; long-term monitoring costs; and future hydrographic conditions (affecting mixing and persistence of sequestration).

149. **Ocean macro-algal "afforestation"** has recently been proposed as an alternative approach[366], involving large-scale seaweed culture in shelf seas. The macro-algae would be harvested to produce methane in anaerobic digesters, with CCS used to prevent CO_2 emissions when the methane is subsequent used for energy generation. This process therefore can be regarded as a marine version of BECCS (Section 3.2). However, the proposed scaling of this technique, to 9% of the global ocean, would seem unrealistic, involving many major (and almost certainly unacceptable) environmental and socioeconomic implications. Nevertheless, the feasibility, cost-effectiveness and impacts of a more modest application of this method arguably warrant further attention, to better assess its potential as a CDR technique.

150. The feasibility and benefits of **artificial upwelling to stimulate ocean productivity** remain controversial. A fundamental criticism, noted in CBD (2012), is that the intended carbon removal by increased phytoplankton growth (brought about by nutrients provided from deeper water) is likely to be matched by the undesirable release of CO_2 (also from the deeper water). Nevertheless, modelling studies at the regional[367] and global[368] scale indicate that net CO_2 drawdown is theoretically possible, assuming that the required rate of upwelling in appropriate locations is physically achievable. Engineering attention is being given to the design of devices that would use renewable energy to deliver such mixing[369]. If such devices were to be deployed as a CDR technique, their large-scale application would be necessary for significant climatic benefits. But such benefits are far from certain, or may not be sustainable: disruption to the ocean thermocline could change atmospheric circulation patterns and cloud cover in ways that, after a period of cooling (relative to RCP 8.5) might subsequently increase global mean surface temperatures[370].

3.6 ENHANCED WEATHERING AND OCEAN ALKALINIZATION

151. Details of the many chemical processes that can be involved in proposed enhanced weathering techniques (predominantly terrestrial) and ocean alkalinization are given in the NAS/NRC report[371], also in other recent reviews[372,373,374,375]. Carbon dioxide removal is usually achieved through the reaction of CO_2 with silicates and other mineral compounds, releasing cations (such as Ca^{2+} and Mg^{2+}) and forming bicarbonate (HCO_3^{2-}) and carbonate ions (CO_3^-). Some of the techniques are conceptually closer to direct air capture (see below), and more

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[363] Lawrence MW (2014)

[364] Harrison DP (2013)

[365] Jones ISF (2014)

[366] N'Yeurt A de R, Chynoweth DP, Capron ME, Stewart JR & Hassan MA (2012)

[367] Pan Y, Fan W, Huang T-H, Wang S-L & Chen C-TA (2015)

[368] Keller DP, Feng EY & Oschlies (2014)

[369] Fan W, Chen J, Pan Y, Huang H, Chen C-TA & Chen Y (2013)

[370] Kwaitkowski L, Ricke KL & Caldeira K (2015)

[371] NRC (National Research Council) (2015a)

[372] Hartmann J, West AJ, Renforth P, Kohler Pet al (2013)

[373] Sanna A, Uibu M, Caramanna G, Kuusik R & Maroto-Valer MM (2014)

[374] Olajire AA (2013)

[375] Schuiling RD (2014)

suited to industrial development[376,377,378]; others are intended for field deployment. The latter are the main focus of interest here, particularly the application of olivine $(Fe,Mg)_2SiO_4$ and other reactive silicates that might make a significant contribution to climate stabilization[379]. In CBD (2012), such potential was noted; however, concern was also expressed regarding the bulk of material required to be processed, the potential for undesirable side-effects, and uncertainties regarding overall cost-effectiveness. The NAC/NRC report reached similar conclusions, while identifying the need for further research. Topics considered important included:

- Mineral dissolution (or other chemical transformations) for CO_2 conversion to bicarbonate or carbonate; potential approaches include mineral pre-treatment, enhancement of acid-base reactivity, synergies with biotic activity, enzymes and electrochemistry
- Experiments and modelling to determine the environmental benefits, impacts, and fate of (bi)carbonate addition to soils, watersheds and the ocean.
- Better determining the environmental impacts of mineral extraction and seawater pumping (where needed), especially relative to downstream environmental benefits and relative to the impacts of other CDR methods.
- Testing and modelling various approaches at meaningful scales[380] to better determine the life cycle economics, net cost/benefit, optimum siting, and global capacities and markets of accelerated mineral weathering in the context of CDR.

152. Recent relevant research on the use of silicate rock flour for enhanced weathering has included a budget[381] of potential CO_2 sequestration against associated CO_2 emissions, using global spatial data sets of potential source rocks, transport networks and application areas in optimistic and pessimistic scenarios. That study showed that 0.5-1.0 t CO_2 might be removed from the atmosphere per tonne of rock mined and processed, with an energy cost of 1.6-9.9 GJ per tonne CO_2 sequestered. Most of the energy requirements related to rock-crushing, with the rate of weathering increasing markedly as particle size decreases (and relative surface area increases). Operational costs cover a wide range: within a single study[382] these were estimated at between $24 -578 per tonne CO_2 sequestered, depending on rock type and other assumptions.

153. Application of olivine to low pH soil can have beneficial effects for crops and grassland. However, it must remain within limits to avoid imbalances in plant nutrition, and to avoid nickel accumulation – with potential for toxic impacts[383]. Factors affecting olivine dissolution in soil are not well-understood, and can be several orders of magnitude slower than those predicted from kinetic information derived from laboratory studies[384]. The potential for mycorrhizal fungi of forest trees[385] and other microbes to accelerate natural weathering of both carbonates and silicates warrants further study, also the potential role of olivine in soil stabilization (on slopes) and other ground improvement[386] – for both climatic and geotechnical geoengineering.

154. The large-scale application of olivine to the land surface would increase the alkalinity and pH of natural waters, with potential implications for rivers, coastal waters and the open ocean[387]. In addition to a possible reduction in

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[376] Rau GH, Carroll SA, Bourcier WL Singleton MJ et al. (2013)

[377] Gadikota G, Swanson EJ, Zhao HJ & Park AHA (2014)

[378] Kirchofer A, Brandt A, Krevor S, Prigiobbe V & Wilcox J (2012)

[379] Cressey D (2014)

[380] The scale required to be (climatically) meaningful is discussed in some detail in the NAS/NRC report.

[381] Moosdorf N, Renforth P & Hartmann J (2014)

[382] Renforth P (2012)

[383] ten Berge HFM, van der Meer HG, Steenhuizen JW, Goedhart PW et al. (2012)

[384] Renforth P, von Strandmann PAEP & Henderson GM (2015)

[385] Thorley RMS, Taylor LL, Banwart SA, Leake JR & Beerling DJ (2014)

[386] Fasihnikoutalab MH, Westgate P, Huat BBK, Asadi A et al. (2015)

[387] Hartmann J, West AJ, Renforth P, Kohler P et al. (2013)

ocean acidification in the affected marine waters, favouring calcifying organisms, enhanced Si availability might favour diatoms (where Si is limiting). If the latter effect were significant, it would strengthen the biological carbon pump, thereby providing a second mechanism for removing CO_2 from the atmosphere. A land-based 'enhanced weathering' CDR method might also then become a technique for 'enhancing ocean productivity'.

155. The direct addition of olivine to open ocean surface waters[388] and coastal areas[389] has also been proposed. While the ecological implications of such interventions have not been experimentally investigated, an optimum grain size of 1µm has been estimated for olivine additions to the open ocean. For coastal waters, it has been proposed that olivine could be added to high-energy, sandy or gravel beaches, with natural abrasion then assisting in reducing grain size and thereby providing a cost-effective, slow-release mechanism[390]. Nevertheless, effects on water clarity could be a concern (particularly for open ocean treatments); e.g. reducing the suitability of the technique for local amelioration of ocean acidification around coral reefs. 'Upstream' treatment might, however, avoid that risk.

156. Scenarios for global-scale ocean alkalinization have been investigated in models[391,392] simulating the addition of quicklime (CaO), lime ($Ca(OH)_2$) and limestone ($CaCO_3$) to the open ocean. Very large quantities of alkalinity (in ratio 2:1 with respect to emitted CO_2)[393] need to be added over very large ocean areas to substantially reduce atmospheric CO_2 and mitigate ocean acidification, accelerating the natural weathering flux by two orders of magnitude and causing major biogeochemical perturbations. High energy costs are associated with the production of quicklime or lime, giving further constraints on the viability of such approaches for the cost-effective delivery of climatic benefits.

3.7 DIRECT AIR CAPTURE

157. Due to the relatively low concentration of CO_2 in ambient air, the cost of its direct air capture (DAC) is necessarily higher than the removal of CO_2 from flue gases produced by fossil fuel power stations, i.e. the capture part of conventional CCS. Thus it is unlikely that DAC will become economically viable until fossil fuel CCS is ubiquitous, and further measures to constrain atmospheric CO_2 are necessary. Nevertheless, there is arguably need (and scope) to improve the technique[394,395], as an option for dealing with CO_2 emissions from mobile dispersed sources, as an insurance for CO_2 leakage from storage, and as a relatively risk-free means of achieving negative emissions. Cost estimates used in CBD (2012) were ~ US$ 1000 per tonne CO_2 captured[396]; more recent estimates have been substantially less, e.g. US$ 60-100 /t CO_2[397,398], although it is not clear if those costs are fully comparable (e.g. capture only, or capture, regeneration and storage). Moisture-swing sorbents[399,400] are now considered the preferred DAC process: they absorb CO_2 when wet, releasing it when dry.

158. The adverse environmental implications for DAC primarily relate to their land and water requirements, and, potentially, the processes involved with CO_2 storage. As noted in CBD (2012), such impacts are likely to be very much less than for other CDR techniques.

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[388] Köhler P, Abrams JF, Völker C, Hauck J & Wolf-Gladrow DA (2013)

[389] Schuiling RD & de Boer PL (2013)

[390] Schuiling RD & de Boer PL (2011)

[391] Paquay FS & Zeebe RE (2013)

[392] Keller DP, Feng EY & Oschlies (2014)

[393] Ilyina T, Wolf-Gladrow D, Munhoven G & Heinze C (2013)

[394] Lackner SK, Breman S, Matter JM, Park AHA et al. (2012)

[395] Goeppert A, Czaun M, Prakash GKS & Olah GA (2012)

[396] House KZ, Baclig AC, Ranjan M, van Nierop EA et al (2011)

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[400] Wang T, Liu J, Fang M & Luo Z (2013)

3.8 REMOVAL OF GREENHOUSE GASES OTHER THAN CO_2

159. CDR techniques are, by definition, focused on CO_2. There is therefore the possibility of inadvertent neglect of processes that might remove other greenhouse gases from the atmosphere; e.g. methane and nitrous oxide[401]. A pre-occupation on carbon removal may also inadvertently miss important changes in the release or uptake of other greenhouse gases fluxes[402] – that may change apparent climatic benefits to actual climatic harm[403].

160. The possibility of removing methane (CH_4) from the atmosphere has received some attention, because of its global warming potential (86 times greater than CO_2 over 20 years, 34 times greater over 100 years; both values including climate-carbon feedbacks[404]) and since there can be relatively high local concentrations near landfill sites, rice paddies, farms with intensive livestock production, and sites of shale gas extraction[405].

161. There are also concerns that future CH_4 emissions could increase dramatically, from thawing permafrost[406,407], and releases from sub-sea methane clathrates[408,409] and sub-glacial sources[410] . While the scale and likelihood of such flux events is uncertain[411], techniques that might address their consequences have attracted research interest[412]. Both biological[413,414] and chemical[415],[416] removal approaches have been proposed, but are not yet sufficiently developed for field application. Vegetation can itself be a sink for CH_4[417] , and there may be potential for manipulation of the processes involved.

162. If large quantities of CH_4 were to be deliberately removed from the atmosphere, it is likely that it would be used for fuel. Without CCS, that would add CO_2 to the atmosphere, i.e. still contributing to global warming, but with much reduced effects. This would represent an additional anthropogenic emission if 'fossil' CH_4 were targeted (e.g. in the vicinity of shale gas extraction), but that status would be more ambiguous for biogenic CH_4 (derived from a mixture of natural and agricultural sources) or if the CH_4 were captured from marine vents or thawing permafrost.

163. No information has been found on research on the removal of N_2O from ambient air. Agricultural emission reduction has, however, been proposed, using nitrification inhibitors[418]. As noted in Section 3.4 above, the application of biochar may also be effective in that regard[419,420].

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401 O Boucher & Folberth GA (2010)
402 Dondini M, Richards M, Pogson M, McCalmont J et al. (2015)
403 Li C, Frolking S & Butterbach-Bahl K (2005)
404 IPCC (Intergovernmental Panel on Climate Change) (2013) [Table 8.7]
405 Howarth RW (2014)
406 Whiteman G, Hope C & Wadhams P (2013)
407 Hope C & Schaefer K (2015)
408 Shakhova N, Semiletov I, Leifer I, Sergienko V et al. (2014)
409 Ruppel CD (2011)
410 Wadham JL, Arndt S, Tulaczyk S, Stibal M et al. (2012)
411 Notz D, Brovkin V & Heimann M (2013)
412 Stolaroff JK, Bhattacharyya, Smith CA, Bourcier WL et al. (2012)
413 Yoon S, Carey JN & Semray JD (2009)
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415 Kim J, Maitui A, Lin L-C, Stolaroff JK et al. (2013)
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417 Sundqvist E, Crill P, Mölder, Vestin P & Lindroth A (2012)
418 Di HJ & Cameron KC (2006)
419 Cayuela LM, Sanchez-Monedero MA, Roig A et al. (2013)
420 Saarnio S, Heimonen K & Kettunen R (2013)

CHAPTER 4

POTENTIAL IMPACTS ON BIODIVERSITY OF CLIMATE GEOENGINEERING ACHIEVED BY SUNLIGHT REFLECTION METHODS AND OTHER PHYSICALLY-BASED TECHNIQUES

4.1 INTRODUCTION AND GENERAL CONSIDERATIONS

164. This chapter focuses on recent advances in knowledge and understanding of sunlight reflection methods, also known as solar radiation management (SRM). Other physically-based techniques are also briefly covered. As in Chapter 3, attention is directed at new literature, major reviews and aspects not previously considered in CBD (2012). Despite the abundance of recent literature on SRM, hardly any research has given specific attention to impacts on ecosystems and biodiversity. Environmental consequences are therefore mostly discussed in terms of climatic effectiveness and agricultural impacts.

165. Model-based simulations of the climatic consequences of SRM provide the main scientific representation of the intended positive impacts (reduction in magnitude of future climatic damage, both for human society and biodiversity) and negative impacts (undesirable additional consequences). Natural analogues, e.g. volcanic eruptions, and historical changes in tropospheric aerosol levels ('global dimming' due to anthropogenic pollutants) also provide relevant information. The quantitative determination of such impacts depends on the comparison conditions. While the most straightforward comparisons are with present-day conditions, those are not an available future option (section 1.4); thus the negative impacts of SRM methods cannot be directly equated to their inexactness in achieving a future match to present-day conditions.

166. An important feature of some, but not all, SRM techniques is that it is likely their development, deployment and climatic effects could all be relatively rapid – with the potential to slow, stop or reverse global warming within months or years, rather than the decadal to century time-scale of many CDR techniques. Such readiness can be perceived as threatening, with the risk of unilateral action providing a potential cause of geopolitical conflict[421,422]; it can also regarded as uniquely advantageous[423] ('only SRM can halt climate change') and a stimulus for international cooperation[424]. The framing, ethics and governance of SRM are discussed further in Chapter 5, with an additional bibliography in Annex 1.

167. SRM is less closely linked to the cause of climate change (greenhouse gases) than CDR, affecting the climate through different processes (Fig 1.2). While modelling studies consistently show that SRM is able to compensate for radiative forcing by anthropogenic greenhouse gases at the global scale, it is near-inevitable that there will be different climate patterns at the regional scale. A range of comparisons are possible to assess the climatic effectiveness of SRM in models, in relation to scenarios based on current emission trajectories or similar (i.e. the unmitigated IPCC scenario RCP 8.5, or quadrupled CO_2); moderate-to-strong conventional mitigation (RCP 6.0, RCP 4.5), that still would result in 'dangerous' climate change; or in the context of strong mitigation plus CDR geoengineering, i.e. to help achieve RCP 2.6, or to meet more exacting radiative forcing and temperature limits. However, the 'success' of SRM cannot be judged by comparing its effects to present day climate conditions, since – even if all greenhouse gas emissions were to cease tomorrow – the Earth is already committed to further warming of ~0.6°C as a result of slow responses in the climate system[425].

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[421] Maas A & Scheffran J (2012)

[422] Nightingale P &Cairns R (2014)

[423] Keith D (2013)

[424] Horton JB (2011)

[425] IPCC (Intergovernmental Panel on Climate Change) (2013) [FAQ 12.3, p 1106-1107]

168. Because there is also political, socioeconomic and technological inertia, high greenhouse gas emissions are expected to continue for several years[426]: it will therefore be extremely challenging to have any confidence of staying much below 2°C of warming[427,428], even with the combination of an exceptionally-high rate of decarbonization of energy generation[429] and rapid cessation of greenhouse emissions from all other sources. However, a lower limit of, say, 1.5°C could potentially be much more achievable if SRM were included in a portfolio of climate policies[430], with its deployment based on a "temporary, moderate and responsive scenario"[431]. Furthermore, SRM might be used to slow, rather than fully counteract temperature change under RCP 4.5 or RCP 6.0 scenarios[432], or only used on a regional basis[433,434].

169. There was only limited consideration of SRM in IPCC AR5 (mostly in 8 pages of the WG I report). In contrast, text on SRM techniques was ~70% longer than for CDR techniques in the NAS/NRC reports[435,436], and ~40% longer in the EuTRACE report[437], although both emphasized SRM's high risks and uncertainties. SRM has also been the main theme of at least six recent books on climate geoengineering[438,439,440,441,442,443] and is the overwhelming concern of governance and acceptability discussions, reflected in many commentaries questioning the desirability of such an approach[444,445,446]. In some cases, geoengineering is considered synonymous with SRM (and, more specifically, stratospheric aerosol injection). According to its footnote, definition (d) in CBD decision XI/20 is intended to limit geoengineering to SRM (see Annex 2).

170. Comparative studies between different SRM methods are limited. While relative effectiveness crucially depends on the scaling and feasibility assumptions used in the models, insights can be obtained on how different techniques might affect temperature and precipitation, i.e. the main climatic components that SRM deployment is intended to stabilize. An intercomparison[447] between three surface SRM methods (albedo changes for crops, desert and ocean), two atmospheric SRM methods (global-scale stratospheric aerosol injection and marine cloud brightening) and cirrus thinning, showed that some, but not all, SRM methods may be able to fully counter-act the climatic forcing of RCP 4.5, but they would also change precipitation relative to present-day conditions. The models showed that changes could be potentially catastrophic in the case of desert albedo modification (drying the Amazon, Sahel, India and China), while generally showing decreased precipitation (particularly over the ocean) for large-scale SRM methods. However, in model projections, cirrus cloud thinning slightly increases global mean precipitation (+0.7% compared to present-day). Only very small, and statistically insignificant, climate forcing changes are obtained from the modelled modification in crop albedo.

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[427] Anderson K & Bows A (2012)

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[435] National Academy of Sciences (2015b)

[436] National Academy of Sciences (2015a)

[437] Schäfer S, Lawrence M, Stelzer H, Born W et al.(2015)

[438] Keith D (2013)

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[444] Hamilton C (2013c)

[445] Sillmann J, Lenton TM, Leverman A, Ott K et al. (2015)

[446] ETC Group: Mooney P, Wetter KJ & Bronson D (2012)

[447] Crook J, Jackson LS, Osprey SM & Forster PM (2015)

171. Reduced global-average precipitation (compared to present day) is a common feature of SRM models that are tuned to fully counteract anthropogenic global warming. Not surprisingly, that effect raises concerns with regard to agricultural productivity, food security and natural ecosystems. However: i) reduction in precipitation depends on the scale of SRM applied – a match to current values is achievable in models if some relative temperature increase is tolerated[448]; and ii) soil moisture may be a more important parameter than precipitation in determining terrestrial productivity, noting that water use efficiency is expected to increase in response to elevated CO_2[449].

172. In CBD (2012), discussion of SRM was grouped under two main headings: generic SRM that causes uniform dimming, and technique-specific considerations. Headings used here cover stratospheric aerosol injection, marine cloud brightening, albedo management and other physically-based techniques. There is no separate section here on solar dimming; e.g. as might be caused by mirrors or dust in space. While there have been research studies[450,451] on how a dust-shade in space might operate, the irreversibility of such an intervention means it is unlikely to be taken seriously as a policy option. The eight key messages relating to SRM in CBD (2012) are re-presented in Table 4.1. With some minor provisos, these summary statements are still considered valid.

Table 4.1. Main conclusions from CBD (2012) relating to sunlight reflection methods (SRM), with some additional information (in italics) on subsequent developments. For full text, see Annex 3.

Key message text originally in bold relating to SRM chapter; re-numbered
1. SRM, if effective in abating the magnitude of warming, would reduce several of the climate-change related impacts on biodiversity. Such techniques are also likely to have other, unintended impacts on biodiversity.
2. Model-based analyses and evidence from volcanic eruptions indicate that uniform dimming of sunlight by 1–2% through an unspecified atmospheric SRM measure could, for most areas of the planet, reduce future temperature changes projected under unmitigated greenhouse gas emissions. *SRM capabilities confirmed by multi-model comparisons. Greater focus on inter-hemispheric and regional-scale variability, and technique-specific effects.*
3. SRM would introduce a new dynamic between the heating effects of greenhouse gases and the cooling due to sunlight reduction. *Note that all RCP scenarios (and CDR geoengineering in response to overshoot) also represent novel climatic conditions.*
4. The amount of anthropogenic CO_2 in the atmosphere is unaffected by SRM. Thus SRM would have little effect on ocean acidification and its associated impacts on marine biodiversity, nor the impacts (positive or negative) of elevated atmospheric CO_2 on terrestrial ecosystems. *Although effects are indirect, SRM can influence the carbon cycle with (modest) reduction in ocean acidification*
5. Rapid termination of SRM, that had been deployed for some time and masking a high degree of warming due to continued greenhouse-gas emissions, would almost certainly have large negative impacts on biodiversity and ecosystem services. *Termination effects could be lessened or if CDR and emission reductions were co-actions with 'temporary' SRM*
6. Stratospheric aerosol injection, using sulphate particles, would affect the overall quantity and quality of light reaching the biosphere; have relatively minor effects on atmospheric acidity; and could contribute to stratospheric ozone depletion.
7. Cloud brightening is a more localized SRM proposal, with its application likely to be limited to specific ocean areas. The predictability of its climatic impacts is currently uncertain
8. Surface albedo changes would need to be deployed over very large land areas (sub-continental scale) or over much of the global ocean to have substantive effects on the global climate, with consequent impacts on ecosystems. Strong localized cooling could have a disruptive effect on regional weather patterns. *CDR techniques may also involve significant albedo changes. 'Ocean foam' technique proposed for modification of ocean albedo*

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[448] Keith DW & MacMartin DG (2015)

[449] Leakey ADB, Ainsworth EA, Bernacchi CJ, Roges A et al. (2009)

[450] Bewick R, Sanchez JP & McInnes CR (2012a)

[451] Bewick R, Sanchez JP & McInnes CR (2012b)

4.2 STRATOSPHERIC AEROSOL INJECTION (SAI)

173. This technique has also been called stratospheric aerosol albedo modification (SAAM). The wide range of possible environmental, scientific, economic, political, social and individual consequences of the SAI approach are summarized in Figure 4.1, with specific issues discussed below.

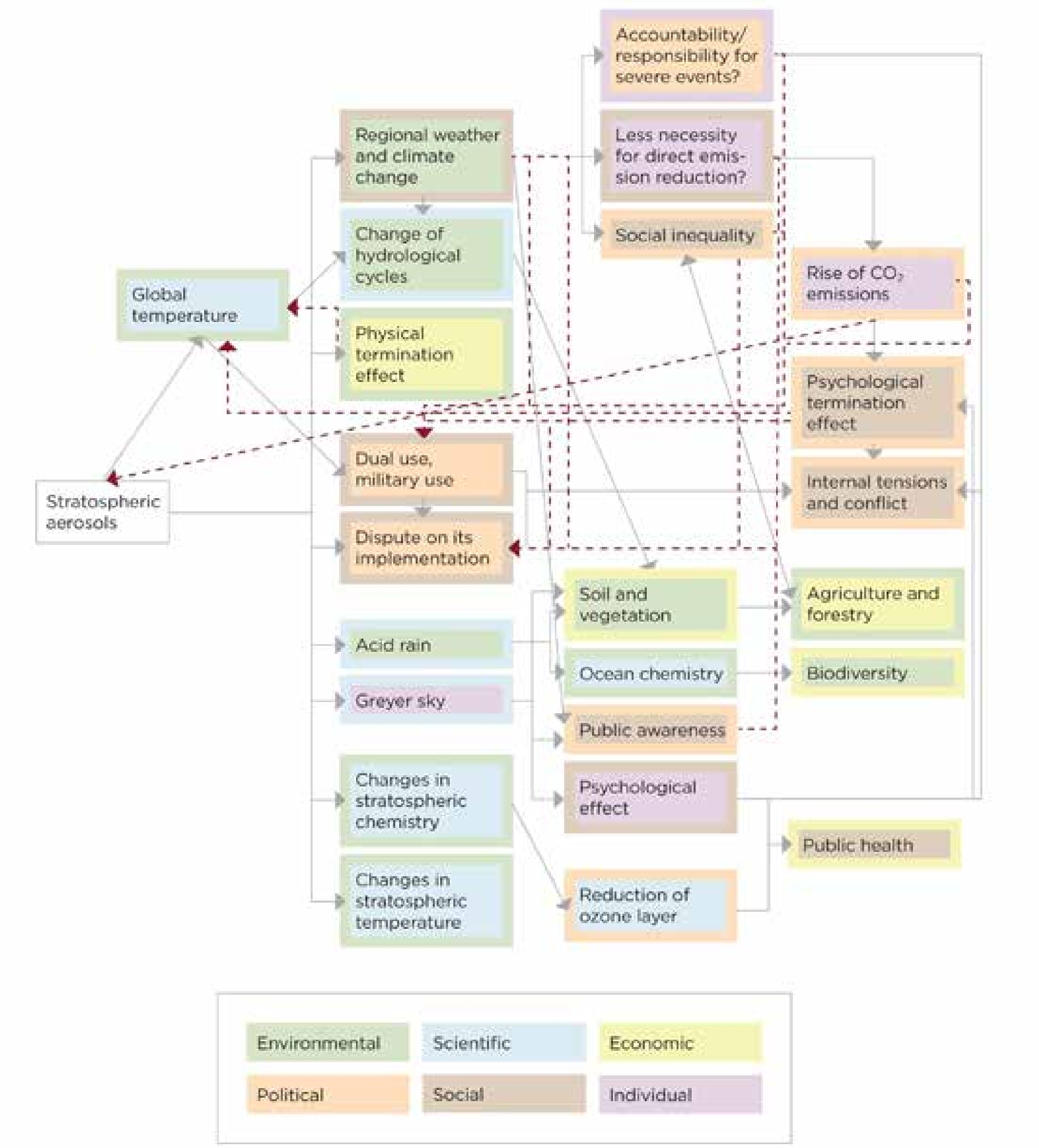

Figure 4.1 Schematic overview of possible implications and impacts of SRM using stratospheric aerosol injection (SAI). Grey arrows, plausible consequences; red arrows, feedbacks. Colour coding key relates to main (in box) and secondary (surrounding border) nature of consequences. Note that potential effects of changes in light levels on animal behaviour (terrestrial, freshwater and marine) are not included. Source: JSA Link & J Scheffran; ref[452]. Reprinted with permission.

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[452] Schäfer S, Lawrence M, Stelzer H, Born W et al. (2015)

174 Model uncertainty is a crucial issue for SRM, affecting the statistical confidence and credibility that can be given to the effectiveness of the approach – and linked to wider concerns relating to the reliability of long-term climate projections. To address such issues, the World Climate Research Programme developed the Coupled Model Intercomparison Project, with its 5th phase (CMIP5) used for the IPCC's 5th Assessment Report. The **Geoengineering Model Intercomparison Project** (GeoMIP)[453] is a sub-project of CMIP5, using simulations from the larger project as controls for solar geoengineering model experiments, including SAI. While a multi-model approach is inherently more robust, it also can identify the mechanisms responsible for differences between models, hence gaps in understanding and the need for further theoretical or practical research.

175. The first two GeoMIP experiments (G1 and G2) simulated the application of geoengineering by a reduction in solar constant, i.e. solar dimming (that might be achieved by space-based methods, see above). Subsequent experiments, G3 and G4, simulated SAI using sulphate aerosols, in either a time-varying way or at the constant rate of 5 Tg SO_2 yr^{-1} for the period 2020-2070 (in comparison, the Mt Pinatubo eruption caused a one-off release of 17 Tg SO_2) in the context of an RCP 4.5 warming scenario. Much higher injection rates (up to 45 Tg S yr^{-1}) would, however, be needed to maintain 2020 temperatures if 'business as usual' emission rates were to continue[454]. Important outcomes from the GeoMIP experiments included:

- Space-based solar dimming and SAI have different regional-scale consequences for temperature and precipitation[455], an effect observed in other comparisons between the two techniques[456,457].
- The response of vegetation to elevated CO_2 levels (and how this is represented in the models) can play a major role in determining the terrestrial hydrological response to solar geoengineering[458]. In the G1 experiment (abrupt 4-fold increase of CO_2, with solar dimming), SRM caused changes in net primary production with regional differences due to interactions between temperature, water stress and CO_2 fertilization effects. Such effects were smaller in models that included a nitrogen cycle[459].
- Crop-specific responses to a 50 year G2 scenario (with CO_2 increasing at 1% per year) have been examined for China. Results from 10 models indicated that maize production could rise, while rice production could slightly decrease[460].
- The GeoMIP G2 experiment confirmed that a rapid increase in global mean temperature (of ~ 1°C per decade) would follow cessation of solar dimming, with faster warming at high latitudes and over land[461] . There was, however, less agreement between the 11 models regarding the patterns of changes in precipitation and primary production. Termination effects are discussed further below.
- In the GeoMIP G4 experiments, SAI caused a significant decrease in average global ozone, of 1.1-2.1 Dobson Units. As a result, UV-B radiation in polar regions increased by ~5% (up to ~12% in springtime); elsewhere, such effects were offset by screening effects of the added aerosols[462].
- The G3 and G4 experiments slowed, but were not able to halt, Arctic sea ice loss (currently declining at ~12% per decade); in two of the five models total September ice loss still occurred before 2060[463].

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[453] Kravitz B, Robock A, Forster PM, Haywood JM et al. (2013)

[454] Niemeier U & Timmreck C (2015)

[455] Yu XY, Moore JC, Cui XF, Rinke A et al. (2015)

[456] Kalidindi S, Bala G, Modak A & Caldeira K (2015)

[457] Ferraro AJ, Highwood EJ & Charlton-Perez AJ (2014)

[458] Irvine PJ, Boucher O, Kravitz B, Alterskjaer K et al. (2014)

[459] Glienke S, Irvine PJ & Lawrence MG (2015)

[460] Xia L, Robock A, Cole J, Curry CL et al. (2014)

[461] Jones A, Haywood JM, Alterskjær K, Boucher O et al. (2013)

[462] Pitari G, Aquila V, Kravitz B, Robock A et al. (2014)

[463] Berdahl M, Robock A, Ji DY, Moore JC et al. (2014)

176. The scale of aerosol additions needed to **maintain Arctic sea ice through SAI** has been explored in two other recent modelling studies (also see Box 4.1). In the first[464], a four-fold increase in aerosol injection to the Arctic stratosphere compared to the rest of the world was found to be necessary to achieve that goal. In the second, more interactive, study[465], an imagined (and simplified) decision-making process was simulated by a predictive control regime[466] based on imperfect 'observations' of the model behaviour, together with a separate model that forecast 'optimal' decision pathways under a RCP 4.5 warming scenario. The simulation began in 2018; however, Arctic ice cover was not restored in the model until 2043.

177. Although other outcomes of that simulation would have been possible, the question is whether there would be the policy commitment 'in the real world' to continue such an intervention for 25 years before it achieved its goals? The answer to that would almost certainly depend on whether climate changes elsewhere might also, either coincidentally or causally, be linked to the Arctic-focussed SAI deployment. While the former cannot be ruled out, the latter also seems very likely. Thus there is strong evidence from both observational (analysis of past volcanic activity) and theoretical (model-based) studies that **hemispherically asymmetric forcing by stratospheric aerosols** can have dramatic effects on rainfall patterns in Africa, particularly the Sahel, and north-eastern South America[467], with potentially catastrophic regional-scale ecological and socioeconomic consequences. The implications of northern hemisphere-only SAI are the most serious; Figure 4.2. Similar potential shifts in the Inter-Tropical Convergence Zone (ITCZ) have been found in another modelling study[468] that limited solar radiation reduction to high latitudes.

178. A global framework for **regional risk assessment** arising from SAI deployment has been developed[469]. Based on a scenario of 4 x CO_2 concentrations and the use of uniform SAI to restore future global temperatures to 20th century levels, substantial precipitation change (compared to 20th century) could be experienced by 42% of the Earth's surface area, containing 36% of its population and 60% of its gross domestic product. However, in a separate study[470] linked to the GeoMIP project, adjustments to the scale of solar irradiance forcing in a multi-model context enabled temperature and precipitation metrics to be closer in all 22 regions to the pre-industrial conditions than for the 4 x CO_2 scenario.

179. The above studies modelled the effects of sulphate aerosols to mimic volcanic injections of stratospheric aerosol. However, the composition and size of volcanic sulphuric acid particles are far from optimal for scattering solar radiation. The suitability of other **aerosols that greatly increase the amount of light scatter** is being investigated[471,472] with candidate materials including alumina, silica oxides and diamond particles. Their advantages would be less mass required for the same radiative effect; also less ozone loss, and less stratospheric heating.

180. The potential **effects of SAI on the quality and quantity of light** reaching the Earth's surface, and possible consequences for organisms and ecosystems, are important considerations. Large-scale SAI would reduce the amount of total light; however, the sky might appear brighter (due to the increase in white light), likely to be discernible in rural areas[473]. Comparable global dimming of 2-3% (and regionally higher, up to 10-15%)[474] occurred, and was largely unnoticed, in the period 1960-1990 due to tropospheric pollution, primarily by SO_2 and black carbon. For terrestrial plants, the effects of decreased photosynthetically active radiation under SAI would be

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[464] Tilmes S, Jahn A, Kay JE, Holland M & Lamarque J-F *(*2014*)*

[465] Jackson LS, Crook JA, Jarvis A, Leedal D et al. (2015)

[466] MacMartin DG, Kravitz B, Keith DW & Jarvis A (2013)

[467] Haywood JM, Jones A, Bellouin N & Stephenson D (2013)

[468] MacCracken MC, Shin H-J, Caldeira K & Ban-Weiss GA (2013)

[469] Ferraro AJ, Charlton-Perez AJ & EJ Highwood (2014)

[470] Kravitz B, MacMartin DG, Robock A, Rasch PJ et al (2014)

[471] Pope FD, Braesicke P, Grainger RG, Kalberer M. et al (2012)

[472] Weisenstein DK & Keith DW (2015)

[473] Kravitz B, MacMartin DG & Caldeira K (2012)

[474] Wild M, Gilgen H, Roesch A, Ohmura A et al. (2005)

countered by diffuse light increasing the net efficiency of carbon fixation[475,476,477]. A modelling study[478] indicates that similar re-balancing, but by different mechanisms, may also occur for marine ecosystems: reductions of surface irradiance by as much as 90% did not, surprisingly, decrease depth-integrated gross primary production in a stratified, oligotrophic subtropical ocean ecosystem (typical of large areas of the global ocean). However, the chlorophyll maximum, and depths of greatest production and biomass occurred nearer to the surface.

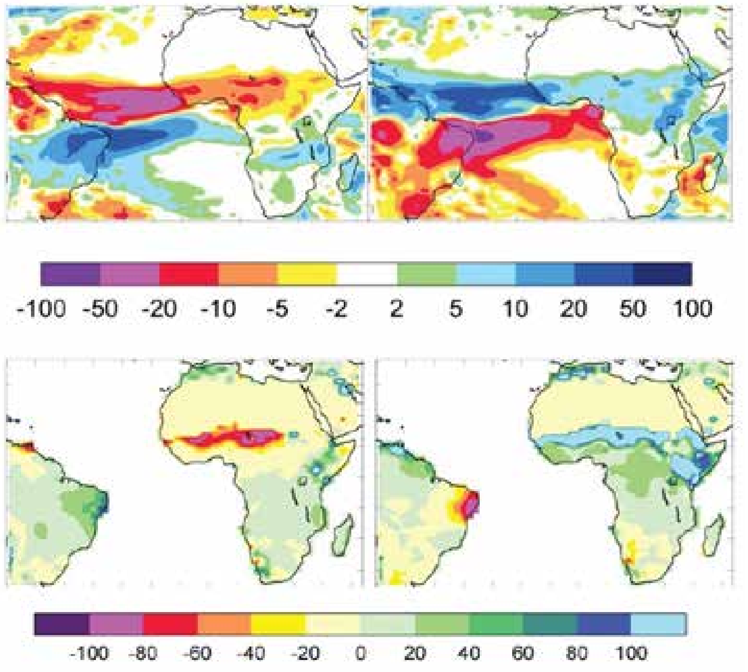

Figure 4.2 Modelled effect of hemispherically asymmetric aerosol sulphate injection. *Upper maps*: Change in mean precipitation (mm/month) for the period 2020-2070 when SO_2 is injected into the northern hemisphere only (left) or southern hemisphere only (right) in comparison to RCP 4.5 scenario. *Lower maps:* Percentage change in net primary production under the same conditions. Reprinted by permission from Nature Publishing Group (MacMillan Publishers Ltd); Haywood et al. (2013) *Nature Climate Change* 3, 660-665.

181. Since SRM methods such as SAI do not address the causes of greenhouse gas emissions, **ocean acidification** will continue, driven by increases in atmospheric CO_2. Nevertheless, the often-made statement that "ocean acidification is unaffected by SRM" is technically incorrect, since SRM cooling reduces biogeochemical feedbacks that would otherwise release additional CO_2 from terrestrial sources (enhanced soil carbon fluxes, tundra methane releases and forest fires)[479]. The magnitude of the SRM effect on ocean acidification has been estimated as a (beneficial) increase in the mean surface ocean pH of 0.05 units by 2100 relative to IPCC A2 scenario[480,481] and an increase of 0.09 units relative to RCP 8.5[482]. The net pH changes relative to present-day values would, however, still be negative, the latter study estimated a pH decrease of 0.20 under RCP 8.5 with SRM, compared to the decrease of 0.29 without. The comparable pH increase achieved in the same study by model-simulated large-scale ocean alkalinization – a

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[475] Mercado LM, Bellouin N, Sitch S, Boucher O et al. (2009)

[476] Wild M, Roesch A & Ammann C (2012)

[477] Kanniah KD, Beringer J, North P & Hutley L (2012)

[478] Hardman-Mountford NJ, Polimene L, Hirata T, Brewin RJW & Aiken J (2013)

[479] Williamson P & Turley C (2012)

[480] Matthews HD, Cao L & Caldeira K (2009)

[481] The A2 scenario was used in the IPCC Fourth Assessment Report. It resulted in an atmospheric CO2 level of ~800 ppm by 2100 (cf ~940 ppm for RCP 8.5)

[482] Keller DP, Feng EY & Oschlies (2014)

technique that might be thought to be particularly effective in countering pH change – was 0.06 relative to RCP 8.5, i.e. less than that achieved by SRM.

182. The effects on ocean acidification are further complicated by interactions with temperature, affecting carbonate saturation state and the biological response to pH reduction[483]. For warm-water corals, the temperature reduction expected to be achieved by SRM cooling would, in model simulations[484] reduce the occurrence of temperature-driven bleaching. However, since aragonite saturation state and calcification rates are temperature-dependent, the ocean acidification stress is likely to be more severe. For cold-water corals, saturation state effects may be the most important, determining the physical sustainability of their reef structures[485] and hence abundances and distributional limits. Despite such complexity, the overall impact of ocean acidification will primarily be determined by atmospheric CO_2 levels - and these could only be indirectly and partly reduced by SRM.

Box 4.1 Can geoengineering save Arctic sea-ice? The Arctic can be considered to be the 'barometer of global climate change' where impacts have already occurred more rapidly than elsewhere – as documented in IPCC AR5 WG I and WG II reports. Such processes are projected to continue to do so in the future, driven by Arctic amplification processes[486], with likely linkage to extreme weather in mid-latitudes[487], and potential risk of irreversible change ('tipping points')[488,489], e.g. methane release from tundra[490] or marine sediments[491]. Many recent changes have been more rapidly than had been expected from models, particularly with regard to decreases in sea ice cover and thickness. Their combined effect has been a decline of sea ice volume of ~70% since 1980, with the likelihood that nearly ice-free summers will occur either by 2020 (by extrapolation) or by 2040 (from models)[492]. Sea ice cover is of very great importance to the entire Arctic ecosystem[493], as well as charismatic species such as polar bears and walrus. The climatological importance of sea ice loss is that it provides a strong positive feedback for further climate change, via albedo decrease, although with theoretical potential for recovery[494].

Such issues have led to calls for action that climate geoengineering is needed as a matter of urgency, primarily using SRM techniques, in order to prevent further Arctic sea ice loss[495]. The effectiveness of a range of methods is discussed in this chapter (Sections 4.2, 4.3 and 4.4), with references given to specific studies. In summary:

- Global stratospheric aerosol injection (SAI) at the scale necessary to keep future global radiative forcing to 2020 levels is very unlikely to prevent total loss of Arctic summer sea ice
- In order to prevent such an outcome, aerosol injection rates in the Arctic would probably need to be ~4 times higher than for the rest of the world
- Such an Arctic focus for SAI intervention would result in an interhemispheric asymmetry, with greater northern hemisphere aerosol forcing causing a southern shift in the Inter-Tropical Convergence Zone, with dramatic consequences for the environment, agriculture and socioeconomics for large areas of Africa
- There may be potential for marine cloud brightening (MCB) to be developed in an Arctic-specific way, but that has yet to be demonstrated
- Generic enhancement of ocean surface albedo could only achieve ~40% of Arctic sea-ice cover in a 4 x CO_2 simulation
- Cirrus cloud thinning may be able to assist in stabilising or restoring Arctic sea ice, since its effects are greatest at high latitudes. However, many uncertainties currently relate to this technique.

Overall, there is no 'obvious solution' through SRM. This is a consequence of global warming patterns driven by greenhouse gases, the main cause of the Arctic amplification effect[496].

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[483] CBD (Secretariat of the Convention on Biological Diversity) (2014c)

[484] Kwiatkowski L, Cox P, Halloran PR, Mumby PJ & Wiltshire AJ (2015)

[485] Hennige SJ, Wicks LC, Kamenos NA, Perna G et al. (2015)

[486] Overland JE (2014)

[487] Francis JA & Vavrus SJ (2012)

[488] Lenton TM (2012)

[489] Wadhams P (2012)

[490] Hope C & Schaefer K (2015)

[491] Shakhova N, Semiletov I, Leifer I, Sergienko V et al. (2014)

[492] Overland JE & Wang M (2013)

[493] Eamer J, Donaldson GM, Gaston AJ, Kosobokova KN et al. (2013)

[494] Serreze MC (2011)

[495] Nissen J (2015)

[496] Pithan F & Mauritsen T (2014)

183. It is of course possible that SAI deployment might be accompanied by CDR to stabilize, and potentially reduce, levels of atmospheric CO_2. Such a strategy would allow 'temporary' (decadal to century) SAI deployment[497,498] that would greatly reduce **SRM termination effects.** However, the alternative – that greenhouse gas levels continue to rise – would be highly risky, since very rapid temperature increases (and other climatic changes) would occur if SAI were to be started, then subsequently discontinued, for whatever reason. The consequences for biodiversity and ecosystem services of such termination effects would be highly damaging, since the scope for biological adaptation would be very much reduced, as discussed in CBD (2012). The climatic changes likely to occur if SRM is abruptly terminated have been explored further by single-model[499,500] studies and by multi-model[501] comparisons; however, environmental consequences have not been given explicit attention.

4.3 MARINE CLOUD BRIGHTENING (MCB)

184. This proposed technique would involve the large-scale addition of cloud condensation nuclei (CCN) to the lower atmosphere, to enhance the production, longevity and brightness of stratocumulus clouds. Areas with existing low-lying cloud cover (rather than cloud-free areas) would mostly be targeted. Sea salt particles would provide the CCN, by finely spraying seawater; the technique is also known as sea-spray climate geoengineering. The main advantage of MCB relates to its controllability, with the intended climatic benefits arising from the cumulative effects of many locally-induced changes to cloud characteristics. However, substantive uncertainties remain regarding the representation of cloud behaviour in climate models, and CBD (2012) expressed concern regarding the regional-scale (un)predictability of the climatic and environmental impacts of MCB deployment.

185. New modelling studies have provided additional insights into MCB processes, and identified the scope for specific regional-scale applications; nevertheless, uncertainties remain with regard to imperfect understanding of key micro-physical interactions and their representation within models. Groups involved in MCB development have identified[502] research needs relating to technical viability, effectiveness, and undesirable impacts of the approach: they recommended further modelling studies (at global-scale; at high spatial resolution; and of the micro-physics); relevant engineering developments (Flettner rotors, for ship propulsion and seawater spraying); and limited-area field research for technology testing.

186. Global modelling studies in the GeoMIP context (based on three Earth system models, and RCP 4.5 scenario) showed that MCB could stabilize top-of-the-atmosphere radiative forcing, i.e. maintain global mean temperatures at 2020 levels[503,504]. Cloud formation was enhanced in low latitudes over both ocean and land, and while the localized cooling decreased precipitation over the ocean it increased precipitation over low-latitude land regions. Another multi-model study[505] showed the variability of the climatic response and its impacts on tropical forests: in one model, MCB reversed the die-back of the Amazon forest, but in two others tropical gross primary production decreased.

187. Under a scenario of doubled atmospheric CO_2, simulated MCB in the North Pacific, South Pacific and South Atlantic (total area 3.3% of world surface) was found likely to reduce water stress in NE China and West Africa, increasing yields and reducing future crop failure rates for spring wheat and groundnuts respectively[506].

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[497] Keith DW & MacMartin DG (2015) .

[498] Kosugi, T (2013)

[499] McCusker KE, Armour KC, Bitz CM & Battiosti DS (2014)

[500] Irvine PJ, Sriver RL & Keller K (2012)

[501] Jones A, Haywood JM, Alterskjaer K, Boucher O et al. (2013)

[502] Latham J, Bower K, Choularton T, Coe H et al. (2012)

[503] Kravitz B, Forster PM, Jones A, Robock A et al. (2013)

[504] Alterskjær K, Kristjánsson JE, Boucher O, Muri H et al (2013)

[505] Muri H, Niemeier U & Kristjánsson (2015)

[506] Parkes B, Challinor A & Nicklin K (2015)

188. Other studies have shown the sensitivity of the response to whether CCN are added to achieve a direct effect, by the scattering of solar radiation from the sea-salt particles themselves, or to maximize cloud brightness and longevity for existing low clouds[507]; there can also be major differences in climatic impacts according to where the MCB is carried out. If MCB deployment is limited to the Pacific, mean global cooling to pre-industrial levels could still be achieved; however, Arctic warming is likely to continue, and major changes to precipitation and atmospheric circulation patterns in the western Pacific region could be expected[508]. It has been proposed[509] that greater specificity in the areas where MCB is applied might provide specific regional benefits; in particular, to reduce coral bleaching[510] and weaken hurricanes[511], and potentially to stabilize the West Antarctic ice sheet, and prevent the loss of Arctic sea-ice. The effectiveness of the technique may be reduced in polar regions (where CCN concentrations are already relatively high); nevertheless, Arctic cooling by Arctic MCB has been simulated, with climatic responses that were highly dependent on the representation of microphysical processes within the model[512].

189. Technical issues that need to be resolved for MCB include those relating to optimum particle size distributions[513,514], cloud droplet number[515]; the modelling of aerosol water[516,517], and effects of timing and injection rate[518]. Variability in meteorological conditions (wind speed and boundary layer stability) may greatly reduce the effectiveness of the technique[519,520]. The direct implications of the seawater removal and spraying for upper ocean plankton have not yet been assessed, nor the effect of increased marine cloud cover on productivity processes. However the volume of water required for MCB is relatively small (in a global context), and the effects of reduced light are expected to be similar to those modelled for SAI[521]. The impacts of the 2-6 fold increase in atmospheric salt loading over tropical land areas is an additional factor requiring consideration[522], since salt stress on vegetation can have significant socioeconomic implications[523].

4.4 SURFACE ALBEDO MODIFICATION

190. **Land-based methods for increasing surface albedo** are generally not considered to be viable or cost-effective for feasible climate geoengineering. Thus it is very unlikely that crop albedo can be altered at a climatically-significant scale[524], while changing the albedo of grassland or desert over sufficiently large areas would be very resource-demanding, environmentally-damaging and not easily controllable; if achievable, the main climatic impacts would be regional-scale perturbations in temperature and precipitation (not necessarily beneficial). When the albedo of all land surfaces is increased in climate models at a scale to counteract a doubling of CO_2, global precipitation decreases by 13% over land (compared to present day) with major interhemispheric differences in temperature change (warming in southern hemisphere; cooling in northern hemisphere)[525].

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[507] Jones A. & Haywood J. M. (2012)

[508] Baughman E, Gnanadesikan A, Degaetano A & Adcroft A (2012)

[509] Latham J, Gadian A, Fournier, Parkes B et al. (2014)

[510] Latham J, Kleypas J, Hauser R, Parkes B & Gadian A (2013)

[511] Latham J, Parkes B, Gadian A & Salter S (2012)

[512] Kravitz B, Wang HL, Rasch PJ, Morrison H & Solomon AB (2014)

[513] Alterskjær K & Kristjánsson JE (2013)

[514] Connolly PJ, McFiggans GB, Wood R & Tssiamis A (2014)

[515] Pringle KJ, Carslaw KS, Fan T, Mann GW et al. (2012)

[516] Jenkins AKL & Forster PM (2013)

[517] Maalick Z, Korhonen H, Kokkola H, Kühn T & Romakkaniemi S (2014)

[518] Jenkins AKL, Forster PM & Jackson LS (2012)

[519] Alterskjær K, Kristjánsson JE & Seland Ø (2012) .

[520] Stuart G.S., Stevens R.G., Partanen A.-I. et al (2013)

[521] Hardman-Mountford NJ, Polimene L, Hirata T, Brewin RJW & Aiken J (2013)

[522] Muri H, Niemeier U & Kristjánsson (2015)

[523] Qadir M, Quillérou E, Nangia V, Murtaza G et al. (2014)

[524] Jackson LS, Crook JA, Osprey SM & Forster P (2014)

[525] Bala G & Nag B (2012)

191. The benefits of albedo modification in urban areas are essentially local rather than global: while it is estimated that worldwide white roof conversion could achieve a mean cooling of ~0.02°C in populated areas, global *warming* of ~0.07°C could also result[526]. If restricted to areas that experience high urban heat island effects, more significant direct benefits may be obtained[527,528], although with risk of changes to local rainfall patterns[529,530]. Indirect climatic consequences might be more important, reducing summer energy use for air conditioning while potentially increasing winter energy use for heating. Green (vegetated) roofs or solar panels would offer alternative environmental and energy/climate benefits, with the scale of those benefits strongly affected by local conditions and economic factors.

192. **Changes in surface ocean albedo** are theoretically able to produce climates closer to the unperturbed state than albedo changes on land. They have been given recent research attention with the study of methods that might be used to produce long-lived ocean foams[531]. While the production of such foams may be technically possible, their use at the scale necessary for climatic effectiveness is unlikely to be societally-acceptable (effects on fishing and tourism, with wind-blown foams affecting coastal communities, particularly on islands) and would have major adverse consequences for biogeochemistry (air-sea exchange rates, including increasing de-oxygenation and reducing net ocean CO_2 uptake), and for ecosystems and organisms (from phytoplankton, to fish, sea mammals and seabirds).

193. An unspecified surface ocean albedo technique was used in a model to determine whether that technique alone could increase Arctic ice cover in a 4 x CO_2 climate simulation[532]. Only partial sea ice recovery and stabilization was achievable: with the most extreme ocean albedo changes (value 0.9 imposed over 70°-90°N; ~ 4 million km^2), September sea-ice cover achieved 40% of its pre-industrial value, compared to 3% without albedo modification. That level of albedo change decreased Arctic surface temperature by ~2°C, and changed temperature and precipitation patterns elsewhere in the northern hemisphere; however, the net effect on global climate was an order of magnitude less.

4.5 CIRRUS CLOUD THINNING AND OTHER PHYSICALLY-BASED TECHNIQUES

194. The intention of **cirrus cloud thinning** is to allow more heat (long wave radiation) to leave the Earth, rather than to reflect light (short wave radiation): its forcing effects are therefore more similar to greenhouse gas reduction than to albedo modification. Nevertheless, because manipulation of cloud processes are involved, the technique has usually been discussed in an SRM context, e.g. by IPCC AR5 WG 1, and in the NAS/NRC and EuTRACE reports, and that convention is followed here.

195. Only limited research attention has been given to the feasibility of cirrus cloud thinning and its impacts since the technique was first proposed in 2009[533]. Potential global cooling of ~1.4°C has been estimated[534] as a result of seeding 15-45% of global cirrus clouds in mid-high latitudes, using particles that promote ice nucleation. Their distribution could be achieved by commercial aircraft. However, the desired effect is only achieved by seeding particle concentrations within a limited range; while under-seeding would have no effect, over-seeding could prolong cirrus lifetime and accelerate global warming[535].

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[526] Jacobson MZ & Ten Hoeve JE (2012)

[527] Santamouris M (2014)

[528] Sproul J, Wan MP, Mandel BH & Resenfeld AH (2014)

[529] Hoag H (2015)

[530] Georgescu M, Morefield PE, Bierwagen BG & Weaver CP (2014)

[531] Aziz A, Hailes HC, Ward JM & Evans JRG (2014) 6

[532] Cvijanovik I, Caldeira K & MacMartin DG (2015)

[533] Mitchell DL *&* Finnegan *W (*2009*)*

[534] Sorelvmo T, Boos WR & Herger N (2014)

[535] Storelvmo T, Kristjansson JE, Muri H, Pfeffer M et al. (2013)

196. Proposed seeding materials include mineral dust particles and bismuth tri-iodide (BiI_3), a non-toxic and relatively inexpensive compound previously considered as an ice nucleant for weather modification[536]. When cirrus thinning was included in the UKMO HadGEM2 climate model in an RCP 4.5 scenario, it slightly increased global mean precipitation, by 0.7% relative to 2020 levels[537]. However, the environmental implications of this technique have yet to be assessed.

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[536] Mitchell DL *&* Finnegan *W (*2009)

[537] Jackson LS, Crook JA, Osprey SM & Forster P (2014)

CHAPTER 5

SOCIOECONOMIC AND CULTURAL CONSIDERATIONS RELATING TO CLIMATE GEOENGINEERING

5.1 INTRODUCTION

197. CBD decision XI/20 specifically requested additional information on the views of a wide range of stakeholders on the potential impacts of geoengineering on biodiversity, and associated social, economic and cultural impacts. Information on such aspects, in the form of peer-reviewed social science publications and reports, is summarized here, with focus on major conceptual developments and evidence since CBD (2012). There has been no shortage of new academic material relating to the human dimensions of climate geoengineering, with topics including framing, governance, ethical considerations, international relations, national and international law, and economics. Only representative papers are cited here and in Chapter 6 (with its focus on regulatory issues and policy); a more comprehensive listing of ~150 additional recent papers on socioeconomic and cultural aspects of climate geoengineering is provided in Annex 1.

198. Despite that apparent wealth of information and analyses, there would seem to be significant gaps in understanding and knowledge:

- Nearly all social science effort has been directed at consideration of sunlight reflection methods (SRM); in particular, issues associated with stratospheric aerosol injection (SAI). The governance of marine cloud brightening (MCB) does not seem to have been explicitly addressed, and when carbon dioxide removal (CDR) is given attention, it is near-exclusively in terms of ocean fertilization. Consideration of the spectrum of other approaches, particularly those involving land-based carbon dioxide removal – also with societally-important issues regarding ethics, acceptability, equity, governance and economics – has been lacking, except in the context of the biofuels/food security debate.
- Nearly all social science publications on climate geoengineering, including analyses of public perceptions and governance, have been authored by researchers in the USA and Europe[538,539]. As a result, existing information may inadvertently include cultural biases regarding decision-making procedures, management strategies and knowledge. Nevertheless, effort has been made to stimulate wider international dialogue in this topic area[540,541], recognizing that a truly global perspective on relevant values and interests needs to take account of, a wider range of stakeholders, presenting the views of developing countries, non governmental organizations and indigenous peoples[542,543].
- The economic analyses of geoengineering have mostly been relatively simplistic, with main focus on operational costs, rather than environmental or social costs ('external' costs), or price effects. The global distribution of benefits, burdens and risks is not only of crucial importance for climate change, but how climate change is addressed[544]. While life cycle assessments have also used to provide a more holistic approach, these do not necessarily take account of all associated risks and uncertainties[545]. In particular, there would seem major gaps regarding the commercial viability of CDR techniques, such as BECCS;

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[538] Belter CW & Seidel DJ (2013)

[539] Oldham P, Szerszynski B, Stilgoe J, Brown C, Eacott B & Yuille A (2014)

[540] Winickoff DE, Flegal JA & AsratA (2015)

[541] African Academy of Sciences and Solar Radiation Management Governance Initiative (2013)

[542] Whyte KP (2012b)

[543] Buck HJ (2014)

[544] Schäfer S, Maas A & Irvine PJ (2013)

[545] Plevin RJ, Delucchi MA & Creutzig F (2013)

their associated institutional frameworks relating to carbon trading or tax incentives; and evaluations of environmental impacts (in context of ecosystem services) and implications for indigenous and local communities.

- While there is an increasing trend towards multidisciplinary and transdisciplinary programmes on climate geoengineering (that are now beginning to deliver more integrated analyses), there would seem scope for closer connections between social science and natural science studies, with the aim of developing a fully transdisciplinary[546] approach to problem-solving.

199. The seven key messages relating to socioeconomic and cultural considerations in CBD (2012) are re-presented in Table 5.1. These summary statements are still considered valid.

Table 5.1 Main conclusions from CBD (2012) relating to social, economic, cultural and ethical considerations of climate geoengineering. Full text in Annex 3.

Key message text originally in bold relating to socioeconomic, cultural and ethical chapter; re-numbered
1. The consideration of geoengineering as a potential option raises many socioeconomic, cultural and ethical issues, regardless of the specific geoengineering approach.
2. Humanity is now the major force altering the planetary environment.
3. The 'moral hazard' of geoengineering is that it is perceived as a technological fallback, possibly reducing effort on mitigation.
4. In addition to limiting the undesirable impacts of climate change, the large-scale application of geoengineering techniques is near-certain to involve unintended side effects and increase socio-political tensions.
5. An additional issue is the possibility of technological, political and social "lock in",
6. Geoengineering raises a number of questions regarding the distribution of resources and impacts within and among societies and across time
7. In cases in which geoengineering experimentation or interventions might have transboundary effects or impacts on areas beyond national jurisdiction, geopolitical tensions could arise

5.2 FRAMING AND DISCOURSE ANALYSIS

200. A major theme in the social science literature on geoengineering relates to how the topic is presented and discussed, not only by scientists of different disciplines but also by politicians, the public and the media. The different backgrounds (cultures) of those groups determine their vocabularies; they also shape thinking, values and interpretation[547]. For climate geoengineering, different perspectives give different frames, with the term geoengineering – or climate engineering, or climate intervention – itself being far from neutral in that regard[548]. Different frames are used, knowingly or unknowingly, as storylines that select aspects of a perceived reality and thereby "amplify different priorities and values"[549]. Identification of the different frames that have arisen in the field of geoengineering, and analysis of their assumptions and context, is therefore not just an academic exercise, but has fundamental implications for communications and decision-making in this controversial policy area[550].

201. Many framings are possible and can co-exist, with potential for complementarity or contradiction. None are inherently 'right' or 'wrong', but some may be more factually-based, and objectively valid, than others. Table 5.2

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[546] Lang DJ, Wiek A, Bergmann M, Stauffacher et al. (2012)

[547] Szerszynski B & Galarraga M (2013)

[548] Cairns R & Stirling A (2014)

[549] Porter KE & Hulme M (2013)

[550] Huttunen S & Hildén M (2014)

summarizes a recent review[551] of geoengineering frames that have featured in the social science literature. Aspects of some of these, and additional frames, are discussed below. Discourse analysis is similar in many regards, although with greater attention given to the conceptual basis of communication, linked to text linguistics and socio-psychological studies.

Table 5.2 Examples of framing for generic climate geoengineering, based on Kreuter (2015) (where 'climate engineering' was used instead of geoengineering). Note that: i) this analysis is most applicable to atmospheric SRM; and ii) other authors have identified other frames, as discussed in text.

Frame	Summary of discussion by Kreuter (2015)
1. Solution to the political problem of climate change (over-arching framing)	Policy option framing, either as directly equivalent to mitigation and adaptation, or providing an imperfect substitute for emissions reductions, i.e. an 'insufficient mitigation' scenario. Potential for complementarity to conventional responses now increasingly recognized.
2. Shield against detrimental societal impacts	Provision of safeguard: as fall-back, insurance policy or 'Plan B' if all else fails. Plan B must be assumed to be feasible when the preferred option is no longer possible, e.g. in climate emergency scenario, or as "lesser of two evils" [Additional discussion of 'emergency' framing given in main text].
3. Source of detrimental societal impacts	'Moral hazard' framing: attention given to geoengineering reduces effort on mitigation and adaptation, while also inherently favouring autocratic governance, generating "a closed and restricted set of knowledge networks, highly dependent on top-down expertise and with little space for dissident science"[552]
4. Driver of transboundary conflict	Unequal distribution of undesirable side effects and/or unilateral action could threaten international security. This view has been challenged[553], and it is also relevant that climate change may itself present security risks.
5. Arena of political interactions, both between states and within societies	Geoengineering provides opportunities for political advantage in a "global thermostat game"[554], and for personal gain by "special interests, including private corporations, conservative think tanks and scientists affiliated with both"[555].
6. Technology framing	Idea of technofix: "the consistent application of science and technology is humanity's greatest hope for improving human life"[556] – countered by the arguments that the success of geoengineering is inherently uncertain, that it avoids the need to tackle fundamental causes, and that its "objective is to manipulate the natural world without any consideration of moral or ethical norms"[557].
7. Moral consideration	Ethical questions involving arguments of right and wrong, in context of respect, beneficence and justice. Geoengineering is considered by some social scientists to be unethical, on the basis that it 'passes the buck' by those originally responsible for climate change.
8. Cost-benefit analysis	Economic framings not considered to be a well-developed rationale in advancing the case for geoengineering. Nevertheless, SRM is generally regarded as the 'inexpensive' option in comparison to mitigation.

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[551] Kreuter J (2015)

[552] Szerszynski B, Kearnes M, Macnaghten P, Owen R & Stilgoe J (2013)

[553] Horton JB (2011)

[554] Ricke K, Moreno-Cruz J & Caldeira K (2013)

[555] Sikka T (2012a)

[556] Scott D (2013)

[557] Sikka T (2012b)

202. Other framings of climate change and societal responses, in addition to those given in Table 5.2, include resilience[558], emancipatory catastrophism[559,560], apocalyptic catastrophism[561], and a range of emergency frames (discussed below). Discourse analyses of geoengineering in the news media have examined the use of metaphors, such as war, controllability and health[562], and have considered geoengineering in the contexts of innovation, risk, governance and accountability, economics, morality, security and justice[563]. An opening-up of the debate in English-language newspapers has been recognized[564]. An analysis[565] of 114 policy documents relating to geoengineering published between 1997 and 2013 showed that concerns were dominated by three themes: technical and risk-related issues; hopes related to new solutions to climate change; and action proposals emphasized the need for further research.

203. None of the wide range of frames used by social scientists (above) gave specific attention to environmental concerns; however, many identify deficiencies in the geoengineering approach. Several academics consider those short-comings to be strong enough to justify rejection of most, if not all, (SRM) geoengineering as either unworkable[566], unethical[567,568,569], naive[570], overly profit-driven[571] or undemocratic[572]. The question has been also raised as whether social scientists are apparently trying to influence (rather than reflect) public opinion by their conclusions, with a perceived asymmetry in the rigour of their critiques of climate geoengineering and more conventional approaches to climate change[573].

204. Framing based on tipping points and climate emergencies has attracted particular media interest and academic discussion[574,575,576], including by those who reject the concept of 'exceptionalism' in the context of climate change and associated policy responses[577]. While SRM, through stratospheric aerosol injection, could provide a means for rapid global cooling, it would not be easy for a worldwide agreement to be reached on when a global climate emergency had arisen. If the emergency were due to (say) a sequence of unexpectedly extreme conditions, that might indicate failure of global climate models in predicting such events – and yet the same models would need to be used to determine the optimal strategy for SRM deployment[578].

205. Such considerations do not seem to justify the 'climate emergency' framings in a policy context[579]. The concept of 'tipping points' does, however, have scientific validity - although difficult to reliably simulate in climate models. Thus the Earth's climate system is susceptible to threshold behaviour[580], with geologically-recent precedents for

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[558] Stafford-Smith M & Russell L (2012)

[559] Beck U (2014)

[560] Beck U (2015)

[561] Asayama S (2015)

[562] Luokkanen M, Huttunen S & Hildén M (2013)

[563] Porter KE & Hulme M (2013)

[564] Scholte S, Vasileiadou E & Petersen AC (2013)

[565] Huttunen S, Skytén E & Hildén M (2015)

[566] Hulme M (2014)

[567] Gardiner SM (2013a)

[568] Taylor Smith P (2014)

[569] Hamilton C (2013d)

[570] Hamilton C (2013c)

[571] Sikka T (2012a)

[572] Macnaghten P & Szerszynski B (2013)

[573] Heyward C & Rayner S (2013)

[574] Markusson N, Ginn F, Ghaleigh NS & Scott V (2013)

[575] Barrett S, Lenton TM, Millner A, Tavoni A et al (2014)

[576] Horton JB (2015)

[577] Sikka T (2012a)

[578] Sillmann J, Lenton TM, Levermann, Ott K et al. (2015)

[579] Horton JB (2015)

[580] Good P, Lowe J, Ridley J, Bamber J et al. (2014)

abrupt changes occurring in response to gradual forcing[581]. Post-AR5 analyses of the (in)stability of the Greenland[582] and East Antarctic ice sheets[583], and the possibility of irreversible changes following the loss of Arctic sea ice[584] give scientific cause for concern, with current and projected rates of climate change being greater than those experienced during the past 10,000 years[585].

206. Framings based on the potential complementarity of SRM geoengineering to other actions have been given recent scientific attention[586,587]. Such complementarity is also implicit in the inclusion of CDR/negative emissions in IPCC scenarios in addition to strong emission reductions.

5.3 PUBLIC ENGAGEMENT

207. Public engagement on potentially-controversial scientific innovation, such as geoengineering[588], can help to improve trust between scientists and public; it can also help to ensure that decisions about research on new technologies and their possible deployment, take account of a broad set of societal interests, values and framings, thereby contributing to a 'collective experimentation' approach to evolving governance[589]. Furthermore, by including affected parties and stakeholders in decision-making processes[590] it addresses the concern that the technological nature of most geoengineering, particularly atmospheric SRM, makes it inherently undemocratic[591].

208. Recent public surveys and more structured dialogues have been carried out in the US[592], UK[593,594,595,596,597] Germany[598], Sweden[599,] and Australia and New Zealand[600]. There has also been a deliberative workshop on SRM hosted by the US[601] with focus on developing country participation, and other workshops held elsewhere, including Asia (Pakistan, India and China) and Africa (Senegal, South Africa and Ethiopia)[602], through the Solar Radiation Management Governance Initiative (SRMGI).

209. Such 'upstream'[603] public engagement in geoengineering is not straightforward: in particular, to have a meaningful dialogue, the non-scientists involved in the discourse need to know something about what is being discussed in order to have views and opinions. It is therefore likely that additional information needs to be presented, raising concerns that the framing provided by survey authors, or workshop hosts, could, to some degree, help to shape public and stakeholder responses.

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[581] Weber ME, Clark PU, Kuhn G, Timmerman A et al (2014)

[582] Enderlin EM, Howat IM, Jeong S, Noh M-J et al. (2014)

[583] Favier L, Durand G, Cornford SL, Gudmundsson et al. (2014)

[584] Lenton TM (2012)

[585] McNeall D, Halloran PR, Good P & Betts RA (2011)

[586] Keith DW & MacMartin DG (2015)

[587] MacMartin DG, Caldeira K & Keith DW (2014)

[588] Stilgoe J, Watson M & Kuo K (2013)

[589] Stilgoe J (2016)

[590] Carr WA, Preston CJ, Yung L, Szerszynski B et al. (2013)

[591] Szerszynski B, Kearnes M, Macnaghten P, Owen R & Stilgoe J (2013)

[592] Borick C & Rabe BG (2012)

[593] Pidgeon N, Corner A, Parkhill K, Spence A et al. (2012)

[594] Corner A, Parkhill K. Pidgeon N & Vaughan NE (2013)

[595] Bellamy R (2015)

[596] Macnaghten P & Szerszynski B (2013)

[597] Cairns R & Stirling A (2014)

[598] Merk C, Pönitzsch G, Kniebes C, Rehdanz K & Schmidt U (2015)

[599] Wibeck V, Hansson A & Anshoelm J (2015)

[600] Wright MJ, Teagle DAH & Feetham PM (2014)

[601] Winickoff DE, Flegal JA & Asrat A (2015)

[602] African Academy of Sciences and Solar Radiation Management Governance Initiative (2013)

[603] Corner A, Pidgeon N & Parkhill K (2012)

210. While some geographical and/or cultural bias may also have occurred, the main findings for the surveys of public perceptions have been relatively consistent: i) an overall negative evaluation of geoengineering as a policy response to climate change (in comparison to more direct measures, i.e. emission reductions); ii) the perceived naturalness of a technique (that may depend on the way it is described) strongly influences its acceptability, with CDR techniques generally favoured over SRM; and iii) cautious support for further research.

211. The possibility of 'moral hazard'[604,605] has been investigated in a recent German public survey[606], to determine whether consideration of (SRM) geoengineering as a climate policy option reduces the credibility of more direct mitigation action. The opposite was found: when presented with information on stratospheric aerosol injection, effort on convention mitigation increased.

212. The 'cultural cognition' theory may be relevant here, since it has been demonstrated that individuals selectively assess information (from logical arguments, empirical data or media reports) in ways that support their own values. Thus those with egalitarian world views were found[607] to be less likely to be skeptical of climate change science than those with more hierarchical and individualistic values. Additional information on the need for stricter CO_2 emission controls reinforced that polarization. However, when US citizens with hierarchical and individualistic values were made aware of geoengineering research, they reacted less dismissively to the climate change study; i.e. also the opposite of the 'moral hazard' argument[608].

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[604] Hale B (2012)

[605] Reynolds J (2014)

[606] Merk C, Pönitzsch & Rehdanz K (2015)

[607] Kahan DM, Jenkins-Smith HC, Tarantola T, Silva CL & Braman D (2015)

[608] Hale B (2012)

CHAPTER 6

POLICY AND REGULATORY FRAMEWORK

6.1 REGULATORY STATUS AT THE TIME OF THE PREVIOUS CBD REPORT ON GEOENGINEERING

213. Regarding the international regulatory framework for climate-related geoengineering relevant to the CBD, CBD (2012) examined the extent to which current mechanisms already addressed geoengineering, and discussed gaps. Most current regulatory mechanisms were developed before geoengineering was a significant issue and, as such, did not currently contain explicit references to geoengineering approaches. CBD (2012) noted, inter alia, that geoengineering was not as such prohibited by international law, although some rules and principles could apply to all or specific geoengineering concepts. The mandate of most treaties allowed for determining whether the treaty in question applies to a specific geoengineering activity and could address it. While, according to their mandate, a number of current mechanisms could address geoengineering activities, only the **CBD Conference of the Parties, at its 10th meeting (COP-10)** had, in decision X/33, addressed the broader concept of geoengineering at an international regulatory level.

214. The governing bodies of the **Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter** 1972 (London Convention) and its 1996 Protocol (London Protocol) had provided detailed guidance regarding specific geoengineering activities, namely ocean fertilization as well as carbon storage. Marine research is also addressed under international law through the UN Convention on the Law of the Sea (UNCLOS), with emphasis on the deployment of technology with known impacts or risks, with special rules in certain areas[609]. CBD (2012) suggested that the need for science-based, global, transparent and effective control and regulatory mechanisms may differ depending on the geoengineering activity in question, and be most relevant for concepts that have a potential to cause significant adverse transboundary effects, and those deployed in areas beyond national jurisdiction and in the atmosphere. It identified the lack of regulatory mechanisms for SRM as a major gap, especially given the potential for significant deleterious transboundary effects.

6.2 RECENT DEVELOPMENTS

6.2.1 London Convention/London Protocol and OSPAR Convention

215. Since the publication of CBD (2012), an important recent development relates to the London Protocol. The Meeting of Contracting Parties to the London Protocol adopted, on 18 October 2013, 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[610,611,612]. The amendment prohibits marine geoengineering activities listed in a new Annex 4 unless they constitute "legitimate scientific research" and are authorized under a permit. Parties have to adopt administrative or legislative measures to ensure that the issuance of a permit complies with a generic Assessment Framework set out in a new annex 5, and takes into account any Specific Assessment Framework that may be adopted by the Meeting of the Parties.

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[609] On existing rules governing research generally (e.g. in UNCLOS) see Chapter 5 of CBD (2012) Part II; for special rules in special areas, see Key Message 22, p 105

[610] Ginzky H & Frost R (2014)

[611] Schäfer S, Lawrence M, Stelzer H, Born W et al. (2015) [p. 86-88]

[612] Scott KN (2013)

216. Currently the only activity listed in Annex 4 is ocean fertilization, and the resolution confirms that the Assessment Framework adopted by the parties in 2010 applies to this activity. The amendment is structured so as to allow other marine geoengineering activities to be considered and listed in Annex 4 in the future if they fall within the scope of the London Protocol and have the potential to harm the marine environment. The amendment will enter into force 60 days after two thirds of the currently 47 Contracting Parties to the London Protocol have deposited an instrument of acceptance of the amendment with the International Maritime Organization. As of 28 September 2016, the amendment has received one acceptance and has not entered into force[613]. This amendment, once it enters into force, will strengthen the regulatory framework for ocean fertilization activities and provide a framework for the further regulation of other marine geoengineering activities. The CBD COP, in decision XII/20, took note of Resolution LP.4(8) and invited parties to the London Protocol to ratify this amendment and other Governments to apply measures in line with this amendment, as appropriate.

217. The **2007 amendment to the OSPAR Convention** which allows storage of carbon dioxide in geological formations under the seabed of the North-East Atlantic[614] entered into force in July 2011 and is currently in force for 11 of the 16 OSPAR parties[615,616].

6.2.2 Eleventh meeting of the Conference of the Parties to the Convention on Biological Diversity

218. Another development is the follow-up under the CBD to COP decision X/33. In the subsequent **decision XI/20 of 2012**, the CBD COP emphasized that climate change should primarily be addressed through mitigation under the UNFCCC[617]. This is the first clear statement by the CBD COP, in the context of geoengineering, that conventional mitigation action should be the priority.

219. The COP also suggested that regulatory mechanisms should focus on activities that have the potential to cause significant transboundary harm, and those deployed in areas beyond national jurisdiction and the atmosphere. It explicitly noted that there is no common understanding on where such mechanisms would be best placed [618,619]. The COP thus developed further its previous guidance: First, the statement sets priorities regarding *which activities* are most relevant to be addressed by international governance. Second, the CBD explicitly leaves open *which body* should address geoengineering.

220. In paragraph 9 of decision XI/20 Parties were also invited to report on measures undertaken in accordance with paragraph 8(w) of decision X/33. The Executive Secretary was requested to make available the information through the CBD clearing-house mechanism[620]. So far only a few submissions have been received[621].

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[613] IMO, Status of multilateral Conventions and instruments in respect of which the International Maritime Organization or its Secretary-General performs depositary or other functions. As at 28 September 2016; http://www.imo.org/en/About/Conventions/StatusOfConventions/Pages/Default.aspx

[614] Key message 17, (p 133-134) in CBD (2012)

[615] The amendment is currently in force for Norway, Germany, United Kingdom, Spain, European Union, Luxembourg, Denmark, Netherlands, Finland, Sweden and France.

[616] Dixon T, Garrett J & Kleverlaan E (2014)

[617] CBD COP decision XI/20 para 4

[618] CBD COP decision XI/20 para 8

[619] Regarding areas beyond national jurisdiction, cf. the work by the UN General Assembly's Ad Hoc Open-ended Informal Working Group to study "issues relating to the conservation and sustainable use of marine biological diversity beyond areas of national jurisdiction", http://www.un.org/depts/los/biodiversityworkinggroup/biodiversityworkinggroup.htm

[620] Available at https://www.cbd.int/climate/geoengineering

[621] Five Parties (Estonia, France the UK, Bolivia and Canada) responded. For a summary of submissions by Estonia, France, and the UK see UNEP/CBD/SBSTTA/18/13 [para 69-76]

6.2.3 United Nations General Assembly

221. The United Nations General Assembly in annual resolutions on Oceans and Law of the Sea continued to take note of relevant decisions under the London Convention and CBD[622] and recalled that in "The Future we Want", States stressed their concerns on the potential environmental impacts of ocean fertilization[623].

6.2.4 Intergovernmental Panel on Climate Change (IPCC), United Nations Framework Convention on Climate Change (UNFCCC) and World Meteorological Organization (WMO)

222. The publication of **IPCC 5th Assessment Report** (AR5) was a further important development, as it also touched upon governance issues relating to geoengineering[624], as reviewed here in Chapter 2. It briefly lists some existing international instruments that "may be relevant" to geoengineering, albeit without analysis or assessment[625]. In this respect it does not add to or call into question the findings of the original CBD (2012) report.

223. With regard to **SRM**, IPCC AR5 notes that "the governance implications... are particularly challenging", in particular in respect of the political implications of potential unilateral action[626]. The spatial and temporal redistribution of risks raises additional issues of intra-generational and inter-generational justice[627], which has implications for the design of international regulatory and control mechanisms. The IPCC considers that the ethical and political questions raised by SRM would require public engagement and international cooperation in order to be addressed adequately[628].

224. With regard to **CDR**, bioenergy with carbon dioxide capture and storage (BECCS) and afforestation play a major role in many AR5 mitigation scenarios. AR5 notes that CDR would need to be deployed on a large scale and over a long time period to be able to significantly reduce CO_2 concentrations[629]. As most terrestrial CDR techniques would involve competing demands for land, and maritime CDR techniques may involve significant risks for ocean ecosystems, large-scale and long-term CDR could raise additional governance issues at the international level[630].

225. Under the **UNFCCC**, a technical paper by the Secretariat noted that many of the IPCC's AR5 scenarios rely on CDR, and the findings in AR5 regarding BECCS[631]. This has so far not been specifically taken up in the deliberations of other UNFCCC bodies. A new climate agreement was adopted at COP21 in Paris at the end of 2015 and will enter into force on 4 November 2016. The concept of negative emissions came up during the negotiations[632] and may be included by the reference to a balance between emissions and removals in Article 4.1, but it remains to be seen if and to what extent it will be addressed in the future.

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[622] UNGA Resolution 67/78. Para 167-171; UNGA Resolution 68/70, para 179-183; UNGA Resolution 69/245, para 195-199 (http://research.un.org/en/docs/ga); UNGA Document A /68/159 of 17 July 2013, para 183

[623] UNGA Resolution 66/288 "The future we want" of 27 July 2012, para 167; (http://research.un.org/en/docs/ga);

[624] See Chapter 2 of this report, also IPCC (Intergovernmental Panel on Climate Change) (2014b) [WG III, p. 487-490 and 1022-1023] and Petersen A (2014)

[625] IPCC (Intergovernmental Panel on Climate Change) (2014b) [WG III, p. 1023]

[626] IPCC (Intergovernmental Panel on Climate Change) (2014c) [Synthesis Report, p. 89]; IPCC (Intergovernmental Panel on Climate Change) (2014b) [WG III, p. 1023]

[627] IPCC (Intergovernmental Panel on Climate Change) (2014c) [Synthesis report, p. 89]; IPCC (Intergovernmental Panel on Climate Change) (2014b) [WG III, p. 488]

[628] IPCC (Intergovernmental Panel on Climate Change) (2014b) [WGIII, p. 489]

[629] IPCC (Intergovernmental Panel on Climate Change) (2014c) [Synthesis report, p. 89, 123]

[630] IPCC (Intergovernmental Panel on Climate Change) (2014c) [Synthesis report, p. 89, 123]

[631] See e.g. UNFCCC Doc. FCCC/TP/2014/13/Add.3 of 26 November 2014, para 10, 33. The paper was prepared for technical expert meetings on raising pre-2020 ambition through carbon dioxide capture, use and storage. It had been requested by the Ad Hoc Working Group on the Durban Platform for Enhanced Action (ADP)

[632] Geneva negotiating text, FCCC/ADP/2015/1 of 25 February 2015, para 5.1 option (d); also contained in subsequent informal iterations of the negotiating text of 11 June 2015 @ 16:30 and ADP.2015.4.InformalNote of 24 July 2015 part I art. 6 opt. 2, available at http://unfccc.int/meetings/bonn_jun_2015/session/8857.php, and http://unfccc.int/bodies/awg/items/9176.php

226. The World Meteorological Organization (**WMO**) discussed geoengineering at its 17th World Meteorological Congress in 2015. The WMO identified climate engineering as an area of research priority and seeks to provide advice on the science, but also on governance, and to "define WMO's role" in international deliberations[633]. It requested its Commission on Atmospheric Sciences (CAS) to coordinate its contribution to "a comprehensive assessment of the state of knowledge, science capacity and understanding of information gaps" in close cooperation with IMO, ICO, IPCC and other relevant international, academic and science bodies. The WMO envisages future "decisions on the appropriate level and the nature of involvement of WMO in climate engineering".[634].

6.2.5 Other recent reports and literature

227. Recent reports and literature[635] suggest that a one-size-fits-all approach to geoengineering governance is neither desirable nor feasible. Instead, regulatory mechanisms should follow a **functional approach** that takes into account the significant differences in the geoengineering activities proposed[636,637,638,639,640] and appropriate time frames. In addition, not all issues would be suitable for, or need to be addressed at the *international* level[641,642,643,644]. One commonly accepted function for international regulatory mechanisms and governance would be to address activities that have the potential to cause significant transboundary harm[645,646,647,648,649,650,651]. There has also been interest in the explicit or underlying political functions addressed by geoengineering governance, for instance by distinguishing scientific input from political decision-making[652,653,654]. The framing of the geoengineering debate has also gained attention. For instance, authors have called into question the narrative of a "climate emergency" that could justify or necessitate geoengineering, and the framing of what they see as essentially political decisions as if they were "objective science"[655,656].

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[633] WMO (World Meteorological Organization) (2015) [p. 7 para 2.1.15]

[634] WMO (World Meteorological Organization) (2015) [p. 159, para 4.3.101-102]

[635] See Annex 1 of this report; also draft bibliography on geoengineering governance at http://dcgeoconsortium.org/ce-governance-bibliography/

[636] Bodle R, Oberthuer S, Donat L., Homann G et al. (2014) [Section 6.3 and p.151; also p. 176-185]

[637] Keith D (2013)

[638] Armeni C & Redgwell C (2015c)

[639] Schäfer S, Lawrence M, Stelzer H, Born W et al. (2015) [p. 89-90]

[640] Rayner S, Heyward C, Kruger T, Pidgeon N. et al. (2013)

[641] Bracmort K & Lattanzio RK (2013) [p. 29]

[642] Bodle R, Oberthuer S, Donat L, Homann G et al. (2014) [p. 126, 136].

[643] Craik N, Blackstock J & Hubert A.-M. (2013)

[644] Wilson G (2014)

[645] CBD decision XI/20

[646] Brent, KA & McGee JS (2012) [p. 11]

[647] Chalecki EL & Ferrari LL (2012) [p.126]

[648] Bodle R, Oberthuer S, Donat L, Homann G et al. (2014) [p.127]

[649] Galaz V (2012) [p, 28]

[650] Owen R (2014) [p. 230]

[651] Lin A (2015)

[652] Bodle R (2013)

[653] Winickoff DE, Flegal JA & Asrat A (2015)

[654] NRC (National Research Council) (2015a)

[655] Markusson N, Ginn F, Ghaleigh NS & Scott V (2013)

[656] Sillman J, Lenton TM, Levermann A, Ott K et al. (2015)

228. Views in recent literature appear to support the original report's key message that, on the basis of potential impact and political challenges, governance of **atmospheric SRM** could be of primary relevance[657,658,659,660,661]. In addition, if the **large-scale BECCS** and afforestation in many IPCC AR5 scenarios were to be pursued, the associated scale of the land use and land use change could raise new governance issues at the international level[662]. These implications have so far not been specifically addressed by the literature nor the international regulatory framework[663,664]; under UNFCCC, governance for land use and land use change is mainly addressed through accounting rules. Most statements on governance in IPCC AR5 specifically address SRM, while simply noting governance implications of large scale CDR[665].

229. However, there is **no emerging common understanding on *"how"*** international regulatory and control mechanisms should work and address the relevant geoengineering activities. While the option of a new international treaty on geoengineering continues to be discussed in academic circles[666,667,668,669,670,671], there has been no initiative at the political level in this regard. So far, only the governing bodies of the CBD and the London Protocol are actively addressing geoengineering as part of a regulatory framework, supplemented to some extent by the OSPAR Convention and the UNFCCC regarding CCS. The CBD has continued to address geoengineering in general, and has started to offer an initial if minimal global platform for exchange of information. However, although it has 196 parties, they do not include the US. Some authors argue in favour of the UNFCCC as the main or even sole forum for addressing geoengineering[672,673,674,675,676,677], as it has a more direct mandate regarding climate change, and because its equally broad participation, in contrast to the CBD, includes the US. It should be noted that some views and proposals in this regard refer to geoengineering in general, while others address specific geoengineering activities. Specialized regimes such as the London Protocol can tailor regulation to specific geoengineering activities within their mandate, and their regulatory approaches could serve as models for other fora, as the CBD made reference to, and built on the work by the London Protocol on ocean fertilization[678,679,680,681]. However, they could be regarded as less suitable fora for broader debates[682].

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[657] Ricke K, Moreno-Cruz J & Caldeira K (2013)

[658] Owen R (2014)

[659] Keith D (2013) [p. 5]

[660] Bodle R, Oberthuer S, Donat L, Homann G et al. (2014) [p.127]

[661] NRC (National Research Council) (2015b) [p. 13]

[662] Schäfer S, Lawrence M, Stelzer H, Born W et al. (2015) [p. 116]

[663] Bodle R, Oberthuer S, Donat L, Homann G et al. (2014) [p.102-103]

[664] Schäfer S, Lawrence M, Stelzer H, Born W et al. (2015) [p. 84-85]

[665] IPCC (Intergovernmental Panel on Climate Change) (2014b) [WG III, p. 1022-1023]

[666] Barret S (2014)

[667] Bracmort K & Lattanzio RK (2013) [p. 29]

[668] Bodansky D (2013)

[669] Garg V (2014)

[670] Kuokkanen T & Yamineva Y (2013) [p. 165]

[671] Schäfer S, Lawrence M, Stelzer H, Born W et al. (2015) [p. 89-90]

[672] Lin AC (2009) [p.18]

[673] Scott KN (2013) [p. 355]

[674] Rickels W, Klepper G, Dovern J, Betz G et al. (2011)

[675] Honegger M, Sugathapala K & Michaelowa A (2013)

[676] Branson MC (2014)

[677] IPCC AR5 emphasises the broad legitimacy of the UNFCCC as an international climate policy forum, based on its broad mandate and 'virtually universal membership', but without direct reference to geoengineering; [e.g. WG III, p. 103]

[678] Markus T & Ginzky H (2011)

[679] Williamson P, Wallace DR, Law CS, Boyd PW et al (2012) [p. 484]

[680] Schäfer S, Lawrence M, Stelzer H, Born W et al. (2015) [p. 90]

[681] Proelss A & Chang H (2012)

[682] Scott KN (2013) [p. 116]

230. Against this background, there is **no clear "centre of gravity"** in the existing international governance[683] - but there might also be no need for it if the regulatory landscape functions as a "patchwork quilt"[684]. For the time being, increased regime cooperation could improve this framework addressing potential fragmentation and incoherence at the operational level, e.g. through coordination by the Secretariats and other relevant bodies[685]. However, this approach has limitations[686], and gaps in the regulatory framework would remain.

231. A recurring theme in literature is whether and how **research activities** should and could be addressed specifically for geoengineering research, in addition to potential deployment[687,688,689,690,691,692,693,694,695,696,697,698,699,700]. Arguments in favour include that experiments could pose physical risks and that research has wider, including political implications[701,702,703,704,705]. It has also been argued that governance can have an enabling function for "safe and useful" research[706]. The London Protocol's concept of "legitimate scientific research" underlying the 2013 amendment[707] can be seen in this context. Proposals have been put forward for tiered approaches to governing research activities according to their nature and scale[708,709,710].

232. Apart from general principles[711], **other cross-cutting issues** addressed in recent literature in relation to international geoengineering governance include, inter alia, **public engagement, transparency and participation** into governance design[712,713,714,715,716]. One emerging lesson could be that traditional environmental assessments might

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683 Bodle R, Oberthuer S, Donat L, Homann G et al. (2014) [p.138]
684 Armeni C & Redgwell C (2015c), [p. 6]
685 Schäfer S, Lawrence M, Stelzer H, Born W et al. (2015) [p. 90.114]
686 Kuokkanen T & Yamineva Y (2013) [p. 165-166]
687 Dilling L & Hauser R (2013)
688 IPCC (Intergovernmental Panel on Climate Change) (2014b) [WG III, p. 61, 489]
689 Bodle R, Oberthuer S, Donat L, Homann G et al. (2014). [p. 140-143]
690 Ghosh A (2014)
691 Parker A (2014)
692 Parson EA & Keith DW (2013)
693 Hamilton C (2013c)
694 Keith DW, Duren R & MacMartin DG (2014)
695 Reynolds J (2014)
696 Armeni C & Redgwell C (2015c) [p 32]
697 Healey P & Rayner S (2015) [p 18]
698 Hubert A-M & Reichwein D. (2015)
699 Lin A (2015)
700 NRC (National Research Council) (2015b) [p. 12]
701 Parson EA (2014) [Section 3.3]
702 Bodle R, Oberthuer S, Donat L, Homann G et al. (2014) [p. 141]
703 Lin A (2015) [p. 14]
704 Schäfer S, Lawrence M, Stelzer H, Born W et al. (2015); [p. 58 et seq]
705 Craik N, Blackstock J & Hubert A.-M. (2013)
706 NRC (National Research Council) (2015b) [p. 12]
707 See London Protocol resolution LP.4(8) of 18 October 2013, para 3 and new Annex 4, para 1.3
708 Parson EA & Keith DW (2013)
709 Parker A (2014) [p. 13-14]
710 NRC (National Research Council) (2015b) [p. 12]
711 Schäfer S, Lawrence M, Stelzer H, Born W et al. (2015) [p 108-111]
712 Whyte KP (2012a)
713 Craik N & Moore N (2014)
714 Healey P (2014)
715 Owen R (2014)
716 Winickoff DE & Brown MB (2013)

be unsuitable to address the challenges posed by geoengineering activities[717,718]. Another aspect that has been raised in the discussion on regulatory and control mechanisms is to improve the **involvement of developing countries** and other stakeholders in the debate, as many would be likely to be most affected by large-scale geoengineering activities[719,720]. In addition to regulatory and governance issues at the international level, literature is now also addressing regulatory issues at national levels as well as the EU level[721,722,723,724,725,726,727].

233. These developments relate to key messages 10, 12, 13, 17, 25 and 26 from Part II of CBD (2012) (given here as Annex 3), but have so far not changed their validity. These include that "the current regulatory mechanisms that could apply to climate-related geoengineering relevant to the Convention do not constitute a framework for geoengineering as a whole that meets the criteria of being science-based, global, transparent and effective" and that "with the possible exceptions of ocean fertilization experiments and CO_2 storage in geological formations, the existing legal and regulatory framework is currently not commensurate with the potential scale and scope of the climate related geoengineering, including transboundary effects."

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[717] Craik N, Blackstock J & Hubert A.-M. (2013) [p. 124]

[718] Blackstock J, Craik N, Doughty J & Horton J (2015)

[719] African Academy of Sciences and Solar Radiation Management Governance Initiative (2013)

[720] Winickoff DE, Flegal JA & Asrat A (2015)

[721] Hester T (2013)

[722] Bracmort K & Lattanzio RK (2013)

[723] Craik N, Blackstock J & Hubert A.-M. (2013)

[724] Armeni C & Redgwell C (2015a)

[725] Bodle R, Oberthuer S, Donat L, Homann G et al. (2014) [Section 5.2-5.3]

[726] Schäfer S, Lawrence M, Stelzer H, Born W et al. (2015) [p. 82 et seq]

[727] Armeni C & Redgwell C (2015b)

CHAPTER 7

CONCLUSIONS

234. The Key Messages given at the start of this report summarize its main findings, complementing those of CBD (2012) that are considered to remain valid. The conclusions here reiterate many of those specific findings; they also identify more general inferences that can be made from relevant recent research literature, and associated advances in conceptual understanding. Chapters 1- 5 provide an update on the implications for biodiversity (and hence for the CBD) of proposed measures to address climate change other than by direct emission reductions. Core considerations therefore relate to impacts on biodiversity, and climate change.

235. As recognized in Strategic Plan for Biodiversity 2011-2020 and in many other CBD documents and decisions, the main direct drivers of biodiversity loss are currently habitat loss, degradation and fragmentation; over-exploitation of harvested species; pollution, including from excess nutrients; and the introduction of invasive alien species. Climate change, and the related phenomena of ocean acidification, are additional drivers, arising from increasing levels of greenhouse gases in the atmosphere. Warming (with linked changes in precipitation patterns, sea ice cover, sea level rise and increased frequency of extreme events) and decreased ocean pH are already having adverse consequences for biodiversity and the delivery of ecosystem services: such impacts are projected to increase in future[728,729], exacerbating the impacts of other pressures.

236. Because of inertia in the climate system, and in socio-economic structures (primarily relating to the use of fossil fuels for energy generation, with associated investments and infrastructure), further climate change is inevitable. While there is scope for local/national action to reduce the scale of such change, and its impacts, the effectiveness of such action depends on a framework of concerted global effort. In particular, deep and very rapid decarbonization by all countries is required if future temperature increase is to be kept within a 2°C limit by emission reduction alone.

237. Greenhouse gas emissions under current trajectories are broadly consistent with RCP 8.5 (the highest of the four representative pathways used in IPCC AR5): the consequent climatic disruption would undoubtedly lead to an extremely large loss of biodiversity. Recent pledges for emission reductions made by Parties to UNFCCC would significantly reduce future climate change and its impacts; however, they are insufficient to keep warming within 2°C.

238. This report addresses the environmental implications, as far as they are known, of other actions to constrain global warming that are theoretically possible and have attracted wider interest. Such actions can be grouped in two main approaches: the deliberate removal of greenhouse gases (particularly carbon dioxide removal, CDR) also known as negative emissions, and sunlight reflection methods (SRM), also known as solar radiation management. Following previous scientific usage[730] and the IPCC definition[731], both those two approaches are here considered as climate geoengineering: "the deliberate intervention in the planetary environment of a nature and scale intended to counteract climate change and/or its impacts". That definition is used here without prejudice to any definition of climate geoengineering that may be subsequently agreed under the Convention, recognising that: other definition options are possible; some CDR techniques have much in common with conventional mitigation techniques (i.e. direct reduction in emissions); and a more exact definition, or definitions, would be needed for regulatory purposes, preferably on a technique-specific basis.

239. If the deployment of CDR and/or SRM techniques were successful in helping to limit future temperature increase, there would be (relative) benefits for biodiversity, in that at least some of the adverse impacts of climate

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[728] IPCC (Intergovernmental Panel on Climate Change) (2014a)

[729] IPCC (Intergovernmental Panel on Climate Change) (2014c)

[730] Royal Society (2009)

[731] IPCC (Intergovernmental Panel on Climate Change) (2014c)

change would be reduced or avoided. However, the effectiveness and viability of the techniques are uncertain, for a wide range of reasons, and in reducing the scale of one problem, other new problems would be created. Thus there would also be risk of the geoengineering action also contributing to other drivers affecting biodiversity loss and ecosystem integrity.

240. The expected climatic benefits of both CDR and SRM techniques crucially depend on their effectiveness. This report therefore devotes considerable attention to that aspect, mostly on a technique-specific basis. Feasibility is closely linked, while involving additional bio-physical and socio-political considerations.

241. Recognizing that the impacts of geoengineering on biodiversity can be both positive and negative, three main categories of impacts can be distinguished:

- **Impacts relating to climatic effectiveness (including associated effects of ocean acidification)**, as harm prevented rather than as an absolute benefit. The scale of that benefit then relates not only to the comparison made for future climatic conditions without the intervention, but also to technique-specific effectiveness (determined by full life cycle analysis) and its maximum feasible scaling (that may involving complex bio-physical and socio-economic considerations, particularly for CDR). For SRM, potential climatic effects must be considered not only at a global scale (i.e. global mean values for temperature and precipitation), but also at regional and local scales. The occurrence of imperfect regional-scale amelioration may be more significant for biodiversity/ecosystems than it is for agriculture, since adaptation for the latter is relatively more achievable, e.g. by changing crops to better suit the change in climatic conditions. Furthermore, decreased crop yields in one locality may be balanced, to some degree, by increased yields elsewhere, either on a national or regional scale. For ecosystems, and most plant and animal species, the scope for adaptation is much more limited, requiring biome migration and/or genetic selection (evolution), both operating on longer timescales than are available under current rates of climate change.
- **Non-climatic ecosystem impacts that are technique inherent,** and therefore a direct (and almost certainly unavoidable) consequence of the deployment of the CDR or SRM technique at a scale necessary to have significant climatic benefits. Such impacts are more likely to be negative than positive, but the latter are also possible. For land-based CDR, the most serious consequences relate to land use/land cover conversions; in particular the near-certain losses of natural land cover (and its biodiversity) involved in large-scale bioenergy with carbon-capture and storage (BECCS). Large-scale biochar is also likely to involve significant land conversion. For land- or ocean based enhanced weathering, there would inevitably be consequences of large-scale mineral extraction, also changes to freshwater/marine chemistry with implications for biota, although not yet well investigated. Marine-based CDR based on enhanced primary production – whether through direct fertilization, upwelling or macro-algal cultivation – inevitably involves changes in community composition as well as productivity changes. Regional-scale considerations (and, to some degree, value judgements) are likely to be involved as to whether such changes are 'good' or 'bad' for biodiversity. For atmospheric-based SRM, the inevitable consequence is reduced light levels at the land or ocean surface; research to date suggests the effects of this change may be relatively slight.
- **Indirect effects of specific techniques on biodiversity, that may be avoidable**. This category covers a wide range of secondary impacts, that could be minimized or perhaps entirely avoided. For example: the scale of BECCS' impact on local water availability (e.g. river flows) and nitrogen pollution will depend on how much irrigation or fertilizers are used; the effect of stratospheric aerosol injection on ozone levels depends on the chemicals used; the impact of marine cloud brightening on terrestrial vegetation (via salt damage) will depend on deployment location and local weather conditions.

Table 7.1 provides a summary of potential impacts of the main CDR and SRM techniques based on the above groupings.

242. Reforestation/afforestation and increases in soil carbon storage (such as might occur through ecosystem restoration) are generally considered as conventional climate mitigation measures, yet may also make a significant contribution to carbon dioxide removal, and are thus also sometimes considered within the scope of 'geoengineering'. Such actions are also expected to significantly benefit biodiversity. Yet such activities on their own would be insufficient to remove carbon at the scale required in most current emission scenarios. Furthermore, climatic benefits may not be as great as intuitively supposed: effects on albedo, atmospheric water content; carbon lability/stability; and the release of other greenhouse gases must all also be taken into consideration. Regardless of whether or not these activities are considered as geoengineering, a more comprehensive characterization and quantitative understanding of their climatic role would seem necessary.

243. In many regards, our understanding of the issues (and associated uncertainties) regarding geoengineering impacts on biodiversity remains much the same in 2015 as it did in 2012. Yet there have also been important developments, as follows:

- **Most IPCC scenarios that limit global warming to 2˚C now include carbon dioxide removal from the atmosphere**. Within IPCC reports, CDR is mostly referred to as negative emissions, and is considered as a mitigation action rather than geoengineering; nevertheless, that action fits the IPCC's own definition of geoengineering, and the one used here. While other scenarios that do not include CDR are also possible, they require reductions in global greenhouse gas emissions of >6% per year.
- **Additional uncertainties have been identified regarding the viability of large-scale BECCS as a CDR technique:** the validity of many assumptions regarding its potential scale-up have been challenged, and its environmental/biodiversity implications do not seem to have been fully taken into account.
- **A better appreciation has been developed of the implications of an overshoot in atmospheric CO_2 concentrations**, when atmospheric levels exceed levels that are considered to be safe but are subsequently reduced by CDR. While much depends on the scale and duration of any overshoot, it would necessarily involve increased risks of irreversible changes with biodiversity implications (e.g. in sea level, and ocean acidification).
- **Improvements have been made in SRM modelling, with greater emphasis on multi-model comparisons and regional-scale effects**. Specific attention on Arctic sea ice cover has shown that the rate of sea ice loss could, potentially, be slowed; however, prevention of total loss is likely to lead to unacceptable climate impacts elsewhere.

244. There has been no shortage of recent scientific publications on geoengineering: around 650 are identified in this report, with ~500 directly cited and a further ~150 identified in Annex 1. Yet of that total, it is estimated that less than 5% *directly* address the impacts of geoengineering on biodiversity. A very much higher proportion is essentially speculative, either relating to modelling (in natural science literature) or conceptual considerations (in social sciences). Much can be achieved by modelling; nevertheless, the validity of its results does depend on the validity of the assumptions made, in turn depending on process studies and actual measurements. Some of these measurements can be made under experimental conditions in the laboratory, but many others require field observations and studies.

245. The need for further research on CDR techniques has been strongly argued in recent reports[732,733,734], and, more cautiously, for SRM techniques. The latter are considered to involve greater risk of moral hazard; however, that concern has not been supported by recent studies (see Chapter 5), and the opposite may apply[735]. Field research

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[732] NRC (National Research Council) (2015a,b)

[733] Schäfer S, Lawrence M, Stelzer H, Born W et al. (2015)

[734] de Guillebon B, Boucher O, Abbadie L, Barré P et al (2014)

[735] The validity of the moral hazard hypothesis has been tested (and found wanting) for SRM, but not for CDR. It is possible that the inclusion of negative emissions in RCP 2.6 scenarios has resulted in less policy attention being given to renewable energy.

for both CDR and SRM techniques may involve environmental risks, yet these will be highly technique specific, and not necessarily greater than for any other field experiments.

246. Chapter 6 provides an update on the policy and regulatory framework. With the exception of the amendment to the London Protocol to regulate the placement of matter for ocean fertilization and other marine geoengineering activities, adopted by the Contracting Parties to the London Protocol by Resolution LP.4(8) but not yet in force, there have been few developments in the international regulatory framework relevant to geoengineering. The lack of a governance framework for SRM remains a major gap. In addition, the large-scale BECCS and afforestration proposed in many IPCC AR5 scenarios may raise new regulatory issues at the international level regarding the associated scale of land use change.

Table 7.1 Summary of main climatic and non-climatic potential impacts of different climate geoengineering techniques on the environment and biodiversity. Techniques are those considered in this report, except that greenhouse gas removal methods are here limited to carbon dioxide removal (CDR). The magnitude and relative importance of the identified impacts, that are not comprehensive, necessarily depends on deployment scale and on which IPCC RCP scenario is used as the comparator; many other aspects are also uncertain. Non-climatic impacts are separated between those considered intrinsic to the technique and other potential side-effects, with the occurrence and scale of the latter depending on how the technique is applied. Deployment of all CDR techniques may involve climatic hysteresis risks associated with overshoot in atmospheric CO_2. Climatic effectiveness for BECCS and DAC assumes feasibility of large-scale carbon capture and storage (CCS), with the CO_2 not used for enhanced oil recovery or for synthesis of non-permanent products.

Technique	Factors relating to climatic effectiveness, including effects on ocean acidification (OA)	Non-climatic impacts relevant to biodiversity	
		Obligatory	Non-obligatory
Greenhouse Gas Removal (CO2 removal)			
Bioenergy with carbon capture and storage (BECCS)	Limited/moderate potential for counter-acting climate change and OA. Other climate-related issues: • Land use change likely to increase release of CO_2 and other greenhouse gases • Albedo change (in either direction) may be involved • Risk of leakage from CO_2 storage	• Large-scale land conversion, expected to have adverse consequences for biodiversity	• Decreased water availability (if irrigation used) • Increased nutrient pollution (if fertilizer used) • Risk of leakage impacts from CO_2 storage
Afforestation and reforestation	Limited potential for counter-acting climate change and OA. Other climate-related issues: • Adverse albedo change • Likely increased release of other greenhouse gases (including water vapour) • Risk of carbon loss (e.g. fire)	• Large-scale land conversion; may have beneficial or adverse impacts: reforestation (and afforestation of previously forested lands) likely to be positive; afforestation of other biomes likely to be negative	• Decreased water availability (if irrigation used) • Increased nutrient pollution (if plantations fertilized)
Soil carbon: land management	Limited potential for counter-acting climate change and OA. Other climate-related issues: • Possibility of increased release of other greenhouse gases • Risk of carbon loss from future changes in management	• Changes in soil fauna and microflora	• Benefits for biodiversity (if achieved through ecosystem restoration)

Technique	Factors relating to climatic effectiveness, including effects on ocean acidification (OA)	Non-climatic impacts relevant to biodiversity	
		Obligatory	Non-obligatory
Biochar	Limited/moderate potential for counter-acting climate change and OA. Other climate-related issues: • Possibility of decreased release of other greenhouse gases • Duration of carbon storage uncertain • Adverse albedo change (but may be small)	• Moderate/large-scale land conversion, expected to have adverse consequences for biodiversity • Changes in agricultural soil fauna and microflora	• Decreased water availability (if biochar crops irrigated) • Increased nutrient pollution (if biochar crops fertilized) • Reduced or increased toxic impacts (depends on biochar feedstock)
Ocean fertilization and enhanced ocean productivity	Limited/moderate potential for counter-acting climate change and OA. Other climate-related issues: • Likely increased release of other greenhouse gases • Duration of carbon storage uncertain • Reduces surface OA, but worsens OA in mid/deep water	• Increased primary production, with associated changes in ecosystem community structure and foodwebs • Increased mid-water and benthic decomposition (and deoxygenation)	• Potential for both benefits and adverse impacts on fisheries • Risk of increase in harmful algal blooms • Secondary impacts of changes in water mixing (if upwelling used to increase productivity) • Land-based impacts of obtaining large amounts of macro-nutrients (if N and P used instead of Fe)
Enhanced weathering: land	Limited/moderate potential for counter-acting climate change? But may help alleviate coastal OA. Other climate-related issues: • Beneficial albedo change (but may be small)	• Large-scale mineral extraction, with associated habitat damage or loss • Changes in agricultural soil fauna and microflora • Changes in freshwater chemistry with biotic implications	• Use of olivine would favour freshwater and marine diatoms (due to Si content) • Potential for nickel toxicity
Enhanced weathering/ alkalinization: ocean	Limited/moderate potential for counter-acting climate change. May alleviate OA.	• Large-scale mineral extraction, with associated habitat damage or loss • Application likely to cause rapid spatial and temporal fluctuations in water chemistry	• Effects on water clarity • Use of olivine would favour marine diatoms (due to Si content) • Smothering of benthic organisms if oilivine applied directly to seafloor
Direct air capture (DAC)	Moderate potential for counter-acting climate change. Other climate related issues: • Risk of CCS leakage	• Land 'footprint' area	• Deployment may have water requirements and/or pollution risks • Risk of leakage impacts from CO_2 storage

Technique	Factors relating to climatic effectiveness, including effects on ocean acidification (OA)	Non-climatic impacts relevant to biodiversity	
		Obligatory	Non-obligatory
Sunlight Reflection Methods and other physically-based techniques			
Stratospheric aerosol injection	Very high potential for counter-acting climate change. Other climate related issues: • Regional variability in climate change amelioration and residual impacts • Termination risks • Temperature-related effects on OA (but CO_2 stays high; may increase)	• Small global reduction in total light reaching the Earth's surface; increase in diffuse light: possibility of both negative and positive effects on primary production	• Ozone loss or delayed ozone regeneration (if sulphur aerosols used) • Possibility of other pollutant impacts (if other aerosols used)
Marine cloud brightening	High potential for counter-acting climate change. Climate related issues: • Regional variability in climate change amelioration (but adjustments possible?) • Termination risks • Some reduction in OA (but CO_2 stays high; may increase)	• Reduction in total light reaching the ocean surface; increase in diffuse light: effects on primary production (may be slight) • Effects of water extraction for spraying on upper ocean marine organisms (fish eggs/ larvae; other plankton)	• Salt damage to terrestrial vegetation (scale of impact will depend on deployment conditions)
Surface albedo: land	Limited/moderate potential for counter-acting climate change. Climate related issues: • High regional variability in climate change amelioration • Scope for reducing urban 'heat island' effects?	• *Urban*: Unlikely to be significant effects on biodiversity • *Crops*: Unlikely to be significant effects on biodiversity • *(Semi-) natural grassland or desert:* major adverse local changes inevitable if land surface covered	
Surface albedo: ocean	Limited/moderate potential for counter-acting climate change? Climate related issues: • Effects on air-sea greenhouse gas transfers (likely reduction in ocean uptake of CO_2) • Termination risks	Coverage of surface ocean by foam or other albedo-enhancers would adversely affect wide range of organisms in upper ocean, including seabirds, sea mammals and plankton. However, techniques insufficiently developed to distinguish technique inherent impacts and other side-effects	
Cirrus cloud thinning	Moderate potential for counter-acting climate change? Climate related issues: • Likely to be regional variability in climate change amelioration (but not investigated) • Termination risks?	Techniques not sufficiently developed to identify obligatory and non-obligatory impacts	

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ANNEX 1

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ANNEX 2

ISSUES RELATING TO DEFINITION OF CLIMATE-RELATED GEOENGINEERING

As noted in Sections 1.3 and 1.4 of the main report, CBD decision XI/20 (Box 1.1) noted, without prejudice to future deliberations, the existence of four definitions for climate-related geoengineering. The expectation was that there would be future work to consider these definitions, and potentially others.

While similar, the four options differ in important regards, with potential for ambiguities to arise when Parties implement decision XI/20 and others relating to climate-related geoengineering, hereafter geoengineering. It is therefore timely to here provide further discussion on their relative merits, noting that the overall need is not only to achieve an appropriate balance between generality and specificity, but also to reflect the wider use of the term, meet pragmatic needs and capturing a scientifically-coherent set of concepts. Consistency with IPCC (and UNFCCC) is of obvious importance in this area, and thus **options (c) and (d)** warrant serious consideration. As follows:

> (c) Deliberate large-scale manipulation of the planetary environment (32nd session of the Intergovernmental Panel on Climate Change);
>
> (d) Technological efforts to stabilize the climate system by direct intervention in the energy balance of the Earth for reducing global warming (Fourth Assessment Report of the Intergovernmental Panel on Climate Change); [*Footnote*: Noting that this definition includes solar radiation management but does not encompass other geoengineering techniques]

Option (d) is taken from the glossary of Working Group III Report of IPCC's Fourth Assessment Report, AR4 (2007)[736]. The footnote in the CBD decision, however, does not appear in IPCC AR4, where discussion of geoengineering mostly relates to ocean fertilization, as a 'mitigation' option in the WG III report. In the IPCC's Fifth Assessment Report, AR5, greater attention is given to geoengineering, and the following – somewhat different – explanation of its meaning is provided in the glossary to the Synthesis Report[737]:

> "Geoengineering refers to 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."

While the first sentence of the above could be used as a definition for geoengineering, it is relatively general without the subsequent text. Furthermore: i) the change of aim from 'stabilize the climate system' (AR4) to 'alter the climate system' (AR5) does not seem helpful (since the purpose of geoengineering is to prevent climate change, i.e. minimize climate alteration); ii) uncertainties remain regarding the 'fuzzy boundary' with weather modification and ecological engineering (both of which could also have substantive undesirable effects that cross national boundaries); and iii) there would seem overlap of the part of the above definition relating to 'increase net carbon sinks' with the IPCC

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[736] IPCC (Intergovernmental Panel on Climate Change) (2007) Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [B Metz, OR Davidson, PR Bosch, R Dave, LA Meyer (eds)], Cambridge University Press, Cambridge UK and New York USA, 851pp.

[737] IPCC (Intergovernmental Panel on Climate Change) (2014) Annex II, Glossary (KJ Mach, S Planton and C von Stechow (eds)]. In: 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 [Core Writing Team: RK Pachauri & LA Meyer (eds.)]. IPCC Geneva, p 117-130.

AR5 definition of 'mitigation (of climate change)' within the same glossary: "A human intervention to reduce the sources or enhance the sinks of greenhouse gases (GHGs)".

Separate IPCC AR5 glossary entries for Solar Radiation Management and Carbon Dioxide Removal give additional detail, as follows:

> "Solar Radiation Management (SRM) refers to the 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.). Artificial injection of stratospheric aerosols and cloud brightening are two examples of SRM techniques. Methods to modify some fast-responding elements of the long wave radiative budget (such as cirrus clouds), although not strictly speaking SRM, can be related to SRM. SRM techniques do not fall within the usual definitions of mitigation and adaptation (IPCC, 2012)[738]. See also Carbon Dioxide Removal (CDR) and Geoengineering."
>
> "Carbon Dioxide Removal (CDR) methods refer to a set of techniques that aim to remove CO_2 directly from the atmosphere by either (1) increasing natural sinks for carbon or (2) using chemical engineering to remove the CO_2, with the intent of reducing the atmospheric CO_2 concentration. CDR methods involve the ocean, land and technical systems, including such methods as iron fertilization, large-scale afforestation and direct capture of CO_2 from the atmosphere using engineered chemical means. Some CDR methods fall under the category of geoengineering, though this may not be the case for others, with the distinction being based on the magnitude, scale and impact of the particular CDR activities. The boundary between CDR and mitigation is not clear and there could be some overlap between the two given current definitions (IPCC, 2012)[14]. See also Solar Radiation Management (SRM).

The above additional definitions/descriptions introduce additional ambiguities and uncertainties. For example: i) the SRM definition is initially in terms of the shortwave radiative budget, yet also includes modification of long wave radiative budget as being in some way "related to SRM"; ii) the geoengineering and CDR glossary entries do not seem fully consistent, since the former could be summarized as "geoengineering comprises SRM, CDR and other methods" and the latter as "not all CDR methods are geoengineering"; iii) while large-scale afforestation is explicitly included, it is not clear that bioenergy with carbon capture and storage (BECCS) is considered as a CDR technique, since the processes involved are arguably not a 'a natural sink' nor CO_2 removal by chemical engineering; and iv) the potential for overlap between CDR and mitigation is identified but not resolved. For those reasons, as well as their length, the IPCC definitions/descriptions of geoengineering do not seem to provide the required clarity for CBD decisions involving regulation of geoengineering and their implementation.

Option a) could be considered the default definition, being previously included in CBD decision X/33 "until a more precise definition can be developed":

> (a) Any technologies that deliberately reduce solar insolation or increase carbon sequestration from the atmosphere on a large scale and that may affect biodiversity (excluding carbon capture and storage from fossil fuels when it captures carbon dioxide before it is released into the atmosphere).

Yet there are several potential problems in that wording:

i) The inclusion of "technologies" suggests that it is intended to be a key criterion for deciding what should (or should not) be regarded as geoengineering; however, the meaning of the term can be very broad, covering the use of any tools, techniques, or methods.

ii) "... reduce solar insolation or increase carbon sequestration ...". The restriction of geoengineering to these two effects excludes other approaches that could (in theory) counteract anthropogenic climate change. These include:

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[738] IPCC (Intergovernmental Panel on Climate Change) (2012) Meeting Report of the Intergovernmental Panel on Climate Change Expert Meeting on Geoengineering [O Edenhofer, R Pichs-Madruga, Y Sokona, C Field, V Barros, TF Stocker, Q Dahe, J Minx, KJ Mach, G-K Plattner, S Schlömer, G Hansen & M Mastrandrea (eds.)]. IPCC Working Group III Technical Support Unit, Potsdam, Germany, 99 pp.

removal from the atmosphere of greenhouse gases other than those containing carbon (e.g. N_2O); changes to clouds in the upper atmosphere that would increase planetary heat loss; large-scale increases in land or ocean surface albedo (no reduction in insolation, but more of that energy is reflected back to space); and the re-distribution of heat energy once received at the Earth's surface.

iii) "... sequestration ...". This term is explained within decision X/33 as "the process of increasing the carbon content of a reservoir/pool other than the atmosphere". But the stability of the carbon within the non-atmospheric reservoir or pool needs to be specified; otherwise all agriculture would be geoengineering, since it involves the (temporary) "sequestration" of carbon.

iv) "... on a large scale ...". What is 'large' in this context? Unless that is defined, the phrase does not add much information to the overall definition.

v) "... that may affect biodiversity ...". The use of 'may' could either imply that geoengineering *must* affect biodiversity in order to be within the definition, or that it *might* do (but does not have to). The phrase would anyway seem unnecessary within a definition of climate geoengineering: if climate is significantly affected, then biodiversity will inevitably also be affected to some degree (either positively or negatively).

vi) The definition does not mention why there should be any effort to either reduce insolation or remove carbon from the atmosphere: some reference to overall intent would seem necessary.

The above issues were identified in UNEP/CBD/COP/11/INF/26, but were not raised by Parties in COP 11 discussions.

Option b) is the definition of geoengineering developed in CBD (2012), and re-used here:

> b) Deliberate intervention in the planetary environment of a nature and scale intended to counteract anthropogenic climate change and/or its impacts. [*Footnote*: Excluding carbon capture and storage at source from fossil fuels where it captures carbon dioxide before it is released into the atmosphere, and also including forest-related activities].

The 'forest-related activities' mentioned in the footnote are only included in as far as they fulfil the other parts of the definition, i.e. at a climatically-relevant scale and with that intent. As noted in CBD (2012):

> "This definition is broad in scope, yet includes important criteria to clarify its intended meaning in an objective and consistent way. Key features of this definition are that the interventions are deliberate, that their purpose is to address human-driven climate change, and that the implementation of the proposed technique is on a scale large enough to have a significant counter-acting effect; i.e. reducing or potentially reversing human-induced temperature increases and associated changes. The definition includes, but is not necessarily limited to, sunlight reflection methods (SRM, also known as solar radiation management), and carbon dioxide removal (CDR) techniques, also known as negative emission methods or negative emission techniques."
>
> "The above definition excludes 'conventional' carbon capture and storage (CCS) from fossil fuels, since that involves the capture of CO_2 before it is released into the atmosphere. Thus that form of CCS reduces the problem of greenhouse gas emissions, rather than counter-acting either their presence in the atmosphere or their climatic effects. Nevertheless, all CDR techniques necessarily involve carbon capture, by either biological or chemical means, and some may involve the same or similar processes of managed carbon storage as used for at-source CCS."

A more radical approach could also be taken: abandoning the term geoengineering altogether, and instead referring to 'climate engineering'[739] or 'climate interventions'. The latter switch was made by the US Committee on Geoengineering

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[739] Boucher O, Forster PM, Gruber N, Ha-Duaong M et al. (2014) Rethinking climate engineering categorization in the context of climate change mitigation and adaptation. WIREs Climate Change, 5, 23-35; doi: 10.1002/wcc.261

Climate: Technical Evaluation and Discussion of Impacts, in its two recent reports[740,741] published by the US National Academy of Sciences and National Research Council (NAS/NRC). The NAS/NRC reports preferred 'climate interventions' since: i) that term avoided potential confusion with other (primarily geological) meanings for geoengineering; ii) both geoengineering and climate engineering implied a more precise and controllable process than was possible; and iii) intervention has the meaning of "an action intended to improve a situation". The Committee also made clear that greenhouse gas removal and sunlight reflection methods were very different approaches, and that using geoengineering as the single descriptor for both could be unhelpful.

Although most media coverage of the NAS/NRC reports still used geoengineering or climate engineering[742], the proposed terminology has been scientifically welcomed:

> "'Climate intervention' is actually a more accurate and less hubristic term than 'geoengineering'. Why is it better? 'Intervention' is something that people from all kinds of fields do. The term has use both in medicine/psychology, and in my field, development studies. Using it opens up the idea that we're not considering how to engineer a natural system, but intervening in a socioecological one… The reports' switch to a language that allows us to better conceptualize coupled and interdependent socioecological systems is a step in the right direction for those seeking to think more holistically about the role of technologies in climate, energy and development"[743].

Based on the text in this Annex, in Chapter 6 and information presented elsewhere in this report, the CBD may wish to consider taking forward its future discussions on the definition of geoengineering on the following basis:

- Overall use of a 'climate intervention' framework, that could be defined relatively broadly by re-using option (b), i.e. the definition for climate geoengineering used in this report. Such a framework would allow continued holistic consideration of the full spectrum of potential techniques, including the potential for their interactions, and both positive and negative impacts
- Greater emphasis on the differences between the two main groups of approaches, greenhouse gas removal (primarily carbon dioxide removal, CDR) and sunlight reflection methods (SRM), noting that there is the close linkage between CDR and conventional mitigation; that both CDR and SRM include a variety of techniques with very different levels of risk; and that approaches other than CDR and SRM are also possible
- For regulatory purposes (for either research or deployment), recognition of the need to develop technique-specific definitions for techniques of particular concern, with other international bodies where appropriate, and with associated definitions of the scale of physical effects that warrant regulatory action.

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740 NRC (National research Council) (2015) Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration. Committee on Geoengineering Climate: Technical Evaluation and Discussion of Impacts; Board on Atmospheric Sciences and Climate; Ocean Studies Board; Division on Earth and Life Studies. The National Academies Press, Washington DC, 140 pp

741 National Academy of Science (2015) Climate Intervention: Reflecting Sunlight to Cool Earth. Committee on Geoengineering Climate: Technical Evaluation and Discussion of Impacts; Board on Atmospheric Sciences and Climate; Ocean Studies Board; Division on Earth and Life Studies. The National Academies Press, Washington DC, 234 pp

742 Svoboda M (2015) Geoengineering: neither geo-, nor engineering? Yale Climate Connections; http://www.yaleclimateconnections.org/2015/03/geoengineering-neither-geo-nor-engineering/

743 Comment by H Buck in http://dcgeoconsortium.org/nas-responses (Forum for Climate Engineering Assessment: Unpacking the social and political implications of climate engineering)

ANNEX 3

KEY MESSAGES FROM CBD (2012) GEOENGINEERING IN RELATION TO THE CONVENTION ON BIOLOGICAL DIVERSITY: TECHNICAL AND REGULATORY MATTERS

Key messages for Parts I and II of the report are given separately, with original numbering. Information in parentheses indicates where full details, with references, can be found in the 2012 report.

PART 1

1. **Biodiversity, ecosystems and their services are critical to human well-being. Protection of biodiversity and ecosystems requires that drivers of biodiversity loss are reduced.** The current main direct drivers of biodiversity loss are habitat conversion, over-exploitation, introduction of invasive species, pollution and climate change. These in turn are being driven by demographic, economic, technological, socio-political and cultural changes. Human-driven climate change due to greenhouse-gas emissions is becoming increasingly important as a driver of biodiversity loss and the degradation of ecosystem services. A rapid transition to a low-carbon economy is the best strategy to reduce such adverse impacts on biodiversity. However, on the basis of current greenhouse-gas emissions, their long atmospheric residence times and the relatively limited action to date to reduce future emissions, the use of geoengineering techniques has also been suggested as an additional means to limit the magnitude of human-induced climate change and its impacts.

Proposed climate-related geoengineering techniques

2. **In this report, climate-related geoengineering is defined as a deliberate intervention in the planetary environment of a nature and scale intended to counteract anthropogenic climate change and its impacts.** Geoengineering techniques include increasing the reflectivity of the Earth's surface or atmosphere, and removing greenhouse gases from the atmosphere; other approaches have also been proposed. This definition of geoengineering encompasses a wide spectrum of possible actions to counteract (or remedy) global warming and its associated consequences. The commonality of those actions is that they could produce global cooling, if applied at sufficient scale. Geoengineering can therefore be differentiated from actions that mitigate (reduce or prevent) anthropogenic greenhouse-gas emissions. Carbon capture and storage (CCS) linked to fossil fuel combustion is not here considered as geoengineering, although some geoengineering techniques may involve the same or similar processes of managed carbon storage. Afforestation/reforestation and large scale land-management changes are, however, included, notwithstanding that such measures are already deployed for climate-change mitigation and other purposes, and that they involve minimal use of new technologies. (*Sections 2.1-2.2*)

3. **Sunlight reflection methods (SRM), also known as solar radiation management, aim to counteract warming and associated climatic changes by reducing the incidence and subsequent absorption of short-wave solar radiation, reflecting a small proportion of it back into space.** They are expected to rapidly have an effect once deployed at the appropriate scale, and thus have the potential to reduce surface global temperatures within a few months or years if that were considered desirable. SRM would not address the root cause of human-driven climate change arising from increased greenhouse-gas concentrations in the atmosphere: instead they would mask the warming effect of accumulating greenhouse gases. They would introduce a new dynamic between the warming effects of greenhouse gases and the cooling effects of SRM with uncertain climatic implications, especially at the regional scale. SRM would not directly address ocean acidification. SRM proposals include:

    1. *Space-based approaches:* reducing the amount of solar energy reaching the Earth by positioning sun-shields in space with the aim of reflecting or deflecting solar radiation;

2. *Changes in stratospheric aerosols*: injecting sulphates or other types of particles into the upper atmosphere, with the aim of increasing the scattering of sunlight back to space;
3. *Increases in cloud reflectivity:* increasing the concentration of cloud-condensation nuclei in the lower atmosphere, particularly over ocean areas, thereby whitening clouds with the aim of increasing the reflection of solar radiation;
4. *Increases in surface albedo:* modifying land or ocean surfaces with the aim of reflecting more solar radiation out to space.

SRM could be implemented separately or in combination, at a range of scales. (*Section 2.2.1*)

4. **Carbon dioxide removal (CDR) techniques aim to remove CO_2, a major greenhouse gas, from the atmosphere**, allowing outgoing long-wave (thermal infra-red) radiation to escape more easily. In principle, other greenhouse gases, such as nitrous oxide (N_2O), and methane (CH_4), could also be removed from the atmosphere or reduced at source, but such approaches are currently highly speculative. Proposed CDR techniques include: *Ocean fertilization:* the enrichment of nutrients in marine environments with the intention of stimulating plant production, hence CO_2 uptake from the atmosphere and the deposition of carbon in the deep ocean;

1. *Enhanced weathering:* artificially increasing the rate by which CO_2 is naturally removed from the atmosphere by the weathering (dissolution) of carbonate and silicate rocks;
2. *Increasing carbon sequestration through ecosystem management:* through, for example: afforestation, reforestation, or measures that enhance natural carbon storage in soils and wetlands
3. *Biological carbon capture, using harvested biomass and subsequent carbon storage:* for example, through biochar, the long term storage of crop residues or timber, or bio-energy with carbon capture and storage; and
4. *Direct, chemical capture of carbon from the atmosphere and its subsequent storage*, for example, with storage as liquid CO_2 in geological formations or in the deep ocean.

CDR approaches involve two steps: (1) CO_2 capture from the atmosphere; and (2) long-term storage (sequestration) of the captured carbon. In the first three techniques, these two steps are very closely linked, although the permanence of the storage may be variable and technique-specific; in the fourth and fifth, capture and storage may be separated in time and space. Ecosystem-based approaches such as afforestation, reforestation or the enhancement of soil carbon are already employed as climate-change mitigation activities, and are not universally regarded as geoengineering technologies. CDR techniques act relatively slowly: to have a significant impact on the climate, such interventions, individually or collectively, would need to involve the removal from the atmosphere of several Gt C/yr (gigatonnes of carbon per year), maintained over decades. This seems unlikely to be achievable for several proposed CDR approaches. (*Section 2.2.2*)

5. **There is no single geoengineering approach that currently meets all three basic criteria for effectiveness, safety and affordability. Different techniques are at different stages of development, mostly theoretical, and many are of doubtful effectiveness.** Few, if any, of the approaches proposed above can be considered well-researched; for most, the practicalities of their implementation have yet to be investigated, and mechanisms for their governance are potentially problematic. Early indications are that several of the techniques, both SRM and CDR, are unlikely to be effective at the global scale. (*Section 2*)

Climate change and ocean acidification, and their impacts on biodiversity

6. **The continued increase in CO_2 and other atmospheric greenhouse gases not only has profound implications for global and regional average temperatures, but also for precipitation, soil moisture, ice-sheet dynamics, sea-level rise, ocean acidification and the frequency and magnitude of extreme events such as floods, droughts and wildfires.** Future climatic perturbations could be abrupt or irreversible, and potentially extend over millennial time scales; they will inevitably have major consequences for natural and human systems, severely affecting biodiversity and incurring very high socioeconomic costs. (*Section 3.1*).

7. **Since 2000, the rate of increase in anthropogenic CO_2 emissions has accelerated, averaging ~3.1% per year. Emissions of other greenhouse gases are also increasing. As a result, it will be extremely challenging to limit global warming to the proposed target of 2°C.** In fact, current commitments to limit greenhouse-gas emissions correspond to a 3–5°C warmer world. Avoidance of high risk of dangerous climate change therefore requires an urgent and massive effort to reduce greenhouse-gas emissions, as well as protecting existing natural carbon sinks, including through sustainable land management. If such efforts are not made, geoengineering approaches are likely to be increasingly proposed to offset at least some of the impacts of climate change, despite the risks and uncertainties involved (*Section 3.1.2*).

8. **Even with strong climate mitigation policies, further human-driven climate change is inevitable due to lagged responses in the Earth climate system.** Increases in global mean surface temperature of 0.3–2.2°C are projected to occur over several centuries after atmospheric concentrations of greenhouse gases have been stabilized, with associated increases in sea level due to thermally-driven expansion and ice-melt. The seriousness of these changes provides the reason why geoengineering has attracted attention. (*Section 3.1.2*)

9. **Human-driven climate change poses an increasingly severe range of threats to biodiversity and ecosystem services, greatly increasing the risk of species extinctions and local losses.** Temperature, precipitation and other climate attributes strongly influence the distribution and abundance of species, and their interactions. Because species respond to climate change in different ways, ecosystems (and the services they provide) will be disrupted. Projected climate change is not only more rapid than recent naturally-occurring climate change (e.g., during ice age cycles) but now the scope for such adaptive responses is reduced by other anthropogenic pressures, including over-exploitation, habitat loss, fragmentation and degradation, introduction of non-native species, and pollution. Risk of global extinction and local extirpations is therefore increased, since the abundance and genetic diversity of many species are already reduced, and their adaptive capacity is lessened. (*Section 3.2.1*)

10. **The terrestrial impacts of projected climate change are likely to be greatest for montane and polar habitats, for coastal areas affected by sea-level change, and wherever there are major changes in freshwater availability.** Species with limited adaptive capability will be particularly at risk; while insect pests and disease vectors in temperate regions are expected to benefit. Forest ecosystems, and the goods and services they provide, are likely to be affected as much, or more, by changes in hydrological regimes (affecting fire risk) and pest abundance, than by direct effects of temperature change. *(Section 3.2.2)*

11. **Marine species and ecosystems are increasingly subject to ocean acidification as well as changes in temperature.** Climate driven changes in the reproductive success, abundance and distribution of marine organisms are already occurring, more rapidly than on land. The loss of summer sea-ice in the Arctic will have major biodiversity implications. Biological impacts of ocean acidification (an inevitable chemical consequence of the increase in atmospheric CO_2) are less certain; nevertheless, an atmospheric CO_2 concentration of 450 ppm would decrease surface pH by ~0.2 units, making large-scale and ecologically significant effects likely. Tropical corals seem to be especially at risk, being vulnerable to the combination of ocean acidification, temperature stress (coral bleaching), coastal pollution (eutrophication and increased sediment load), sea-level rise and human exploitation (over-fishing and coral-harvesting). (*Section 3.2.3*)

12. **The biosphere plays a key role in climate processes, especially as part of the carbon and water cycles**. Very large amounts of carbon are naturally circulated and stored by terrestrial and marine ecosystems, through biologically-driven processes. Proportionately small changes in ocean and terrestrial carbon stores, caused by changes in the balance of natural exchange processes, can have climatically-significant implications for atmospheric CO_2 levels. Potential tipping points that may cause the rapid release of long-term carbon stores, e.g., as methane, are poorly understood. (*Section 3.3*)

Potential impacts on biodiversity of SRM geoengineering

13. **SRM, if effective in abating the magnitude of warming, would reduce several of the climate-change related impacts on biodiversity. Such techniques are also likely to have other, unintended impacts on biodiversity.** Assessment of the totality of those impacts is not straightforward: not only are the effects of specific SRM measures uncertain, but the outcome of the risk assessment will depend on the alternative, non-SRM strategy used as the 'control' for comparisons. Because climate change is projected to occur, climate-change scenarios provide relevant controls for assessing the risks and benefits of geoengineering, including the implications for biodiversity (*Chapter 4; Introduction*)

14. **Model-based analyses and evidence from volcanic eruptions indicate that uniform dimming of sunlight by 1–2% through an unspecified atmospheric SRM measure could, for most areas of the planet, reduce future temperature changes projected under unmitigated greenhouse gas emissions.** Overall, this would reduce several of the adverse impacts of projected climate change on biodiversity. These benefits would vary regionally, and might be negligible or absent for some areas. However, only limited research has been done; uniform dimming is a theoretical concept and may not be achievable; and many uncertainties remain concerning the effects of different atmospheric SRM measures and their geo-spatial consequences, for the hydrological cycle as well as for heat distribution. It is therefore not yet possible to predict effects with any confidence. (*Section 4.1.1*)

15. **SRM would introduce a new dynamic between the heating effects of greenhouse gases and the cooling due to sunlight reduction**. There are no known palaeo-precedents for the radiative impacts of high greenhouse-gas concentrations to be balanced by reduced light quantity; thus the stability of that combination is uncertain, and it is not clear what specific environmental challenges an "SRM world" might present to individual species and ecosystems, either on a short-term or a long-term basis. (*Section 4.1.3*)

16. **The amount of anthropogenic CO_2 in the atmosphere is unaffected by SRM. Thus SRM would have little effect on ocean acidification and its associated impacts on marine biodiversity, nor the impacts (positive or negative) of elevated atmospheric CO_2 on terrestrial ecosystems.** Some indirect effects of SRM on atmospheric CO_2 are possible; e.g., if such techniques prevent the temperature-driven release of additional CO_2 from natural systems. Nevertheless, SRM cannot be considered as an alternative to emission mitigation or CDR in terms of avoiding detrimental effects on the (marine) biosphere. (*Section 4.1.4*)

17. **Rapid termination of SRM, that had been deployed for some time and masking a high degree of warming due to continued greenhouse-gas emissions, would almost certainly have large negative impacts on biodiversity and ecosystem services.** Those adverse consequences would be more severe than those resulting from gradual climate change, since the opportunity for adaptation, including through population migration, would be much reduced. (*Section 4.1.5*)

18. **Stratospheric aerosol injection, using sulphate particles, would affect the overall quantity and quality of light reaching the biosphere; have relatively minor effects on atmospheric acidity; and could also contribute to stratospheric ozone depletion.** All these unintended impacts have implications for biodiversity and ecosystem services. Stratospheric aerosols would decrease the amount of photosynthetically active radiation (PAR) reaching the Earth by 1–2%, but would increase the proportion of diffuse (as opposed to direct) radiation. This would be expected to affect community composition and structure. It may lead to an increase of gross primary productivity (GPP) in forest ecosystems while decreasing ocean productivity. However, the magnitude and nature of effects on biodiversity are likely to be mixed, and are currently not well understood. Increased ozone depletion, primarily in the polar regions, would cause an increase in the amount of ultra violet (UV) radiation reaching the Earth, although potentially offset by the UV scattering of the aerosol particles themselves. (*Section 4.2.1*)

19. **Cloud brightening is a more localized SRM proposal, with its application likely to be limited to specific ocean areas. The predictability of its climatic impacts is currently uncertain;** nevertheless regional cooling with associated atmospheric and oceanic perturbations are likely, with potentially significant effects on terrestrial and marine biodiversity and ecosystems. Unintended impacts could be positive as well as negative. (*Section 4.2.2*)

20. **Surface albedo changes would need to be deployed over very large land areas (sub-continental scale) or over much of the global ocean to have substantive effects on the global climate, with consequent impacts on ecosystems. Strong localized cooling could have a disruptive effect on regional weather patterns.** For instance, covering deserts with reflective material on a scale large enough to be effective in addressing the impacts of climate change would greatly reduce habitat availability for desert fauna and flora, as well as affecting its customary use. (*Section 4.2.3*)

Potential impacts on biodiversity of CDR geoengineering techniques

21. **Carbon dioxide removal techniques, if effective and feasible, would be expected to reduce the negative impacts on biodiversity of climate change and, in most cases, of ocean acidification.** By removing CO_2 from the atmosphere, CDR techniques reduce the concentration of the main causal agent of anthropogenic climate change. Acidification of the surface ocean would also be reduced, but the effect of CDR on the ocean as a whole will depend on the location of long-term carbon storage. CDR methods are generally slow in affecting the atmospheric CO_2 concentration, with further substantial time-lags in the climatic benefits. Several of the techniques are of doubtful effectiveness, because of limited scalability. (*Section 5.1*)

22. **Individual CDR techniques may have significant unintended impacts on terrestrial, and/or ocean ecosystems, depending on the nature, scale and location of carbon capture and storage.** In some biologically-driven processes (ocean fertilization; afforestation, reforestation and soil carbon enhancement), carbon removal from the atmosphere and its subsequent storage are very closely linked. In these cases, impacts on biodiversity are likely to be limited to marine and terrestrial systems respectively. In other cases, the steps are discrete, and various combinations of capture and storage options are possible. Thus the carbon that is fixed within land biomass, for example, could be either: dumped in the ocean as crop residues; incorporated into the soil as charcoal; or used as fuel with the resultant CO2 chemically removed at source and stored either in sub-surface reservoirs or the deep ocean. In these cases, each step will have different and additive potential impacts on biodiversity, and potentially separate impacts on marine and terrestrial environments. (*Section 5.1*)

23. **Ocean fertilization involves increased biological primary production with associated changes in phytoplankton community structure and species diversity, and implications for the wider food web.** Ocean fertilization may be achieved through the external addition of nutrients (Fe, N or P) or, possibly, by modifying ocean upwelling. If carried out on a climatically significant scale, changes may include an increased risk of harmful algal blooms, and increased benthic biomass. Potential effects on fisheries are uncertain. If Fe is used to stimulate primary production, increases in one region may be offset, to some degree, by decreases elsewhere. Ocean fertilization is expected to increase the midwater production of methane and nitrous oxide; if released to the atmosphere, these greenhouse gases would significantly reduce the effectiveness of the technique. Large-scale ocean fertilization would slow near-surface ocean acidification but increase acidification (and potential anoxia) in mid- and deep-water. The small-scale experiments conducted to date indicate that this is a technique of doubtful effectiveness for geoengineering purposes. (*Sections 5.2–5.3*)

24. **Enhanced weathering would involve large-scale mining and transport of carbonate and silicate rocks, and the spreading of solid or liquid materials on land or sea. The scale of impacts (that may be positive as well as negative) on terrestrial and coastal ecosystems will depend on the method and scale of implementation.** CO2 is naturally removed from the atmosphere by the weathering (dissolution) of carbonate and silicate rocks. This process could be artificially accelerated by techniques that include releasing calcium carbonate or other dissolution products of alkaline minerals into the ocean or spreading abundant silicate minerals such as olivine over agricultural soils. In the ocean, this technique could, in theory, be used to counter ocean acidification; the practicalities have yet to be tested. (*Section 5.4*)

25. **The impacts on biodiversity of ecosystem carbon storage through afforestation, reforestation, or the enhancement of soil and wetland carbon depend on the method and scale of implementation.** If managed

well, such approaches have the potential to increase or maintain biodiversity. Afforestation, reforestation and land-use change are already being promoted as climate change mitigation options, and are not considered by many to be geoengineering. Much guidance has already been developed, by the Convention on Biological Diversity and others, to maximize the biodiversity benefits of these approaches and minimize the disadvantages (e.g., planting assemblages of native species rather than exotic monocultures). (*Section 5.5*)

26. **Production of biomass for carbon sequestration on a scale large enough to be climatically significant is likely to either compete for land with food and other crops or involve large-scale land-use change, with impacts on biodiversity as well as greenhouse-gas emissions that may partially offset (or even exceed) the carbon sequestered as biomass.** The coupling of biomass production with its use as bioenergy in power stations equipped with effective carbon capture at source has the potential to be carbon negative. The net effects on biodiversity and greenhouse-gas emissions would depend on the approaches used. The storage or disposal of biomass may have impacts on biodiversity separate from those involved in its production. Removal of organic matter from agricultural ecosystems is likely to have negative impacts on agricultural productivity and biodiversity, and may increase the need for fertilizer application to maintain soil fertility. (*Section 5.6.1*)

27. **The impacts of long-term storage of biochar (charcoal) in different soil types and under different environmental conditions are not well understood.** Important issues that need to be resolved include the stability of carbon in the biochar, and effects on soil water retention, N_2O release, crop yields, mycorrhizal fungi, soil microbial communities and detritivores. (*Section 5.6.2*)

28. **Ocean storage of terrestrial biomass (e.g., crop residues) is expected to have a negative impact on biodiversity.** The deposition of ballasted bales would likely have significant local physical impacts on the seabed due to the sheer mass of the material. Wider, long-term indirect effects of oxygen depletion and deep-water acidification could be regionally significant if there were cumulative deposition, and subsequent decomposition, of many gigatonnes of organic carbon. (*Section 5.6.3*)

29. **Chemical capture of CO_2 from ambient air would require a large amount of energy. Some proposed processes may also have high demand for freshwater, and potential risk of chemical pollution from sorbent manufacture; otherwise they would have relatively small direct impacts on biodiversity.** Removal of CO_2 from the ambient air (where its concentration is 0.04%) is much more difficult and energy intensive than its capture from flue gases of power stations (where levels are about 300 times higher, at ~12%); it is therefore unlikely to be viable without additional carbon-free energy sources. CO_2 extracted from the atmosphere would need to be stored either in the ocean or in sub-surface geological reservoirs with additional potential impacts; alternatively, it could be converted to carbonates and bicarbonates. (*Section 5.7.1*)

30. **Ocean CO_2 storage will necessarily alter the local chemical environment, with a high likelihood of biological effects.** Effects on mid-water and seafloor ecosystems are likely through the exposure of marine invertebrates, fish and microbes to pH reductions of 0.1–0.3 units. Near-total destruction of deep seafloor organisms can be expected if lakes of liquid CO_2 are created. Chronic effects on ecosystems of direct CO_2 injection into the ocean over large ocean areas and long time scales have not yet been studied, and the capacity of ecosystems to compensate or adjust to such CO2 induced shifts is unknown. (*Section 5.7.2*)

31. **Leakage from CO_2 stored in sub-seafloor geological reservoirs, though considered unlikely if sites are well selected, would have biodiversity implications for benthic fauna on a local scale.** CO_2 storage in sub-seafloor geological reservoirs is already being implemented at pilot-scale levels. Its effects on lithospheric microbial communities seem likely to be severe, but have not been studied (*Section 5.7.2*)

Social, economic, cultural and ethical considerations of climate-related geoengineering

32. **The consideration of geoengineering as a potential option raises many socioeconomic, cultural and ethical issues, regardless of the specific geoengineering approach.** Such issues include global justice, the unequal

spatial distribution of impacts and benefits, and intergenerational equity. Confidence in technological solutions, or alternatively risk-aversion, may be both highly differentiated across social groups and highly dynamic. (*Section 6.3*)

33. **Humanity is now the major force altering the planetary environment**. This has important repercussions, not only because it forces society to consider multiple and interacting global environmental changes, but also because it requires difficult discussions on whether it is desirable to move from (1) unintentional modifications of the Earth system, with implications that until a few decades ago we were unaware of; to (2) attempts to reach international agreement to reduce the actions causing the damage; and finally to (3) consideration of actions to deliberately modify global cycles and systems, to try to avoid the worst outcomes of climate change. (*Section 6.3.1*)

34. **The 'moral hazard' of geoengineering is that it is perceived as a technological fallback, possibly reducing effort on mitigation.** However, the opposite may also occur: when there is wider knowledge on geoengineering, and its limitations and uncertainties, increased policy effort might be directed at emission reductions. Other ethical considerations include the question of whether it is acceptable to remediate one pollutant by introducing another. (*Section 6.3.1*)

35. **In addition to limiting the undesirable impacts of climate change, the large-scale application of geoengineering techniques is near-certain to involve unintended side effects and increase socio-political tensions.** While technological innovation has helped to transform societies and improve the quality of life in many ways, it has not always done so in a sustainable manner. Failures to respond to early warnings of unintended consequences of particular technologies have been documented, and it has been questioned whether technological approaches are the best option to address problems created by the application of earlier technologies. (*Section 6.3.2*)

36. **An additional issue is the possibility of technological, political and social "lock in"**, whereby the development of geoengineering technologies might also result in the emergence of vested interests and increasing social momentum. It has been argued that this path of dependency could make deployment more likely, and/or limit the reversibility of geoengineering techniques. To minimize such risks, research to assess the safety, feasibility and cost-effectiveness of geoengineering must be open-minded and objective, without prejudice to the desirability or otherwise of geoengineering implementation. (*Section 6.3.2*)

37. **Geoengineering raises a number of questions regarding the distribution of resources and impacts within and among societies and across time.** Access to natural resources is needed for some geoengineering techniques. Competition for limited resources can be expected to increase if land-based CDR techniques emerge as a competing activity for land, water and energy use. The distribution of impacts (both positive and negative) of SRM geoengineering is unlikely to be uniform—neither are the impacts of climate change itself. (*Section 6.3.4*)

38. **In cases in which geoengineering experimentation or interventions might have transboundary effects or impacts on areas beyond national jurisdiction, geopolitical tensions could arise** regardless of causation of actual negative impacts, especially in the absence of international agreement. As with climate change, geoengineering could also entail intergenerational issues: future generations might be faced with the need to maintain geoengineering measures in order to avoid termination effects that might be mostly caused by emissions from several decades earlier. (*Section 6.3.5*)

Synthesis

39. **The deployment of geoengineering techniques, if feasible and effective, could reduce the magnitude of climate change and its impacts on biodiversity. At the same time, most geoengineering techniques are likely to have unintended impacts on biodiversity, particularly when deployed at a climatically-significant scale, together with significant risks and uncertainties.** The nature of the unintended effects, and their spatial distribution, will vary among techniques; overall outcomes are difficult to predict. For several techniques, there would increases in land use change, and there could also be an increase in other drivers of biodiversity loss. (*Section 7.1*)

40. **There are many areas where knowledge is still very limited**. These include: (1) the overall effectiveness of some of the techniques, based on realistic estimates of their scalability; (2) how the proposed geoengineering techniques can be expected to affect weather and climate regionally and globally; (3) how biodiversity, ecosystems and their services are likely to respond to geoengineered changes in climate; (4) the unintended effects of different proposed geoengineering techniques on biodiversity; and (5) the social and economic implications, particularly with regard to geo-political acceptability, governance and the potential need for international compensation in the event of there being 'winners and losers'. Targeted research could help fill these gaps (*Section 7.3*)

41. **There is very limited understanding among stakeholders of geoengineering concepts, techniques and their potential positive and negative impacts on biodiversity.** Not only is much less information available on geoengineering than for climate change, but there has been little consideration of the issues by indigenous peoples, local communities and marginalized groups, especially in developing countries. Since these communities play a major role in actively managing ecosystems that deliver key climatic services, the lack of knowledge of their perspective is a major gap that requires further attention (*Section 7.3*)

PART 2

1. **The Conference of the Parties to the Convention on Biological Diversity, taking into account *the possible need for science based global, transparent and effective control and regulatory mechanisms*, requested a study to be undertaken on gaps in such existing mechanisms for climate-related geoengineering relevant to the Convention on Biological Diversity** (decision X/33, paragraph 9 (m)). This request was made in the context of the CBD decision on geoengineering which provides guidance for Parties and other Governments to ensure, "*in the absence of science based, global, transparent and effective control and regulatory mechanisms for geoengineering*", that no climate-related geoengineering activities that may affect biodiversity take place, until certain conditions are met, with some exceptions for small scale research (decision X/33, paragraph 8(w)). (*Section 1.1)*

2. **"Climate-related geoengineering" is a general term that encompasses several different geoengineering concepts, techniques or technologies.** The Conference of the Parties to the Convention on Biological Diversity, at its tenth meeting adopted a preliminary definition for climate-related geoengineering in 2010 and will further discuss the matter in 2012. In the study on the potential impacts on biodiversity, climate-related geoengineering is defined as a deliberate intervention in the planetary environment of a nature and scale intended to counteract anthropogenic climate change and/or its impacts through, *inter alia*, sunlight reflection methods or removing greenhouse gases from the atmosphere. However, there is no universal and uniform use of the term "geoengineering". Thus, the definition will need to be analysed for its suitability for governance in a normative context. (*Section 1.3*)

3. **The need for science-based global, transparent and effective control and regulatory mechanisms may be most relevant for those geoengineering concepts that have a potential to cause significant adverse transboundary effects, and those deployed in areas beyond national jurisdiction and in the atmosphere.** For example, injection of aerosols into the atmosphere would have transboundary effects that may be deleterious, while ocean fertilization would be carried out in areas that extend beyond national jurisdiction. Some activities such as afforestation, reforestation and terrestrial biomass production, when carried out within a single country, might be deemed to be adequately governed through domestic regulations. (*Section 1.3*)

4. **The existing regulatory framework includes general customary rules of international law and specific international treaties.** The rules of customary international law and other general principles of international law apply to all activities and therefore would, in principle, be relevant to geoengineering. In addition, some international treaties have provisions that may be relevant to particular categories of activities. (*Section 1.5*)

General rules of customary international law

5. **State responsibility describes the rules governing the general conditions under which a State is responsible for wrongful actions or omissions, and the resulting legal consequences**. Although the rules on State responsibility provide a general framework for addressing breaches of international law, they do not address under which conditions geoengineering activities would be permitted or prohibited. They require a breach on an obligation without defining these obligations. States are not as such responsible for acts for private actors. However, a State might have to address private actors in order to fulfil its own obligation. A State could be in breach of an obligation if it fails to take necessary measures to prevent effects caused by private actors. (*Section 2.1*)

6. **All States are under a general obligation to ensure that activities within their jurisdiction or control respect the environment of other States or of areas beyond national jurisdiction or control**. This duty to respect the environment does not mean, however, that *any* environmental harm, pollution, degradation or impact is generally prohibited. The duty prohibits a State from causing *significant transboundary* harm and obliges a State of origin to take adequate measures to control and regulate in advance sources of such potential harm. States have to exercise "due diligence" before carrying out potentially harmful activities. What constitutes "due diligence" would largely depend on the circumstances of each case. Establishing State responsibility for any harm from a geoengineering activity would require that (i) the geoengineering activity can be attributed to a particular State and (ii) can be associated with a significant and particular harm to the environment of other States or of areas beyond national jurisdiction or control. (*Section 2.2*)

7. **States have the duty to carry out an environmental impact assessment for activities that may have a significant adverse impact in a transboundary context, in particular, on a shared resource**. Among others, the Convention on Biological Diversity includes a provision for environmental assessment in Article 14 that is referred to in its decision on geoengineering (decision X/33 8(w)). An environmental impacts assessment (EIA) is required in many domestic legal orders and the International Court of Justice has recently recognized that the accepted practice among States amounts to "a requirement under general international law". Thus, where there is a risk that a proposed industrial activity may have a significant adverse impact in a transboundary context, the requirement to carry out an environmental impact assessment applies even in the absence of a treaty obligation to this effect. However, this does not necessarily extend to a requirement to undertake strategic environmental assessments. (*Section 2.3*)

8. **The precautionary principle or approach is relevant but its legal status and content in customary international law has not yet been clearly established, and the implications of its application to geoengineering are unclear.** Under the Convention, the precautionary approach has been introduced recognizing 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 minimize such a threat". This has been invoked in its decision on geoengineering which invites Parties and others to ensure (with some exceptions and until certain conditions are met) that no geoengineering activities take place (decision X/33 paragraph 8(w)). Under the London Protocol, Article 3.1 requires the application of the precautionary approach. Under the United Nations Framework Convention on Climate Change (UNFCCC), the precautionary approach is generally considered as intending to prevent States from postponing mitigation measures by referring to scientific uncertainty about climate change. However, an interpretation in support of geoengineering or pursuing further geoengineering research would not be evidently contrary to the wording. (*Section 2.4*)

9. **Other relevant general concepts include sustainable development, common but differentiated responsibilities, and concepts addressing international interest in the protection of areas beyond national jurisdiction and shared resources as well as issues of common concern such as biodiversity**. However the status of these concepts as customary international law is not clearly established. (*Section 2.6*)

Specific treaty regimes and institutions

10. **The Convention on Biological Diversity has adopted a decision on geoengineering that covers all technologies that may affect biodiversity.** The Convention contains many provisions that are relevant but not specific to geoengineering, including provisions on environmental assessment. Additional relevant guidance has been developed under the Convention. The CBD decision on geoengineering invites Parties and others to ensure (with some exceptions and until certain conditions are met) that no geoengineering activities take place (decision X/33 paragraph 8(w)). The decision refers specifically to "the precautionary approach and Article 14 of the Convention. While not expressed in legally binding language, the decision is important for a global governance framework because of the wide consensus it represents. The Parties to the Convention have also recognized that while science-based global transparent and effective control and regulatory mechanism for geoengineering may be needed, they may not be best placed under the Convention. The Convention on Biological Diversity has referred to and incorporated the work of the London Convention and its Protocol (LC/LP) on ocean fertilization in its own decisions, thus widening the application of this work beyond the smaller number of Parties to the LC/LP. (*Section 3.1*)

11. **The United Nations Convention on the Law of the Sea (UNCLOS) sets out the legal framework within which all activities in the oceans and seas must be carried out, including relevant geoengineering activities**, such as ocean fertilization, modification of downwelling and/or upwelling, maritime cloud albedo enhancement, and altering ocean chemistry through enhanced weathering. Under the Convention, States have the general obligations to protect and preserve the marine environment and to take all measures necessary to prevent, reduce and control pollution of the marine environment from any source, including pollution by dumping. While States are allowed to pursue a range of activities under the "freedom of the high seas", these activities must be exercized in accordance with the provisions of UNCLOS and with due regard for the interests of other States. Rules and standards established under LC/LP are considered to be relevant for the implementation of UNCLOS. (*Section 3.2*)

12. **The London Convention and its Protocol (LC/LP) have provided detailed guidance on ocean fertilization, as well as carbon storage, and are considering wider application to other marine geoengineering activities within their mandate. Disposal of CO2 in the water column or on the seabed is not allowed under the London Protocol**. The LC/LP are global instruments that address marine pollution from dumping of wastes and other matter at sea. In 2010 the Parties adopted the "Assessment Framework for Scientific Research Involving Ocean Fertilization". This non-binding Assessment Framework, which has been recognized by the Convention on Biological Diversity, guides Parties as to how proposals they receive for ocean fertilization research should be assessed and provides criteria for an initial assessment of such proposals and detailed steps for completion of an environmental assessment, including risk management and monitoring. The LP has also adopted amendments to regulate CO2 sequestration in sub-seabed geological formations supported by a risk assessment and management framework and additional guidelines. (*Section 3.3*)

13. **The UNFCCC and Kyoto Protocol have not addressed geoengineering concepts as such or its governance[744].** The objective of both instruments as stated in Article 2 of UNFCCC is to stabilize greenhouse-gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Under these instruments, guidance has been developed that address afforestation, reforestation and enhancement of soil carbon. Beyond these techniques, the obligations on Parties to take measures to limit emissions and protect carbon sinks do not promote or prohibit geoengineering measures as such. (*Section 3.4*)

14. **The Vienna Convention for the Protection of the Ozone Layer requires Parties, *inter alia*, to take measures to protect human health and the environment against likely adverse effects resulting from human activities that modify or are likely to modify the ozone layer. The Montreal Protocol requires Parties to phase down certain substances that deplete the ozone layer.** Activities such as aerosol injection could raise issues under these agreements, particularly if they involve a substance covered by the Montreal Protocol. The Vienna Convention

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[744] However, they have addressed carbon capture and storage, which has relevance for CO2 storage.

defines “adverse effects” as 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. (*Section 3.5*)

15. **The Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques (ENMOD) would only apply directly to geoengineering if it were used as a means of warfare.** The main substantial obligation is that listed parties “undertake not to engage in military or any other hostile use of environmental modification techniques having widespread, long-lasting or severe effects as the means of destruction, damage or injury to any other State Party”. However, the Convention could be a possible source of ideas, concepts and procedures useful for addressing geoengineering. (*Section 3.6*)

16. **The deployment of shields or mirrors in outer space to reflect or block solar radiation would fall under Space Law.** The international legal regime regulating environmental aspects of outer space includes the Outer Space treaty, four other main treaties and several resolutions of the United Nations General Assembly. The Outer Space Treaty provides that experiments that “would cause potentially harmful interference with activities of other States” are subject to prior appropriate international consultation. Activities such as aerosol injection in the stratosphere would not be regarded as falling under the purview of space Law because they would be below 80 km. (*Section 3.7*)

17. **The Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR Convention) prohibits CO_2 storage in the water column or on the seabed and has developed rules and guidance for the storage of CO_2 in geological formations under the seabed.** The amendments allowing sub-surface CO_2 storage were adopted in 2007 but have not yet entered into force. (*Section 3.9*)

18. **The Convention on Long Range Transboundary Air Pollution (LRTAP) may be relevant for geoengineering concepts such as aerosol injection, which introduce sulphur or other substances into the atmosphere.** It is a regional convention covering most States in Europe and North America. Although the LRTAP Convention requires parties to make efforts at limiting, gradually reducing and preventing air pollution including long-range transboundary air pollution”, the wording of these obligations and the definition of air pollution soften its content considerably. The same goes for the obligation on parties to develop policies and strategies for combating the discharge of air pollutants. These general obligations do not require specific legal measures to prevent air pollution or to restrict aerosol injection. Apart from this obligation, LRTAP requires the sharing of data on pollutants and stipulates procedural obligations that may apply to certain geoengineering activities. Several protocols under the LRTAP impose specific obligations to reduce sulphur emissions or transboundary fluxes, but at most only up to 2010. (*Section 3.10*)

19. The Antarctic treaty system would apply to geoengineering activities carried out in the Antarctic. (*Section 3.8*)

20. **Human rights law would be relevant if a particular geoengineering activity violates specific human rights.** Which human right could be impacted would depend on how a particular geoengineering activity would be carried out and which effects it might actually have. In addition, impacts on human rights might be justified in a particular case. Most human rights are not absolute and are subject to restrictions under certain conditions, e.g. that the restrictions are provided by law, address specific aims and are necessary to achieve a legitimate purpose. (*Section 3.11*)

21. **International institutions such as the United Nations General Assembly, United Nations Environment Programme (UNEP), World Meteorological Organization (WMO) and Intergovernmental Oceanographic Commission (IOC) of UNESCO are relevant to the governance of geoengineering**. The United Nations General Assembly has addressed ocean fertilization and could address additional issues related to geoengineering. It has also encouraged the further development of EIA processes. In 1980, UNEP developed guidelines on weather modification. The mandate of WMO covers meteorology, the atmosphere and hydrology and could, in principle, address sunlight reflection methods. It has issued non-binding guidance on weather modification. UNESCO’s IOC has assessed the potential impact of ocean fertilization. In addition, depending on the impacts and activity in question, States might argue that geoengineering activities constitute a threat to or breach of the peace or aggression under Article 39 of the Charter of the United Nations. However, the current state of knowledge concerning geoengineering

reveals a great deal of uncertainty. In any event, the Security Council has wide discretion in determining whether the requirements of Article 39 of the Charter of the United Nations are met and deciding on its response. (*Section 4.2; Section 4.4; Section 4.5; Section 4.6; Section 2.5*)

22. **Research is generally not specifically addressed under international law as distinct from the deployment of technology with known impacts or risks, apart from special rules in certain areas**. In a few cases, certain types of research might be prohibited, for instance if it would encourage nuclear weapons test explosions prohibited by the Partial Test Ban Treaty or the Comprehensive Nuclear-Test-Ban Treaty. While the CBD decision on geoengineering invites Parties and others to ensure (until certain conditions are met) that no geoengineering activities take place, it excludes from this limitation small scale scientific research studies that are conducted in a controlled setting, scientifically justified and subject to prior environmental impact assessments (decision X/33 paragraph 8(w)). UNCLOS has provisions that address marine scientific research. The LC/LP assessment framework on ocean fertilization provides guidance that is applicable to research studies. A major gap concerns sunlight reflection methods. (*Section 5.1; Section 5.2*)

Gaps in the current regulatory framework

23. **The current regulatory mechanisms that could apply to climate-related geoengineering relevant to the Convention on Biological Diversity do not constitute a framework for geoengineering as a whole that meets the criteria of being science-based, global, transparent and effective.** While the CBD decision on geoengineering provides a comprehensive non-binding normative framework, there is no legally-binding framework for geoengineering as a whole. With the possible exceptions of ocean fertilization experiments and CO_2 storage in geological formations, the existing legal and regulatory framework is currently not commensurate with the potential scale and scope of the climate related geoengineering, including transboundary effects. (*Section 6*)

24. **Some general principles of international law such as the duty to avoid transboundary harm, and the need to conduct an environmental impact assessment (EIA), together with the rules of State responsibility provide some guidance relevant to geoengineering.** However, they are an incomplete basis for international governance, because of the uncertainties of their application in the absence of decision-making institutions or specific guidance and because the scope and risks associated with geoengineering are so large-scale. As an overarching concept including several distinct concepts and technologies, geoengineering is currently not as such prohibited by international law. Specific potential impacts of specific geoengineering concepts might violate particular rules, but this cannot be determined unless there is greater confidence in estimates of such potential impacts. (*Section 6*)

25. **Some geoengineering techniques are regulated under existing treaty regimes, while others are prohibited**:

(a) **Disposal of CO_2 in the water column or on the seabed is not allowed under the LP**. It is also prohibited under OSPAR;
(b) **Ocean fertilization experiments are regulated under the LC/LP's provision on dumping and additional non-binding guidance including a risk assessment framework**; and
(c) **CO_2 storage in sub-surface geological formations is regulated under the LC/LP and the OSPAR Convention**. Further guidance has been developed under the UNFCCC based on IPCC assessments. (*Section 6.1*)

26. **Some other geoengineering techniques would be subject to general procedural obligations within existing treaty regimes, but, to date, no specific rules governing these particular techniques have been developed**:

(a) Storage of biomass in the ocean would be subject to the LC/LP and UNCLOS;
(b) Altering ocean chemistry through enhanced weathering would be subject to the LC/LP and UNCLOS;
(c) LRTAP might impose procedural obligations on the use of aerosols in the atmosphere; and
(d) Deployment of mirrors in space would be subject to space law (Outer Space Treaty). (*Section 6.1*)

27. **Most, but not all treaties, potentially provide for mechanisms, procedures or institutions that could determine whether the treaty in question applies to a specific geoengineering activity and address such activities**. In legal terms, the mandate of several major treaties or institutions is sufficiently broad to address some or all geoengineering concepts. However, this could lead to potentially overlapping or inconsistent rules or guidance. From a global perspective, the different regimes and institutions have different legal and political weight, depending, for instance, on their legal status, particular mandate or their respective levels of participation. (*Section 1.3; Section 6*)

28. **The lack of regulatory mechanisms for sunlight reflection methods is a major gap, especially given the potential for significant deleterious transboundary effects** of techniques such as stratospheric aerosols and maritime cloud albedo enhancement. In principle, existing institutions, such as the World Meteorological Organization have a mandate that could address such issues. (*Section 4.5; Section 6*)

29. **Most regulatory mechanisms discussed in the report were developed before geoengineering was a significant issue and, as such, do not currently contain explicit references to geoengineering approaches**. However, many of the treaties examined impose procedural obligations on geoengineering activities falling within their scope of application. Moreover, the international regulatory framework comprises a multitude of treaties, actual and potential customary rules and general principles of law, as well as other regulatory instruments and mechanisms that could apply to all or some geoengineering concepts. As a minimum, it is suggested that States engaged in geoengineering field activities have a duty to inform other States prior to conducting them e.g., as required in the London Convention/Protocol Ocean Fertilization Assessment Framework. Few rules provide for public participation beyond the representation of the public by delegates, except for the usual rules on observer participation in treaty regimes and institutions. The treaties examined provide few *specific* rules on responsibility and liability, but the International Law Commission's articles on State responsibility provide general rules in cases where geoengineering would be in breach of an international obligation. (*Section 1.3; Section 6*)

ANNEX 4

ADDITIONAL BIBLIOGRAPHY, 2015–2016

The ~260 papers listed here were published between mid-2015 and September 2016, too late to be taken into account in the main text for this report, prepared for the 19th Meeting of the CBD Subsidiary Body on Scientific, Technical and Technological Advice in November 2015 (UNEP/CBD/SBSTTA/19/INF/2). These additional publications are grouped by the relevant chapter section for Chapters 3, 4 and 5 of the main report. For Chapters 1 and 6, no sub-groupings are given; for Chapter 2 (Relevant international and national syntheses, assessments and reviews), no new references are given here. Papers listed for Chapter 5 are additional to those given in Annex 1. This listing does not claim to identify all relevant publications. In particular, those providing context for Chapter 1 are necessarily representative, rather than comprehensive, and it is possible that important new papers relevant to other chapters may have been missed.

These more recent papers are considered to strengthen and support the Key Messages in the main report. They also provide discussion and analysis of the Paris Agreement, adopted at the 21st Conference of the Parties of the UN Framework Convention on Climate Change in December 2015. The Paris Agreement does not specifically mention climate geoengineering; nevertheless, it is widely considered (as discussed in several of the Chapter 1 references below) that negative emissions, i.e. greenhouse gas removal, will be needed not only to limit global warming limit to 2°C or below, but also to achieve net zero greenhouse gas emissions in the latter part of the current century.

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CHAPTER 1. CONTEXT, MANDATE AND SCOPE

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CHAPTER 3. REMOVAL OF CARBON DIOXIDE OR OTHER GREENHOUSE GASES

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CHAPTER 4: SUNLIGHT REFLECTION METHODS AND OTHER PHYSICALLY-BASED TECHNIQUES

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