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Item 4.2 of the provisional agenda* - UNEP/CBD/SBSTTA/19/INF/2

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

1. In response to decision X/33, the Secretariat published, in 2012, CBD Technical Series No. 66: Geoengineering in Relation to the Convention on Biological Diversity: Technical and Regulatory Matters (http://www.cbd.int/doc/publications/cbd-ts-66-en.pdf). The study provided a scientific reference basis for the decision adopted at the eleventh meeting of the Conference of the Parties.

2. In decision XI/20, paragraph 16 (a), the Conference of the Parties requested 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 (SBSTTA), 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 Environment Management Group.

3. An interim update of information on the potential impacts of climate geoengineering on biodiversity and the regulatory framework relevant to the CBD was made available in June 2014 for the eighteenth meeting of SBSTTA (UNEP/CBD/SBSTTA/18/INF/5). The Synthesis Report of the Fifth Assessment Report of the Intergovernmental Panel on Climate Change now having been published, the update requested by the Conference of the Parties has been prepared for consideration by SBSTTA at its nineteenth meeting.

4. The present note 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, and other more recent publications. This report has been prepared by the CBD Secretariat with the assistance of the lead authors[1] of Parts I and II of CBD (2012).

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* UNEP/CBD/SBSTTA/19/1.

[1] Chapters 1-5: Phillip Williamson, acting in an independent capacity with support from the UK Natural Environment Research Council, and with assistance on BECCS-related text by Naomi Vaughan (University of East Anglia) and Clair Gough (University of Manchester). Chapter 6: Ralph Bodle, Ecologic Institute, Berlin, Germany.

UPDATE ON CLIMATE GEOENGINEERING IN RELATION TO THE CONVENTION ON BIOLOGICAL DIVERSITY

Potential Impacts and Regulatory Framework

CONTENTS

Key messages (to be developed: The key messages will build on those provided in the previous review of climate geoengineering prepared by the CBD Secretariat (Technical Series No. 66: *Geoengineering in Relation to the Convention on Biological Diversity: Technical and Regulatory Matters*, *Parts I and II*; 2012). The previous key messages relating to specific geoengineering techniques are re-presented in Chapters 3 and 4, with update comments**)**

Chapter 1. Context, mandate and scope of work

Chapter 2. Relevant international and national syntheses, assessments and reviews

Chapter 3. Potential impacts on biodiversity of climate geoengineering achieved by removal of carbon dioxide or other greenhouse gases

Chapter 1. CONTEXT, MANDATE AND SCOPE OF WORK

1.1 Climate change, climate geoengineering and the CBD

1. The simplest, most direct way of preventing human-driven climate change is not in doubt: a rapid decrease in the global emissions of greenhouse gases. 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)[1,2]. Recent progress includes the G7 statement on decarbonizing the global economy by the end of the century[3], the US Clean Power Plan to limit CO_2 emissions[4], and the call for action by a major religious leader[5]. Nevertheless, the profound societal changes required to address the causes of the problem are such that many other approaches to counter-act climate change – collectively known as climate geoengineering – have also been proposed. There is now increasing recognition that at least some of these approaches are near-certain to be necessary as additional measures (rather than alternatives) to emission reductions if future increases in global temperature are to be 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.

2. Whilst a universal definition of climate geoengineering has yet to be reached (see 1.3 below, and Annex 2), a very wide spectrum of climate geoengineering techniques have been proposed to moderate, and potentially reverse, global warming and its associated climatic, ecological and socio-economic consequences. Predominantly, these involve either greenhouse gas removal or sunlight reflection. However, most of the proposed approaches are speculative 'socio-technical imaginaries'[6,7], and none have proven efficacy in achieving desired results at the scale required. Their climatically-significant implementation therefore involves risks of unintended consequences, uncertain feasibility and opportunity costs, with many unresolved financial, governance and ethical issues. These uncertainties would seem to provide a strong rationale for further research in climate geoengineering, to inform decision-making by improving knowledge of those risks. The opposite case can also be made: that, at least for some techniques, further research may itself be either dangerous or diversionary.

3. 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 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 Group on Biological Diversity and Climate Change

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[1] UNFCCC (United Nations Framework Convention on Climate Change) (2010) *Copenhagen Accord.* http://unfccc.int/resource/docs/2009/cop15/eng/107.pdf.

[2] UNFCCC (United Nations Framework Convention on Climate Change) (2014) *Lima Call for Action.* http://unfccc.int/files/meetings/lima_dec_2014/application/pdf/auv_cop20_lima_call_for_climate_action.pdf[3] *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

[3] *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

[4] https://www.whitehouse.gov/the-press-office/2015/08/03/fact-sheet-president-obama-announce-historic-carbon-pollution-standards

[5] *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

[6] Jasanoff S (2015) Future imperfect: Science, technology and the imaginations of modernity. Chapter 1 in: *Dreamscapes of Modernity: Sociotechnical Imaginaries and the Fabrication of Power* (eds: S Jasanoff & H-Y Kim). Univ of Chicago Press 360pp

[7] Rayner S (2015) To know or not to know? A note on ignorance as a rhetorical resource in geoengineering debates. Chapter 32 in *Routledge International Handbook of Ignorance Studies* (eds: M Gross & L McGoey). Routledge, Oxford; 408 pp.

(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).

4. Negative environmental impacts can arise from some schemes that generate energy from renewable sources, and potentially also by techniques that enhance carbon sinks. Whilst 'conventional' mitigation is limited to the protection and enhancement of natural carbon sinks, the UNFCCC Convention defines 'sinks' in very broad terms[8] and a wide range of sink-enhancement processes are included in the definition of mitigation by the Intergovernmental Panel on Climate Change[9], overlapping with climate geoengineering. Under such circumstances, careful consideration must be given to maximise the benefits whilst minimising deleterious – and unintended – impacts. At the ninth meeting of the Conference of Parties (COP-9, in 2008) when the COP requested Parties to ensure that ocean fertilization activities (a proposed means of large-scale carbon dioxide removal) did not take place until a stronger scientific basis and regulatory framework had been developed (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[10] on that topic, published in 2009.

5. A second report[11] 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 further attention to the implications of climate geoengineering, 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."

6. 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 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."

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[8] ""Sink" means any process, activity or mechanism which removes a greenhouse gas, an aerosol or a precursor of a greenhouse gas from the atmosphere" Definition 8 of Article 1 of UN Framework Convention on Climate Change

[9] IPCC (2014) Annex II, Glossary (KJ Mach, S Planton & 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.

[10] CBD (Secretariat of the Convention on Biological Diversity) (2009a) *Scientific Synthesis of the Impacts of Ocean Fertilization on Marine Biodiversity*. CBD, Montreal, Technical Series No. 45, 53 pp

[11] CBD (Secretariat of the Convention on Biological Diversity) (2009b) *Connecting Biodiversity and Climate Change Mitigation and Adaptation*. Report of the Second Ad Hoc Technical Expert Group on Biodiversity and Climate Change. CBD Montreal, Technical Series No. 41, 126 pp

7. 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)[12] that was available to inform discussions at the eleventh meeting of the Conference of the Parties (COP-11).

1.2 Mandate

8. 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, whilst 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).

Box 1.1 Decision relating to climate geoengineering made at the eleventh CBD Conference of the Parties, 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], whilst 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:

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[12] CBD (Secretariat of the Convention on Biological Diversity) (2012) *Geoengineering in Relation to the Convention on Biological Diversity: Technical and Regulatory Matters.* CBD Montreal, Technical Series No. 66, 152 pp

(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 socio-economic, 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 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.

9. 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.

10. 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".

11. SBSTTA-18 accepted 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".

12. 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[13] of Parts I and II of CBD (2012).

1.3 Scope

13. 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.

14. Figure 1.1 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).

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[13] Chapters 1 -5: Phillip Williamson, acting in an independent capacity with support from the UK Natural Environment Research Council, and with assistance on BECCS-related text by Naomi Vaughan (University of East Anglia) and Clair Gough (University of Manchester). Chapter 6: Ralph Bodle, Ecologic Institute, Berlin, Germany.

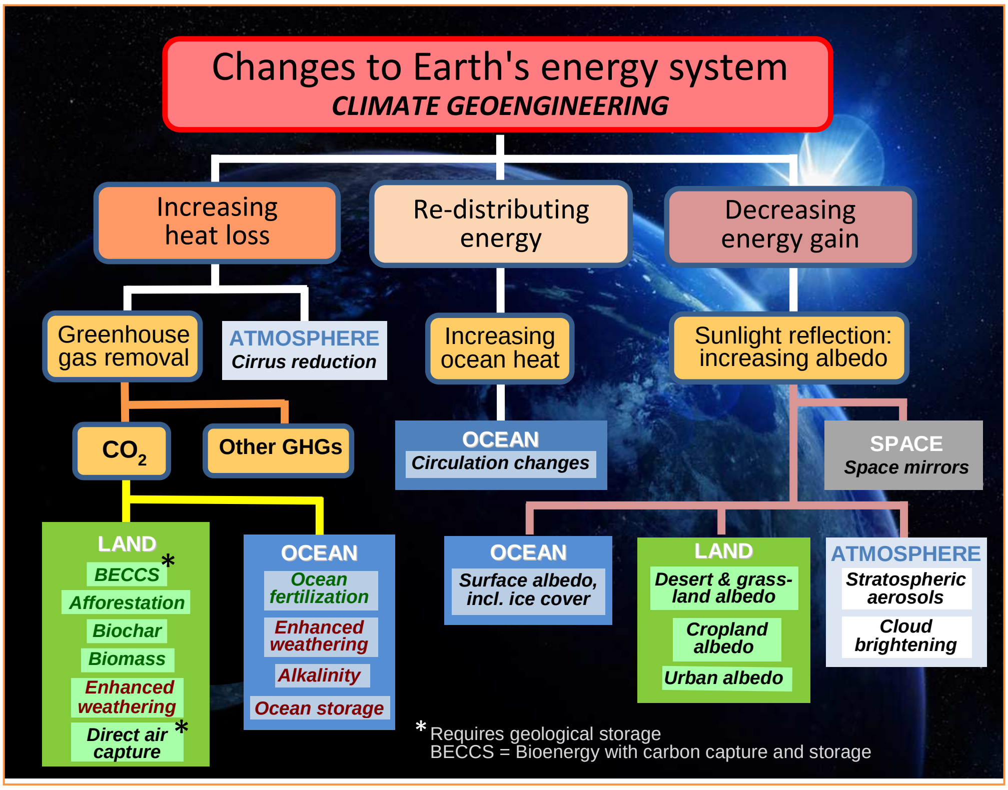

Figure 1.1 Main climate geoengineering techniques based on typology presented in CBD (2012) [Part 1, Annex II; Table1]. Greenhouse gas removal (GGR) techniques indicated by yellow/orange branching; carbon dioxide removal (CDR) by yellow branching; sunlight reflection methods (SRM) by pink branching. GHGs, greenhouse gases; BECCS, bioenergy with carbon capture and storage. Note that some land-based CDR techniques, e.g. enhanced weathering may also affect the ocean.

15. In this report, the definition of climate geoengineering developed in CBD (2012) 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". That definition, although relatively general, 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.

16. Despite the differences in definitions used for climate geoengineering, including between the options identified in decision XI/20 (Box 1.1), all geoengineering definitions exclude actions taken to directly decrease emissions of greenhouse gases from fossil fuel combustion and other anthropogenic activities (e.g. by at-source carbon capture and storage, CCS, or by changing to renewable or nuclear energy generation). Such emission reductions are unambiguously 'mitigation'. Although there is not always clarity in the literature, that is how the term will be used in this report (unless directly quoting other sources), notwithstanding that reliable, longterm CO_2 removal, particularly for bioenergy with carbon capture and storage (BECCS), shares many processes with at-source CCS.

1.4 Alternative futures for climate change

17. 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[14,15], ecosystems[16] and species' distributions[17],

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[14] Warren R, VanDerWal J, Price J, Walbergen JA *et al.* (2013) Quantifying the benefit of early climate change mitigation in avoiding biodiversity loss. *Nature Climate Change*, 3, 678-682; doi: 10.1038/nclimate1887.

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[18] – with associated societal needs for increased food and water, and other environmental goods and services.

18. Attention frequently focusses on the negative impacts of geoengineering on biodiversity, occurring as unintended and undesirable side-effects; nevertheless, impacts can also be positive. In particular, the 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 extremely 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[19,20,21,22,23, 24], particularly for SRM.

ii) Many impacts are highly scale-dependent[25,26,27], spatially and temporally – particularly for CDR, varying with the intensity of the intervention and also between short-term and longterm.

iii) The climatic benefits are crucially linked to the technical feasibility and potential effectiveness of the geoengineering technique, aspects that may extremely uncertain and difficult to quantify in advance of large-scale testing or actual implementation[28,29].

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.

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[15] Moritz C & Agudo R (2013) The future of species under climate change: resilience or decline? *Science*, 341, 504-508; doi: 10.1126/science.1237190

[16] Bopp L, Resplandy L, Orr JC, Doney SC *et al* (2013) Multiple stressors of ocean ecosystems in the 21st century: projections with CMIP5 models. *Biogeosciences*, 10, 6225-6245.

[17] Burrows MT, Schoeman DS, Richardson AJ, Molinos JG *et al.* (2014) Geographical limits to species-range shifts are suggested by climate velocity. *Nature* 507, 492-495; doi: 10.1038/nature12976

[18] OECD (Organisation for Economic Co-operation and Development) (2014) *Long Term Baseline Projections: Potential Output of Total Economy*. Economic Outlook No. 95; http://stats.oecd.org

[19] Klepper G. (2012) What are the costs and benefits of climate engineering? And can we assess them? S+F Sicherheit und Frieden. Special issue *Geoengineering: An Issue for Peace and Security?* no. 4

[20] Preston C.J. (2013) Ethics and geoengineering: reviewing the moral issues raised by solar radiation management and carbon dioxide removal. *WIREs Clim. Change*, 4, 23-37; doi: 10.1002/wcc.198

[21] Keith D (2013) *A Case for Climate Engineering*. MIT Press, Cambridge MA. 112 pp

[22] Morrow DR (2014) Why geoengineering is a public good, even if it is bad. *Clim. Change*, 123, 95-100; doi: 10.1007/s10584-013-0967-1

[23] Gardiner SM (2013) Why geoengineering is not a 'global public good', and why it is ethically misleading to frame it as one. *Climatic Change*, 121, 513-525

[24] Hamilton C (2013) No, we should not just 'at least do the research'. *Nature*, 496, 139

[25] McLaren D. (2012) A comparative global assessment of potential negative emissions technologies. *Process Safety Environ. Protection*, 90, 489-500.

[26] Jones C, Williamson P, Haywood J, Lowe J *et al* (2013) *LWEC Geoengineering Report. A forward look for UK research on climate impacts of geoengineering*. Living With Environmental Change (LWEC), UK; 36 pp. http://www.lwec.org.uk/publications/lwec-geoengineering-report-forward-look-uk-research-climate-impacts-geoengineering

[27] Hill S & Ming Y (2012) Nonlinear climate response to regional brightening of tropical marine stratocumulus. *Geophys. Res. Lett.*, 39, Article 15707

[28] MacMynowski DG, Keith D, Caldeira K & Shin HJ (2011) Can we test geoengineering? *Energy & Environmental Science* 4, 5044-5052; doi: 10.1039/C1EE01256H

[29] Seidel DJ, Feingold G, Jacobson AR & Loeb N (2014) Detection limits of albedo changes induced by climate engineering. *Nature Climate Change*, 4, 93-98; doi: 10.1038/nclimate2076

19. General aspects relevant to issues (i) - (iii) above are considered further in section 1.5 below; technique-specific aspects are discussed in Chapters 3 and 4. Here, issue (iv), the need for valid comparisons, is given further attention.

20. The main problem is that present-day conditions are only of limited value as a control or baseline. Climate change and its associated environmental impacts are already underway, interacting with other human-driven global changes[30]: 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 societal behaviour.

21. Examples of possible future climate scenarios are provided by IPCC Representative Concentration Pathways[31] (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 (or 1.5°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 is not necessarily 'safe', since it only provides a probabilistic likelihood of avoiding + 2°C; furthermore, many deleterious climate impacts occur at lower temperature increases[32, 33].

22. 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 assessment models (IAMs) are used to simulate the main socio-economic, ecological and physical processes involved (Figure 1.2). For RCP 2.6, most (~90%) IAMs assume that negative emissions (i.e. CDR) will be achievable after 2050, and the 'central' RCP 2.6 pathway is also based on that assumption (Figure 1.3). An alternative approach, based on Earth System Models, has also recently been used[34]: that also found that negative emissions (of 0.5 – 3 Gt C yr^{-1}) were necessary to keep global warming below 2˚C, even with the most optimistic emission reduction scenario.

23. Although not explicitly covered by IPCC RCPs or UNFCCC agreements, more exacting limits would reduce environmental damage[35] and longterm socio-economic costs (e.g. sea level rise after 2100). For example, by re-defining the temperature threshold distinguishing 'safe' from 'dangerous' to ~1.5°C, as tentatively proposed in the Final Report of the UNFCCC Structured Expert Dialogue[36]:

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[30] Steffen W, Richardson K, Rockström J, Cornell SE et al. (2015) Planetary boundaries: guiding human development on a changing planet. *Science* 347, no. 6223; doi: 10.1126/science,1259855

[31] Van Vuuren DP, Edmonds J, Kainuma M, Riahi K et al. (2011) The Representative Concentration Pathways: an overview. Climatic Change 109, 5-31

[32] UNFCCC (United Nations Framework Convention on Climate Change) (2015) *Report on the Structured Expert Dialogue on the 2013–2015 Review* http://unfccc.int/documentation/documents/advanced_search/items/6911.php?priref=600008454#beg (FCCC/SB/2015/INF.1).

[33] Gattuso J-P, Magnan A, Billé R, Cheung WWL et al. (2015) Contrasting futures for ocean and society from different anthropogenic CO_2 emissions scenarios. *Science* 349; doi: 10.1126/science.aac4722

[34] Gasser T, Guivarch C, Tachiiri K, Jones CD & Ciais P (2015) Negative emissions physically needed to keep global warming below 2˚C. *Nature Communications* 6, 7958; doi: 10.1038/ncomms8958

[35] Steinacher M, Joos F & Stocker TF (2013) Allowable carbon emissions lowered by multiple climate targets. *Nature* 499, 197-201; doi: 10.1038/nature12269

[36] UNFCCC (United Nations Framework Convention on Climate Change) (2015) *Report on the Structured Expert Dialogue on the 2013–2015 Review* http://unfccc.int/documentation/documents/advanced_search/items/6911.php?priref=600008454#beg (FCCC/SB/2015/INF.1).

> "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)

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 ~10ºC 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 ~0.6ºC in global mean surface temperature is considered inevitable, due to slow-acting climate responses. From Moss et al (2010)[37] and IPCC WG I AR5 report[38]

RCP	Greenhouse gas emissions	Atmospheric CO_2 concentrations by 2100	Mean and likely range for increase in global mean surface temperature by 2081- 2100, ºC		Increase in ocean acidity (pH fall)
			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

24. For CDR geoengineering, comparisons are usually based on assumptions regarding the amount of carbon dioxide that might be removed (as Gt or Pg, of either C or CO_2). Hence the climatic consequences are closely 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. For SRM geoengineering, climatic effects are more usually estimated in terms of radiative forcing (W m^{-2}); the major uncertainties are then the skill of the climate model, particularly at the regional level, affected by the validity of its assumptions.

25. There are also many model-based future climate scenarios that involve emission pathways that are intermediate between the RCPs (Figure 1.3), 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[39]), reviewed here in Chapter 2.

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[37] Moss RH, Edmonds JA, Hibbard KA, Manning MR et al. (2010). The next generation of scenarios for climate change research and assessment. *Nature* 463, 747-756; doi: 10.1038/nature088232

[38] IPCC (Intergovernmental Panel on Climate Change) (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the IPCC* (Eds: TF Stocker et al). Cambridge University Press, Cambridge UK and New York, USA.

[39] IPCC (Intergovernmental Panel on Climate Change) (2014b) *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (Eds: O Edenhofer et al.). Cambridge University Press, Cambridge UK and New York USA, 1435 pp.

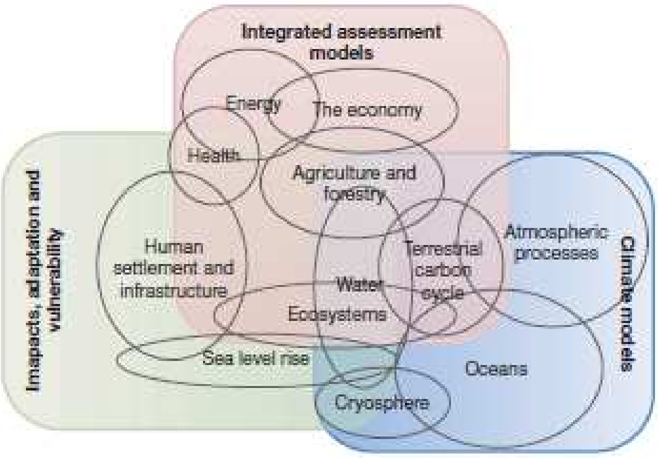

Figure 1.2 Simplified conceptual representation of the overlapping and interacting components of integrated assessment models, climate system models, and factors relating to impacts, adaptation and vulnerability. Geoengineering actions (not explicitly included) would have either direct or indirect effects on all these components. From Moss et al (2010)[40] *In the process of obtaining permission to re-use this figure.*

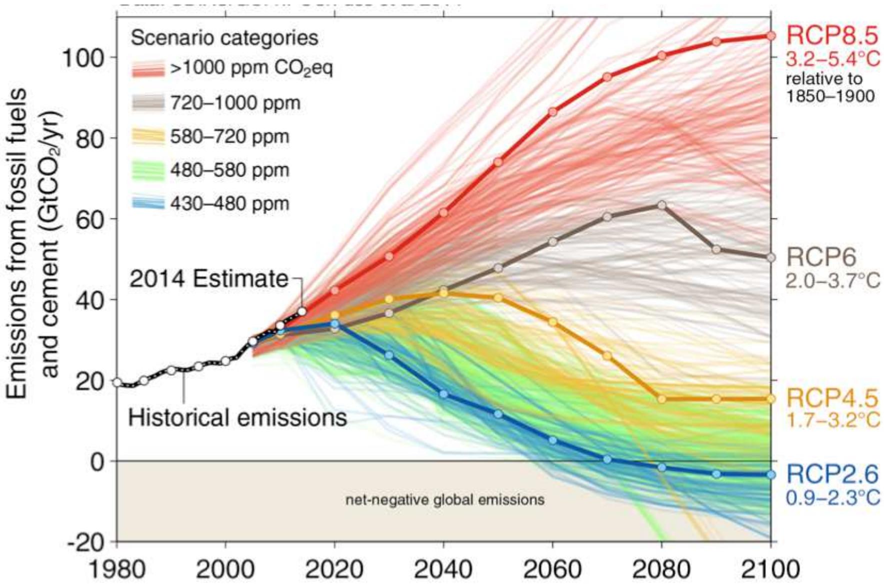

Figure 1.3. Historical (1980-2014) and projected (2005 – 2100) industrial emissions of carbon dioxide, with ~1000 scenarios for the latter shown in comparison to the four IPCC Representative Concentration Pathways. From Fuss et al (2014)[41]; data from IPCC AR5 database, Global Carbon Project and Carbon Dioxide Information Analysis Centre. I*n the process of obtaining permission to re-use this figure.*

26. 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[42], allowing 44 metrics (covering lifestyle, technology and fuels, land and food, and

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[40] Moss RH, Edmonds JA, Hibbard KA, Manning MR et al. (2010). The next generation of scenarios for climate change research and assessment. *Nature* 463, 747-756; doi: 10.1038/nature088232

[41] Fuss S, Canadell JG, Peters GP, Tavoni M et al. (2014) Betting on negative emissions. *Nature Climate Change* 4, 850-853; doi: 10.1038/nclimate2392

[42] DECC (UK Department of Energy & Climate Change) and partners (2015) *Prosperous Living for the World in 2050: Insights from the Global Calculator*. DECC, London. 18 pp. Also see www.globalcalculator.org

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 whilst 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 near-essential feature of pathways that limit emissions to 3010 Gt CO_2e by 2100, and therefore have a 50% chance of constraining global mean temperature increase to 2°C.

27. 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. Whilst noting that recent global emissions still closely follow (or exceed) the highest assumptions used in IPCC RCP 8.5, preparatory discussions and commitments under the UNFCCC[43] indicate that global energy policy is changing from 'business as usual'.

28. 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 more beneficial 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[44]; see Figure 1.4.

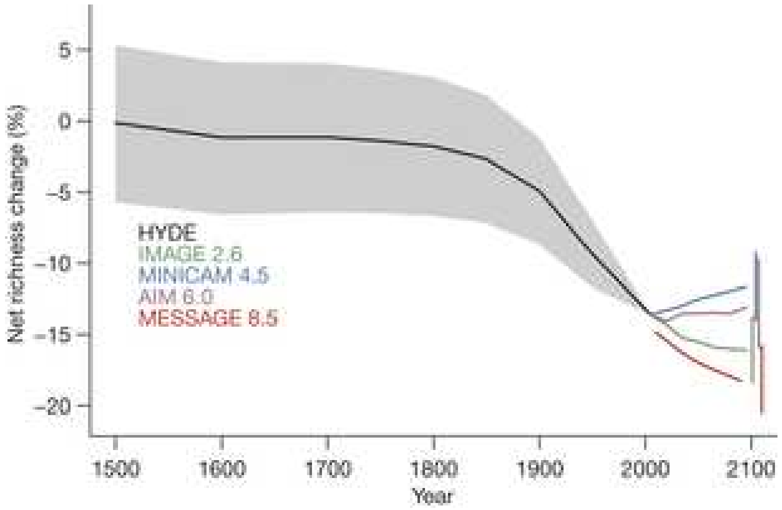

Figure 1.4. Hindcast and projected change in terrestrial local species richness 1500-2000 and 2000-2100, with the latter four pathways based on IPCC RCP 2.6, 4.5, 6.0 and 8.5. From Newbold et al (2015), see Fn. 44. *In the process of obtaining permission to re-use this figure.*

1.5 Evaluating geoengineering techniques in CBD context

29. 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'. Whilst from the CBD perspective, impacts (positive or negative) on biodiversity, ecosystems and indigenous communities are of greatest concern and

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[43] UNFCCC Subsidiary Body for Scientific and Technological Advice (SBSTA) (2015) *Scientific, technical and socioeconomic aspects of mitigation of climate change. Draft conclusions proposed by the Chair.* FCCC/SBSTA/2015/L.12, online at http://unfccc.int/documentation/documents/advanced_search/items/6911.php?priref=600008513#beg

[44] Newbold T, Hudson LN, Hill SLL, Contu S et al. (2015) Global effects of land use on local terrestrial biodiversity. *Nature*, 520, 45-50.

interest, a very wide range of other factors are also involved in deciding whether serious policy attention ought to be given to either GGR/CDR and SRM approaches.

30. In the 2009 Royal Society report on geoengineering[45], 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[46] of visual representations of such evaluations, and a recent, more comprehensive treatment of appraisal criteria[47] 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, cost/affordability can be crucial, and when negative emission techniques (e.g. BECCS) are simulated in integrated assessment models, direct economic factors are also included, with future discounting. However, much less attention has been given to assessing non-monetized environmental costs.

Table 1.2 Main factors and additional issues that might be used to evaluate scientific and societal suitability of climate geoengineering techniques, based on Royal Society (2009) and Kruger (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 and applied?*	• Technological readiness; time required for research and development • Time required for full scale-up and/or for climatic benefits to be unambiguously demonstrated • 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, others highly uncertain • Temporal controllability: 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/minimise 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

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[45] Royal Society (2009) *Geoengineering the Climate: Science, Governance and Uncertainty*. RS Policy document 10/09. The Royal Society, London

[46] Kruger T (2015) *Dimensions of Geoengineering – an Analysis of the Royal Society's 'Blob' Diagram*. Climate Geoengineering Governance (CGG) Working Paper 26.

[47] Bellamy R (2015) A sociotechnical framework for governing climate engineering. *Science, Technology & Human Values* (online) doi: 10.1177/0162243915591855

Governance and ethics: *who decides?*	• Legality and agreement at international and national levels • Risk of conflict arising from uncoordinated actions • Social licence to operate; acceptability by 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 unintended effects • 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

31. 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[48,49,50], also relevant text from the Synthesis report[51]. The report of the IPCC Expert Meeting on Geoengineering[52] was available to CBD (2012); many aspects were also included in the AR5 WG reports.

32. 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).

33. 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 1.4), 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 synthesise relevant climate change research since the cut-off dates (March - October 2013) for literature included in the AR5 reports. As follows:

- The report on the Structured Expert Dialogue process under the UNFCCC, post AR5[53]
- A post-AR5 literature review on observed and predicted impacts of climate change on ocean processes[54]
- A review of recent research on climate instabilities[55]
- A review of recent research on climate impacts[56].

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[48] IPCC (Intergovernmental Panel on Climate Change) (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the fifth Assessment Report of the Intergovernmental Panel on Climate Change* (Eds: TF Stocker et al.). Cambridge University Press, Cambridge UK and New York USA, 1535 pp.

[49] IPCC (Intergovernmental Panel on Climate Change) (2014a) *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (Eds: CB Field et al.). Cambridge University Press, Cambridge UK and New York USA, 1132 pp.

[50] IPCC (Intergovernmental Panel on Climate Change) (2014b) *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (Eds: O Edenhofer et al.). Cambridge University Press, Cambridge UK and New York USA, 1435 pp.

[51] IPCC (Intergovernmental Panel on Climate Change) (2014c) *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* (Eds: Core Writing Team, RK Pachauri & LA Meyer). IPCC Geneva,168 pp.

[52] 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.

[53] UNFCCC (United Nations Framework Convention on Climate Change) (2015) *Report on the Structured Expert Dialogue on the 2013–2015 Review* http://unfccc.int/documentation/documents/advanced_search/items/6911.php?priref=600008454#beg (FCCC/SB/2015/INF.1).

[54] Howes EL, Joos F, Eakin CM & Gattuso J-P (2015) An updated synthesis of the observed and projected impacts of climate change on the chemical, physical and biological processes in the oceans. *Frontiers in Marine Science* 2, Article 36 (27 pp); doi: 10.3389/fmars.2015.00036

[55] Good P, Lowe J, Ridley J, Bamber J et al. (2014) *Post-AR5 An Updated view of Tipping Points and the Relevance for Long-term Climate Goals.* AVOID2 programme on avoiding dangerous climate change. AVOID2 WPA Report 1; DECC, London. 61 pp. http://www.avoid.uk.net/downloads/avoid2/AVOID2_WPA5_v2_final.pdf

34. There have also been four relevant CBD publications:

- Global Biodiversity Outlook 4, an overview of biodiversity status and pressures[57]
- CBD Technical Series No. 78, on progress towards the Aichi Biodiversity Targets[58]
- CBD Technical Series No. 75, on the impacts of ocean acidification on marine biodiversity[59]
- CBD Technical Series No. 65, on biofuels and biodiversity[60]

2.2 Fifth Assessment Report of the Intergovernmental Panel on Climate Change

2.2.1 Overview of geoengineering in IPCC AR5

35. 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. Whilst 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. An overall conclusion from the AR5 reports is that deployment of GGR/CDR (hereafter CDR unless other greenhouse gases are also under consideration) is now regarded as a near-essential component of mitigation, in addition to direct emission reductions, in order to keep within limits agreed under the UNFCCC for climate change, exemplified by RCP 2.6. Bioenergy with carbon capture and storage (BECCS) is identified as the main approach to achieve that objective.

36. The WG III Report and Synthesis Report both recognise that there are major uncertainties relating to the large-scale use of BECCS, and that it is likely to have serious implications for land use and biodiversity. However, these issues were not assessed in any detail. For example, there did not seem to be any quantitative information presented on model assumptions of 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.

37. 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 substantive attention in previous IPCC assessments.

2.2.2 Working Group I: Physical Science

38. The **Summary for Policymakers** in the IPCC WG I Report[61] 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):

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[56] Warren R, Arnell N, Brown S, Kjellstrom T et al. (2014) *Post-IPCC Assessment of Climate Impacts using Existing Scenarios – Advances in Understanding*. AVOID2 programme on avoiding dangerous climate change; AVOID2 WP3.1a Report 1; DECC, London, 36 pp. http://www.avoid.uk.net/downloads/avoid2/AVOID2_WP_B.1a_report_v1_fina.pdf

[57] CBD (Secretariat of the Convention on Biological Diversity) (2014) *Global Biodiversity Outlook 4*. CBD Montreal, 155 pp; https://www.cbd.int/gbo/gbo4/publication/gbo4-en.pdf

[58] CBD (Secretariat of the Convention on Biological Diversity) (2014a) *Progress towards the Aichi Biodiversity Targets: An Assessment of Biodiversity Trends, Policy Scenarios and Key Actions.* (Eds: PW Leadley, CB Krug, R Alkemade, HM Pereira et al.). CBD Montreal, Technical Series No. 78, 500 pp.

[59] CBD (Secretariat of the Convention on Biological Diversity) (2014b) *An Updated Synthesis of the Impacts of Ocean Acidification on Marine Biodiversity* (Eds: S Hennige, JM Roberts & P Williamson). CBD Montreal, Technical Series No. 75, 99pp

[60] CBD (Secretariat of the Convention on Biological Diversity) (2012) *Biofuels and Biodiversity* (Eds. A Webb & D Coates)., CBD Montreal, Technical Series No. 65, 69 pp

> "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."

39. 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."

40. 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.

41. 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.

42. **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[62,63]. 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[64].

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[61] IPCC (Intergovernmental Panel on Climate Change) (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the fifth Assessment Report of the Intergovernmental Panel on Climate Change* (Eds: TF Stocker et al.). Cambridge University Press, Cambridge UK and New York USA, 1535 pp

[62] Kirschbaum MUF (2003) Can trees buy time? An assessment of the role of vegetation sinks as part of the global carbon cycle. *Climate Change* 58, 47-71

[63] Herzog`H, Calfeira K & Reilly J (2003) An issue of permanence: Assessing the effectiveness of temporary carbon storage. *Climate Change* 59, 293-310

Table 2.1 Uncertainty treatment from text and tables in IPCC AR5 (WG I)[65]. '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	0-33% probability
Low	Medium agreement, limited evidence, *or* low agreement, medium evidence	Very unlikely	0-10% probability
Very low	Low agreement, limited evidence	Exceptionally unlikely	0-1% probability

- 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 stabilise 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"[66,67] [*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. Whilst 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*].
- 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*].

43. Technique-specific aspects of CDR methods are also discussed in WG I Chapter 6, and estimates of the maximum (idealised) potential for CO_2 removal are summarised 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".

44. **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

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[64] Dornburg V & Marland G (2008) Temprary storage of carbon in the biosphere does have value for climate change mitigation: A response to the paper by Miko Kirschbaum. *Mitig. Adapt. Strat. Global Change* 13, 211-217

[65] IPCC (Intergovernmental Panel on Climate Change) (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Eds: TF Stocker et al]. Cambridge University Press, Cambridge UK and New York USA, 1535 pp

[66] Wu PL, Wood R, Ridley J & Lowe J (2010) Temporary acceleration of the hydrological cycle in response to a CO_2 rampdown. *Geophysical Research. Letters* 37, L12705

[67] Cao L, Bala G, & Caldeira K (2011) Why is there a short-term increase in global precipitation in response to diminished CO2 forcing? *Geophysical Research. Letters* 38, L06703

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[68], 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, whilst 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.

2.2.3 Working Group II: Impacts, Adaptation and Vulnerability

45. There is no mention of geoengineering in the Summary for Policymakers of the IPCC WG II Report[69]. 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".

46. **Chapter 6** of the WG II Report, Ocean Systems, considers the impacts and effective 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:

- 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).*

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[68] English JT, Toon OB & Mills MJ (2012) Microphysical simulations of sulphur burdens from stratospheric sulphur geoengineering. *Atmospheric Physics & Chemistry* 12, 4775-4793

[69] IPCC (Intergovernmental Panel on Climate Change) (2014a) *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Eds: CB Field et al] Cambridge University Press, Cambridge UK and New York USA, 1132 pp

47. **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[70]. In addition, without global agreements on how and how much geoengineering to use, SRM presents a risk for international conflict[71]. Because the direct costs of stratospheric SRM have been estimated to be in the tens of billions of U.S. dollars per year[72,73], it could be undertaken by non-state actors or by small states acting on their own[74], potentially contributing to global or regional conflict[75,76]. 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

48. The **Summary for Policymakers** of the IPCC WG III Report[77] 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_2eq 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 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

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[70] Lin A (2013) Does geoengineering present a moral hazard? *Ecology Law Quarterly* 40, 673-712.

[71] BrzoskaM, Link PM, Maas A &. Scheffran J (2012) Editorial. Geoengineering: an issue for peace and security studies? *Sicherheit & Frieden / Security & Peace*,30 (4 SI), IV.

[72] Robock A, Marquardt A, Kravitz B & Stenchikov G (2009) Benefits, risks, and costs of stratospheric geoengineering. *Geophysical Research Letters*, 36, L19703, doi:10.1029/2009GL039209.

[73] McClellan J, Keith DW & Apt J (2012) Cost analysis of stratospheric albedo modification delivery systems. *Environmental Research Letters,* 7, 034019, doi:10.1088/1748-9326/7/3/034019.

[74] Lloyd ID & Oppenheimer M (2014) On the design of an international governance framework for geoengineering. *Global Environmental Politics,* 14, 45-63.

[75] Robock A (2008a) Whither geoengineering? *Science*, 320, 1166-1167.

[76] Robock A (2008b) 20 reasons why geoengineering may be a bad idea. *Bulletin of the Atomic Scientists*, 64, 14-18.

[77] IPCC (Intergovernmental Panel on Climate Change) (2014b) *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (Eds: O Edenhofer et al.). Cambridge University Press, Cambridge UK and New York USA, 1435 pp.

> 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."

49. 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 ofpractices 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, Miscanthus, 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*)."

50. 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 CO2 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.”

51. 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.”

52. **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[78] 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[79] (CBD, 2010). Of critical importance in this regard are favourable institutional and policy mechanisms for reforestation / afforestation and bioenergy that complement mitigation actions.”

53. 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). Whilst 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[80,81,82], with initial cost estimates also varying greatly, from 60 - 250 USD / tCO_2[83]. Important limiting factors for BECCS include land availability, a sustainable supply of biomass, and storage capacity[84].

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[78] PBL (Netherlands Environmental Assessment Agency) (2012). *Roads from Rio+20. Pathways to Achieve Global Sustainability Goals by 2050*. PBL,The Hague. 286 pp.

[79] CBD (Convention on Biological Diversity (2010). COP 10 Decision X/2: Strategic Plan for Biodiversity 2011- 2020.

[80] Koornneef J et al. (2012). Global potential for biomass and carbon dioxide capture, transport and storage up to 2050. *International Journal of Greenhouse Gas Control* 11, 117 – 132. doi: 10.1016/j.ijggc.2012.07.027

- 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[85,86,87]. 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.
- Pathways that assume future large-scale availability of CDR shift the mitigation burden in time, and could therefore exacerbate inter-generational impacts.

54. WG III **Chapter 11** covers Agriculture, Forestry and Other Land Use (AFOLU). The mitigation potential of biochar is summarised 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.”

55. 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%

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[81] McLaren D (2012). A comparative global assessment of potential negative emissions technologies. *Process Safety & Environmental Protection* 90,489-500. doi: 10.1016/j.psep.2012.10.005

[82] Van Vuuren DP, Deetman S, van Vliet J, van den Berg M et al (2013). The role of negative CO_2 emissions for reaching 2°C - insights from integrated assessment modelling. *Climatic Change* 118, 15 – 27. doi:10.1007/s10584-012-0680-5

[83] McGlashan N, Shah N, Caldecott B & Workman M (2012). High-level techno-economic assessment of negative emissions technologies. *Process Safety & Environmental Protection* 90, 501-510. doi: 10.1016/j.psep.2012.10.004

[84] Gough C & Upham P (2011) Biomass energy with carbon capture and storage (BECCS or Bio-CCS). *Greenhouse Gases: Science and Technology* 1, 324-334.doi: 10.1002/ghg.34

[85] Pielke Jr RA (2009). An idealized assessment of the economics of air capture of carbon dioxide in mitigation policy. *Environmental Science & Policy* 12, 216 – 225.

[86] Nemet GF & Brandt A R (2012). Willingness to pay for a climate backstop: Liquid fuel producers and direct CO_2 air capture. *The Energy Journal* 33, 59-81.

[87] Chen C & Tavoni M (2013). Direct air capture of CO_2 and climate stabilization: A model based assessment. *Climatic Change* 118, 59-72. doi: 10.1007/s10584-013-0714-7

> on average across models) than the potential price effects induced by climate impacts on crop yields (+25% on average across models[88]. 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[89]. 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[90]."

2.2.5 Synthesis Report

56. The **Summary for Policymakers** of the AR5 Synthesis Report[91] 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 near-essential to meet agreed upper limits for climate change, either in terms of atmospheric CO_2 or global mean temperature rise.

57. 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 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]

58. 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 CO2 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].

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

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[88] Lotze-Campen H, von Lamp M, Kyle P, Fujimori S et al. (2013) Impacts of increased bioenergy demand on global food markets: an AgMIP economic model intercomparison. *Agricultural Economics*, doi: 10.1111 / agec.12092

[89] Groom M, Gray E & Townsend P (2008) Biofuels and Biodiversity: Principles for creating better policies for biofuel production. *Conservation Biology* 22, 602 – 609. doi: 10.1111/j.1523-1739.2007.00879.x

[90] Nijsen M, Smeets E, Stehfest E & Vuuren DP (2012) An evaluation of the global potential of bioenergy production on degraded lands. *GCB Bioenergy* 4,130 – 147. doi: 10.1111/j.1757-1707.2011.01121.x

[91] IPCC (Intergovernmental Panel on Climate Change) (2014c) *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,168 pp.

> "In the majority of low-concentration stabilization scenarios (about 450 to about 500 ppm CO2-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."

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

61. 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.

62. 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

63. Two closely-linked US reports on climate geoengineering were published[92,93] in early 2015, with a complex authorship involving the Committee on Geoengineering Climate: Technical Evaluation and

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[92] National Academy of Sciences (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

Discussion of Impacts; Board on Atmospheric Sciences and Climate; Ocean Studies Board; Division on Earth and Life Studies; and 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.

64. 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).

65. 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.

Table 2.1. Overview of differences between carbon dioxide removal (CDR) and albedo modification proposals, as included in both NAS/NRC reports[94,95]. 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

66. Whilst 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*

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[93] National Academy of Sciences (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

[94] National Academy of Sciences (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

[95] National Academy of Sciences (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

on mitigating 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

67. 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[96] 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, 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 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.

68. 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 this 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)]

69. 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)

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[96] 'relatively little' relates to the scale of the natural uptake and release processes. Under stable climatic conditions, CO_2 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.

- Governance challenges for deployment at scale
- Risk of detrimental deployment from unilateral and uncoordinated actors.

70. 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 is considered essential to achieve climatic stability within 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)[97]."

71. 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.*

2.3.2 NAS/NRC report on Reflecting Sunlight to Cool Earth

72. 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.*

73. 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)[98]]
- 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.

74. 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.

75. 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).

76. 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

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[97] NRC (National Research Council) (2011) *Climate Stabilization Targets: Emissions, Concentrations, and Impacts over Decades to Milennia*. National Academies Press, Washington DC.

[98] Sillman J, Lenton TM, Levermann A, Ott K et al. (2015) Climate emergencies do not justify engineering the climate. *Nature Climate Change* 5, 290-292.

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.

77. Three concluding recommendations are made:

NAS/NRC recommendation 4: *The Committee recommends an albedo modification research program 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 in Box 5.1.

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 (b0 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.*

78. 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). Whilst 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 overviews and reports

2.4.1 UNEP Emissions Gap Report 2014

79. The 5th report in the “emissions gap” series was published[99] 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)

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[99] UNEP (United Nations Environment Programme) (2014) *The Emissions Gap Report 2014*. UNEP, Nairobi. 57 pp. http://www.unep.org/emissionsgapreport2014 ,

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[100,101] 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.

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

80. 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.

81. The EuTRACE final report[102], 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".

82. 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.

83. 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 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.

84. 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

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[100] Riahi K, Dentener F, Gielen D, Grubler A et al. (2012) Energy pathways for sustainable development. Chapter 17 in *Global Energy Assessment – Towards a Sustainable Future*. Cambridge University Press, Cambridge UK and New York, USA; International Institute for Applied Systems Analysis, Laxenburg, Austria; p 1203-1306

[101] Edmonds J, Luckow P, Calvin K Wise M et al. (2013) Can radiative forcing be limited to 2.6 Wm^{-2} without negative emissions from bioenergy AND CO_2 capture and storage? *Climatic Change* 118, 678; doi: 10.1007/s10584-012-0678-z

[102] Schäfer S, Lawrence M, Stelzer H, Born W et al.(2015) *The European Transdisciplinary Assessment of Climate Engineering (EuTRACE): Removing Greenhouse Gases from the Atmosphere and Reflecting Sunlight away from Earth*. 169 pp; http://www.iass-potsdam.de/de/publikationen/projektberichte

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.

85. 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

86. 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[103] 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. Whilst the focus of the report was on natural science linkages between geoengineering and climate change, the fundamental importance of interdisciplinarity and socio-economic considerations was emphasized.

87. 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

88. Three recent analyses[104,105,106] provide information on the development of geoengineering research from a bibliometric perspective. A common feature is the near-exponential increase in scientific publications in the topic (using a wide range of search terms to cover different nomenclatures) since ~2000; see Figure 2.1.

89. Ref[107] identified a total of 825 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. One of the stated aims of this analysis was to 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". Additional attention to framing issues is given in Chapter 5.

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[103] Jones C, Williamson P, Haywood J, Lowe J *et al* (2013) *LWEC Geoengineering Report. A forward look for UK research on climate impacts of geoengineering*. Living With Environmental Change (LWEC), UK; 36 pp. http://www.lwec.org.uk/publications/lwec-geoengineering-report-forward-look-uk-research-climate-impacts-geoengineering

[104] Belter CW & Seidel DJ (2013) A bibliometric analysis of climate engineering research. *Wiley Interdisciplinary Reviews: Climate Change* 4, 417-427; doi: 10.1002/wcc.229

[105] Oldham P, Szerszynski B, Stilgoe J, Brown C, Eacott B & Yuille A (2014) Mapping the landscape of climate engineering. *Philosophical Transactions of the Royal Society A*, 372, article 20140065; doi: 10.1098/rsta.2014.0065.

[106] Linnér B-O & Wibeck V (2015) Dual high stake emerging technologies: a review of climate engineering research literature. *WIREs Climate Change* 2015; doi: 10.1002/wcc.333

[107] Oldham P, Szerszynski B, Stilgoe J, Brown C, Eacott B & Yuille A (2014) Mapping the landscape of climate engineering. *Philosophical Transactions of the Royal Society A*, 372, article 20140065; doi: 10.1098/rsta.2014.0065.

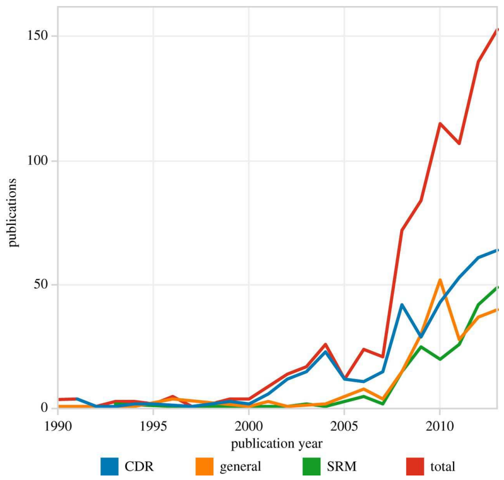

Figure 2.1. The growth of publications in carbon dioxide removal (CDR), sunlight reflection methods (SRM), general climate geoengineering and their total, 1990-2013. From Oldham et al (2014). I*n the process of obtaining permission to re-use this figure.*

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

90. This chapter focuses on recent advances in knowledge and understanding of techniques to remove carbon dioxide, and potentially other greenhouse gases, from the atmosphere. Attention is directed at new literature and aspects not previously considered by Technical Series No. 66 (CBD, 2012)[108], noting that there have been high-profile calls to prioritise CDR research[109,110]. 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.

91. Two journals, Process Safety and Environmental Protection, and Climatic Change, published special issues on negative emission technologies in 2012 and 2013 respectively; these included a total of 16 papers, several of which are cited here. Similar to CBD (2012),the introductory paper[111] in the Climatic Change special issue emphasised 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.

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)

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[108] CBD (Secretariat of the Convention on Biological Diversity) (2012) *Geoengineering in Relation to the Convention on Biological Diversity: Technical and Regulatory Matters.* CBD Montreal, Technical Series No. 66, 152 pp. https://www.cbd.int/doc/publications/cbd-ts-66-en.pdf

[109] National Academy of Sciences (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

[110] Lomax G, Lenton TM, Adeosun A & Workman M (2015) Investing in negative emissions. *Nature Climate Change* 5, 498-500

[111] Tavoni M & Socolow R (2013) Modeling meets science and technology: an introduction to a special issue on negative emissions, *Clim. Change*, 118, 1-14; doi: 10.1007/s10584-013-0757-9

92. The removal-storage paradigm can, however, be considered over-simplistic, since there is increasing attention being given to possibilities for industrial use of captured CO_2, as a feedstock for other products. Whilst fully worthy of scientific investigation, such processes are not given further attention here, nor geological storage, since they are essentially “CCS issues”.

93. As previously noted**,** the IPCC WG I report identified the importance of carbon cycle dynamics when assessing the effectiveness of negative emission approaches. Thus CO_2 removal from the atmosphere is partly offset by outgassing from natural sources[112,113], and the quantity to be removed to correct for the ‘overshoot’ in most RCP 2.6 scenarios (or, more ambitiously, to return to pre-industrial levels[114]), is closely similar to the amount that was anthropogenically added since the specific target level of atmospheric CO_2 was previously experienced. However, there is a range of time delays in the responses of different climate processes to changes in radiative forcing, and for re-adjustments to other Earth system components (e.g. sea ice[115,] sea level[116] and ocean pH). 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[117]. As an example, mean global temperatures and rainfall, and their regional variability, under (say) 450 ppm CO_2 will depend on whether ~ 20 years earlier it was also 450 ppm, or 440 ppm, or 460 ppm (assuming that a reduction from 460 ppm to 440 ppm can be achieved by CDR).

94. For the above reasons, the climatic and environmental consequences of the RCP 2.6 overshoot in the relatively near-term cannot be directly cancelled by future negative emissions. On that basis, the evaluation of the potential role of CDR techniques should primarily focus on their effectiveness in helping to achieve rapid decrease, to zero, of emissions, rather than future remediation. This conclusion applies to all CDR techniques: the net effect of adding 1 Gt $CO_2$and then subtracting 1 Gt CO_2 does not equal zero when there is a significant time difference between the addition and subtraction processes.

95. 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 alkalinisation; direct air capture; and removal of greenhouse gases other than CO_2. .

96. 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; the comments relate to aspects of confirmed importance and main subsequent developments.

Table 3.2. Main conclusions from CBD (2012) relating to greenhouse gas removal (primarily CDR)

	Key message (text originally in bold; re-numbered)	**Comments**
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 unintended impacts).
2.	Individual CDR techniques may have significant unintended impacts on terrestrial, and/or ocean ecosystems, depending on the nature, scale	A range of biological, chemical and geophysical processes are involved, linked

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[112] Boucher O, Halloran P, Burke E, Doutriaux-Boucher M *et al.* (2012) Reversibility in an Earth System model in response to CO_2 concentration changes. *Environ. Res. Lett*. 7, 024013 (9pp). doi: 10.1088/1748-9326/7/2/024013

[113] Vichi M, Navarra A & Fogli PG (2013) Adjustment of the natural ocean carbon cycle to negative emission rates. *Clim. Change*, 118, 105-118; doi: 10.1007/s10584-012-0677

[114] MacDougall A. H. (2013) Reversing climate warming by artificial atmospheric carbon–dioxide removal: Can a Holocene-like climate be restored? *Geophys. Res. Lett.*, 40, 5480-5485

[115] Ridley JK, Lowe JA & Hewitt HT (2012) Hiow reversible is sea-ice loss? *Cryosphere* 6, 193-198

[116] Bouttes N, Gregory JM & Lowe JA (2013) The reversibility of sea level rise. *J. Clim*. 26, 2502-2513

[117] Wu P, Ridley J, Pardaens A, Levine R & Lowe J (2015) The reversibility of CO_2 induced climate change. *Climate Dynamics* 45, 745-754

and location of carbon capture and storage.	in many different ways.
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.	Additional (unregulated) field experiment 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.	New studies in this topic area, mostly on olivine.
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.	The inclusion of afforestation/ reforestation within geoengineering remains controversial. Its effectiveness for that purpose is, however, low.
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.	No known new research in this topic area.
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.	Some technical innovations, with cost reductions.
10. Ocean CO_2 storage will necessarily alter the local chemical environment, with a high likelihood of biological effects	No known new research in this topic area.
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.	Leakage impacts have been experimentally studied in shallow-water.

3.2 Bioenergy with carbon capture and storage (BECCS)[118]

3.2.1 The role of BECCS in climate policy

97. There is an extensive literature on the opportunities and risks of greatly expanding the use of terrestrial biomass as an energy source. Such bioenergy provides a direct alternative to fossil fuels and offers a mechanism for net carbon removal when linked to CCS. Bioenergy with carbon capture and storage (BECCS) meets both these needs, and is economically an attractive policy option[119,120] to contribute to addressing the problem of climate change. BECCS is therefore widely included in integrated assessment models (IAMs) that are specifically structured to deliver cost-minimizing scenarios.

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[118] This section acknowledges the contributions of Naomi Vaughan (UEA) and Clair Gough (Univ of Manchester) through pre-publication access to Gough C & Vaughan N (2015) *Synthesising Existing Knowledge on the Feasibility of BECCS*. AVOID 2 report, ref WPD1a (contract 1104872). Department of Energy & Climate Change (DECC), London; www.avoid.uk.net/publications

[119] van Vuuren DP, Deetman S, van Vliet J, van der Berg M *et al*. (2013) The role of negative CO_2 emissions for reaching 2°C – insights from integrated assessment modelling. *Climatic Change* 118, 15-27; doi: 10.1007/s10584-012-0680-5

[120] IPCC (Intergovernmental Panel on Climate Change) (2014b) *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (Eds: O Edenhofer et al.). Cambridge University Press, Cambridge UK and New York USA, 1435 pp.

98. The feasibility of large-scale BECCS deployment is, however, uncertain. Whilst a recent major review has expressed confidence that bioenergy can greatly increase its contribution to global energy needs [121], other analyses and reviews have been more cautious[122,123,124], giving greater emphasis to ecological[125,126,127] and societal[128,129] considerations and constraints. That range of perspectives is exemplified by the lack of consensus on the scale of bioenergy yields that might be sustainably achieved, 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[130], 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.

99. 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 other multi-technique reviews[131,132,133,134]. Nevertheless, nearly 90% (101 out of 116) of scenarios or similar 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[135]. To meet the less stringent requirements of RCP 4.5 and RCP 6.0, around 36% of model scenarios (235 of 653) 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 2.1).

100. That rate of development would be challenging, requiring considerable scaling-up[136,137]. At present, less than 10% of total primary energy from biomass is suitable for use in a BECCS system: that

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[121] Souza GM, Victoria R, Joly C & Verdade L (eds) (2015) *Bioenergy & Sustainability: Bridging the Gaps*. Scientific Committee on Problems in the Environment (SCOPE) Report 72, 779 pp.

[122] Creutzig F, Ravindranath NH, Berndes G, Bolwig S et al. (2014) Bioenergy and climate change mitigation: an assessment. *Global Change Biology Bioenergy* (online) doi: 10.111/gcbb.12205

[123] Searchinger T & Heinlich (2015) *Avoiding Bioenergy Competition for Food Crops and Land*. Working Paper 9 of *Creating a Sustainable Food Future*. World Resources Institute, Washington DC, 44pp. www.worldresourcesreport.org

[124] CBD (Secretariat of the Convention on Biological Diversity) (2012) *Biofuels and Biodiversity* (Eds. A Webb & D Coates)., CBD Montreal, Technical Series No. 65, 69 pp

[125] Smith LJ & Torn MS (2013) Ecological limits to terrestrial biological carbon dioxide removal. *Climatic Change* 118, 89-103

[126] Immerzeel DJ, Verweij PA, van der Hilst F & Faaji ACP (2014) Biodiversity impacts of bioenergy crop production: a state of the art review. *Global Change Biology Bioenergy* 6, 183-209,

[127] Creutzig F (2014) Economic and ecological views on climate change mitigation with bioenergy and negative emissions. *Global Change Biology Bioenergy* (online) doi: 10.111/gcbb.12235

[128] Powell TWR & Lenton TM (2012) Future carbon dioxide removal via biomass energy constrained by agricultural efficiency and dietary trends. *Energy & Environmental Science* 5, 8116

[129] Hunsberger C, Bolwig S, Corbera & Creutzig F (2014) Livelihood impacts of biofuel crop production: Implications for governance. *Geoforum* 54, 248-260.

[130] Slade R, Bauen A & Gross R (2014) Global energy resources. *Nature Climate Change* 4, 99-105.

[131] Keller DP, Feng EY & Oschlies A (2014) Potential climate engineering effectiveness and side effects during a high carbon dioxide-emission scenario. Nature Communications 5, 3304; doi: 10.1038/ncomms4304

[132] McGlashan N, Shah N, Caldecott B & Workman M (2012) High level techno-economic assessment of negative emissions technologies. *Process Safety & Environmental Protection* 90, 501-510

[133] McGlashan NR, Workman MHW, Caldecott B & Shah N (2012) *Negative Emissions Technologies*. Grantham Institute for Climate Change Briefing Paper No 8, 27 pp

[134] Lomax G, Lenton TM, Adeosun A & Workman M (2015) Investing in negative emissions. *Nature Climate Change* 5, 498-500

[135] Fuss S, Canadell JG, Peters GP, Tavoni M *et al*. (2014) Betting on negative emissions. *Nature Climate Change* 4, 850-853; doi: 10.1038/nclimate2392

[136] Herzog HJ (2011) Scaling up carbon dioxide capture and storage: from megatons to gigatons. *Energy Economics* 33, 597-604

would need to be increased around forty-fold by 2050 to reach the value of ~200 EJ yr^{-1} commonly assumed in RCP 2.6 scenarios[138]. Furthermore, 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 Gt per year.

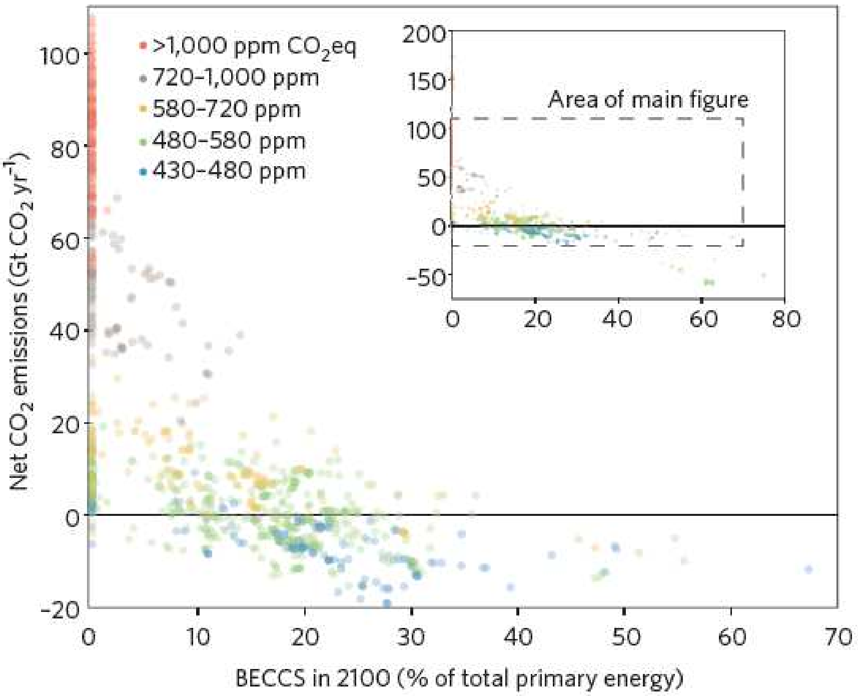

Figure 2.1. The importance of BECCS in limiting net CO_2 emissions and atmospheric CO_2eq concentrations in climate change scenarios. From Fuss et al. (2014); data from IPCC AR5 database, Global Carbon Project and Carbon Dioxide Information Analysis Centre. *In the process of obtaining permission to re-use this figure.*

3.2.2 Impacts, assumptions and uncertainties relating to BECCS

101. Integrated assessment models (IAMs) make many assumptions regarding BECCS and the wider impacts of its large-scale deployment. Whilst some assumptions may be explicit and well-founded, others are implicit and/or highly uncertain[139,140]. A summary of the main environmental, scientific, economic, political, social and individual consequences is given in Figure 2.2, with associated main assumptions and uncertainties identified in Table 3.3. Biodiversity-related considerations are discussed in greater detail in subsequent text.

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[137] Wiltshire A & Davies-Barnard T (2015) *Planetary Limits to BECCS Negative Emissions*. AVOID 2 report, ref WPD2a. Department of Energy & Climate Change (DECC), London; http://www.avoid.uk.net/publications

[138] van Vuuren DP, Stehfest E, den Elzen MJ, Kram T et al. (2011) RCP 2.6: exploring the possibility to keep global mean temperature increase below 2°C. *Climatic Change* 109, 95-116

[139] Creutzig F, Ravindranath NH, Berndes G, Bolwig S et al. (2014) Bioenergy and climate change mitigation: an assessment. *Global Change Biology Bioenergy* (online) doi: 10.111/gcbb.12205

[140] Searchinger T, Edwards R, Mullinger D, Heimlich R & Plevin R (2015) Do biofuel policies seek to cut emissions by cutting food? *Science* 347, 1420-1422

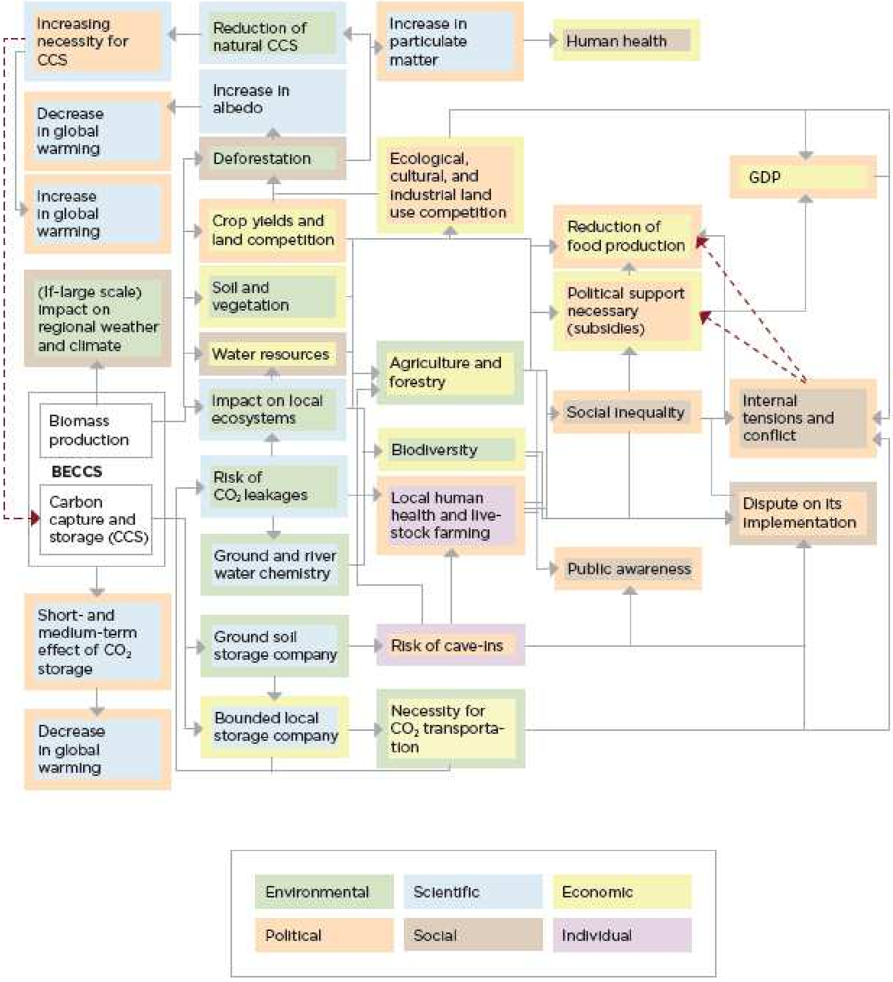

Figure 2.2 Schematic overview of possible consequences of large-scale BECCS deployment. Grey arrows, plausible consequences; red arrows, feedbacks. Colour coding key relates to main (in box) and secondary (surrounding border) nature of consequences. Source: JSA Link & J Scheffran; ref[141]. *In the process of obtaining permission to re-use this figure.*

Table 3.3 Summary of BECCS-related assumptions and uncertainties. Many aspects are closely linked, requiring consequential (rather than attributional) life cycle assessments[142] to evaluate their implications for BECCS effectiveness as a CDR technique. Based on ref[143].

Assumption	**Detail**
1. Bioenergy technical potential	
1.1 Land area required/available for BECCS	BECCS necessarily displaces an existing land use/land cover. 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

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[141] Schäfer S, Lawrence M, Stelzer H, Born W et al.(2015) *The European Transdisciplinary Assessment of Climate Engineering (EuTRACE): Removing Greenhouse Gases from the Atmosphere and Reflecting Sunlight away from Earth*. 169 pp; http://www.iass-potsdam.de/de/publikationen/projektberichte

[142] Plevin RJ, Delucchi MA & Creutzig F (2013) Using attributional life cycle assessment to estimate climate-change mitigation benefits misleads policy makers. *Journal of Industrial Ecology* 18, 73-83

[143] Gough C & Vaughan N (2015) *Synthesising Existing Knowledge on the Feasibility of BECCS*. AVOID 2 report, ref WPD1a (contract 1104872). Department of Energy & Climate Change (DECC), London; http://www.avoid.uk.net/publications

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
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-characterised; potential for regional mismatch between CO_2 production via BECCS and storage capabilities.
3. Political and socio-economic	
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.

102. The scale of BECCS impacts is necessarily linked with the area of land used for bioenergy crops and the previous status of that land. Within 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[144]. 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 unmanaged forest and ~90% loss of unmanaged pasture by 2100 unless appropriate environmental safeguards are in place[145]. 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 1.4), the land use changes within the IMAGE RCP 2.6 scenario have serious implications for terrestrial species richness, with effects this century expected to be greater than climatic impacts occurring in either RCP 4.5 or 6.0[146] .

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

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[144] FAO (Food & Agriculture Organization) (2013) *Statistical Yearbook 2013. World Food and Agriculture* http://www.fao.org/docrep/018/i3107e/i3107e.PDF

[145] Wise M, Calvin K, Thomson A, Clarke L et al. (2009) Implications of limiting CO_2 concentration for land use and energy. *Science* 324, 1183-1186

[146] Newbold T, Hudson LN, Hill SLL, Contu S et al (2015) Global effects of land use on local terrestrial biodiversity. *Nature*, 520, 45-50.

- The loss of soil carbon (with associated greenhouse gas emissions) when abandoned land and 'marginal land'[147] is returned to, or brought into, cultivation[148]. In one scenario, the expected BECCS benefit of a global reduction of 1.34°C by 2100 was reduced to 0.15°C when this factor is taken into account[149].
- 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 yield assumptions seem speculative and over-optimistic[150]. In practice, actual yields may be ~50% of those that are theoretically plausible. The higher yields would require massive fertilizer applications, with consequences for greenhouse gas emissions. Future yields are likely (at best) to grow linearly rather than exponentially. They are more likely to either 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[151], 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 additional water demand (of ~0.6m^3 kg^{-1} feedstock) for biofuel powerplant and CCS processes[152]; and iv) future nutrient constraints are likely to limit CO_2 fertilization effects, for both managed and unmanaged terrestrial vegetation[153].
- 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[154].
- Changes in albedo may occur when land is used for bioenergy production[155]. If the conversion is from forest, albedo-induced cooling effects may provide greater climatic benefits than those obtained from BECCS[156]. 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 unintended 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

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[147] Shortall O (2013) "Marginal" land for energy crops: Exploring definitions and embedded assumptions. *Energy Policy* 62, 19-27

[148] Searchinger T, Heimlich R, Houghton RA, Dong F et al (2008) Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science* 319, 1238-1240.

[149] Wiltshire A & Davies-Bernard T (2015) *Planetary Limits to BECCS Negative Emissions*. AVOID 2 report, ref WPD2a. Department of Energy & Climate Change (DECC), London; http://www.avoid.uk.net/publications

[150] Creutzig F (2014) Economic and ecological views on climate change mitigation with bioenergy and negative emissions. *Global Change Biology Bioenergy* (online) doi: 10.111/gcbb.12235

[151] Bonsch M, Humpenöder F, Popp A, Bodirsky B et al. (2014) trade-offs between land and water requirements for large-scale bioenergy production. *Global Change Biology Bioenergy*, doi: 10.111/gcbb.12226

[152] Smith LJ & Torn MS (2013) Ecological limits to terrestrial biological carbon dioxide removal. *Climatic Change* 118, 89-103

[153] Wieder WR, Cleveland CC, Smith WK & Todd-Brown K (2015) Future productivity and carbon storage limited by terrestrial nutrient availability. *Nature Geoscience* 8, 441-445; doi: 10.1038/ngeo2413

[154] Searchinger T, Edwards R, Mulligan D, Heimlich R & Plevin R (2015) Do biofuel policies seek to cut emissions by cutting food? *Science* 347, 1420-1422.

[155] Bright RM, Cherubini F & Strømman AH (2012) Climate impacts of bioenergy: inclusion of carbon cycle and albedo dynamics in life cycle impact assessment. *Environmental Impacts Assessment Review* 37, 2-11,

[156] Wiltshire A & Davies-Barnard T (2015) *Planetary Limits to BECCS Negative Emissions*. AVOID 2 report, ref WPD2a. Department of Energy & Climate Change (DECC), London; http://www.avoid.uk.net/publications

2.11 Gt of carbon in switchgrass biomass, i.e. an overall efficiency of 47%[157]. 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[158] 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.

3.3 Afforestation and reforestation

104. 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[159]. 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[160], and are subject to ongoing discussions under the UNFCCC as well as at CBD SBSTTAs and COPs.

105. 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[161]. 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).

106. In a specific scenario[162], tropical afforestation on 7 Mha yr^{-1} could remove 3.7 Gt CO_2 yr^{-1}, whilst 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 would cause N_2O release (a greenhouse gas, with century-scale global warming potential ~300 times greater than CO_2) reducing or over-riding the benefits of CO_2 drawdown. Global supplies of phosphate rock, the source of phosphorus fertilizer, are likely to be exhausted sometime between 2050-2100 years[163].
- The effectiveness of CO_2 removal decreases as a forest system matures, generally approaching net balance in 50-100 years[164] ; however, old-growth forests can also be net carbon sinks[165]

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[157] Smith LJ & Torn MS (2013) Ecological limits to terrestrial biological carbon dioxide removal. *Climatic Change* 118, 89-103

[158] Stephenson AL & Mackay DJC (2014) *Life Cycle Impacts of Biomass Electricity in 2020*. UK Department of Energy & Climate Change, London. 153 pp

[159] National Academy of Sciences (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

[160] CBD (Secretariat of Convention on Biological Diversity) (2011) *REDD-plus and Biodiversity* (T Christophersen & J Stahl, Eds). CBD Montreal, Technical Series No 59; 65 pp:

[161] National Academy of Sciences (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

[162] Smith LJ & Torn MS (2013) Ecological limits to terrestrial biological carbon dioxide removal. *Climatic Change* 118, 89-103

[163] Cordell D, Drangert J-O & White S (2009) The story of phosphorus: Global food security and food for thought. *Global Environmental Change* 19, 292-305.

[164] Ryan MG, Binkley D & Fownes JH (1997) Age-related decline in forest productivity: Pattern and process. *Advances in Ecological Research*, 27, 213-262; doi: 10.1016/S0065-2504(08)60009-4

- Future climate change will jeopardise *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 when the need for negative emissions is greatest under RCP 2.6.
- Whilst 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[166], and future increases may anyway be constrained by nutrient limitation[167]
- Changes in albedo and evapotranspiration resulting from large-scale afforestation are complex[168,169,170] 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[171], may counter-intuitively have a net warming effect, over-riding the benefits of CO_2 removal. Thus such afforestation would not only reduce albedo (particularly during seasonal snow cover) but it would also significantly increase atmospheric water vapour (a greenhouse gas, although not usually considered as such) [172,173].

107. A modelling study[174] 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.

108. CBD (2012) emphasised the importance of maximising the biodiversity benefits of managed forests by planting assemblages of native trees rather than exotic monocultures, and that conclusion is re-iterated here. From a climatic perspective, the benefits of reducing deforestation seem much greater, and more certain, than afforestation/reforestation.

3.4 Soil carbon – with focus on biochar

109. This section focuses on biochar. No specific attention is given to increasing soil carbon, other than by biochar and enhanced weathering, because of the limited sequestration potential and lack of permanence of approaches[175] based on soil-management- and the consequent lack of recent literature

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[165] Luyssaert S, Schulze E-D, Börner A, Knohl , Hessenmöller D et al. (2008) Old-growth forests as global carbon sinks. *Nature* 455, 213-215; doi: 10.1038/nature07276

[166] van der Sleen P, Groenendijk, Vlam M, Anten NPR et al. (2015) No growth stimulation of tropical trees by 150 years of CO2 fertilization but water-use efficiency increased. *Nature Geoscience* 8, 24-28

[167] Wieder WR, Cleveland CC, Smith WK & Todd-Brown K (2015) Future productivity and carbon storage limited by terrestrial nutrient availability. *Nature Geoscience* 8, 441-445; doi: 10.1038/ngeo2413

[168] Arora VK & Montenegro A (2010) Small temperature benefits provided by realistic afforestation efforts. *Nature Geoscience* 4, 514-518

[169] Anderson RG, Canadell JG, Randerson JT, Jackson RB et al. (2011) Biophysical considerations in forestry for climate protection. *Frontiers in Ecology & Environment* 9, 174-182

[170] Bonan GB (2008) Forests and climate change: Forcings, feedbacks, and the climate benefits of forests. *Science* 320, 1444-1449

[171] Boucher J-F, Tremblay P, Gaboury S & Villeneuve C (2012) Can boreal afforestation help offset incompressible GHG emissions from Canadian industries? *Process Safety & Environmental Protection* 90, 459-466

[172] Swann AL, Fung IY, Levis S, Bonan GB & Doney SC (2010) Changes in Arctic vegetation amplify high-latitude warming through the greenhouse effect. *Proceedings National Academy of Science* 107, 1295-1300

[173] Swann ALS, Fung IY & Chiang JCH (2012) Mid-latitude afforestation shifts general circulation and tropical precipitation. *Proceedings National Academy of Science* 109, 712-716

[174] Keller DP, Feng EY & Oschlies A (2014) Potential climate engineering effectiveness and side effects during a high carbon dioxide-emission scenario. *Nature Communications* 5, 3304; doi: 10.1038/ncomms4304

[175] Mackey B, Prentice IC, Steffen W, House JI et al. (2013) Untangling the confusion around land carbon science and climate change mitigation policy. *Nature Climate Change* 3, 552-557; doi: 10.1038/nclimate1804

considering soil carbon enhancement *per se* as a geoengineering technique. However, the avoidance of further emissions from soil and other land carbon sinks (and re-filling depleted stocks), is an important component of climate-change mitigation, as recognised by IPCC WG III and CBD decisions X/33 and X1/20, and could assist in reducing the need for other, more radical, negative emission technologies[176].

110. 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 storage. There is an extensive literature on the topic, primarily because biochar is increasingly being used for soil improvement[177,178], 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.

111. The effectiveness of biochar for long-term CO_2 removal is, however, controversial. A relatively high (upper) estimate of 130 Gt C for century-scale removal was provided in IPCC AR5 (WG I report, Table 6.15), greater than the BECCS estimate of 100 Gt C. In contrast, the potential for biochar as a climate intervention technique was only summarily considered in the text of the NAC/NRC report[179], since it was "not classified… as a CDR technology" (although included in concluding comparative evaluations). That relatively unfavourable assessment seems to have mostly been due to one review[180], based on literature up to 2011. That review emphasised uncertainties, both with regard to biochar's proposed role in carbon removal and its other possible environmental benefits.

112. In the CBD interim report on climate geoengineering (UNEP/CBD/SBSTTA/18/INF/5), 34 peer-reviewed publications on biochar were listed for the period mid-2012 to mid-2014, and more than 50 other recent papers have since been identified. The clear consensus from that literature, that includes meta-analyses[181,182,183,184] and several other reviews[185,186,187], is that biochar does have potential as a CDR technique – whilst recognizing that its contribution may not be as great as has been claimed (e.g. up to 130 Gt C by 2100, as cited in IPCC AR5[188]), and that the term biochar covers many products, with

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[176] Edmonds J, Luckow P, Calvin K, Wise M et al. (2013) Can radiative forcing be limited to 2.6 Wm^{-2} without negative emissions from bioenergy AND CO2 capture and storage? *Climatic Change* 118, 678; doi: 10.1007/s10584-012-0678-z

[177] Lehmann J & Joseph S (eds) (2015) *Biochar for Environmental Management: Science, Technology and Implementation* (2nd Edition). Routledge; 944 pages.

[178] Cernansky R (2015) State-of-the-art-soil. *Nature* 517,258-260

[179] National Academy of Sciences (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

[180] Gurwick NP, Moore LA, Kelly C & Elias P (2013) A systematic review of biochar research, with focus on its stability *in situ* and its promise as a climate mitigation strategy. *PLoS ONE* 8, e75932

[181] Biederman LA & Harpole WS (2013) Biochar and its effects on plant productivity and nutrient cycling: a meta-analysis. *Glob. Change Biol. Bioenergy*, 5, 202-214

[182] Liu X, Zhang A, Ji C *et al.* (2013) Biochar's effect on crop productivity and the dependence on experimental conditions-a meta-analysis of literature data. *Plant & Soil*, 373, 583

[183] Jeffery S, Verheijen FGA, van der Velde M & Bastos AC (2011) A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. *Agriculture,EcosystemS & Environment* 144,175-187

[184] Crane-Droesch A, Abiven S, Jeffery S et al. (2013) Heterogeneous global crop yield response to biochar: a meta-regression analysis. *Env. Res. Lett.*, 8, 044049

[185] Xie T, Reddy KR , Wang C, Yargicoglu & Spokas K (2015) Characteristics ans applicatioons of biochar for environmental remediation: a review. *Critical Reviews in Environmental Science and Technology* 45, 939-969

[186] Lehmann J, Abiven S, Kleber M, Pan G et al. (2015) Persistence of biochar in soil. Chapter 10 (p 235-282) in: *Biochar for Environmental Management: Science, Technology and Implementation* (2nd Edition) (J Lehmann J & S Joseph S, eds). Routledge; 944 pages

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different properties. Thus there can be many equally valid values for biochars' persistence/recalcitrance in soil (hence effectiveness in carbon storage), 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).

113. Standard methods and metrics to obtain a process-based understanding of the effects of these factors on biochar persistence have been developed and are being applied[189,190,191,192]. Multi-year experiments under a range of field conditions are needed for these methods to be tested on different biochars, to enable projections on 50-100 year timescales to be confidently made.

114. Variability also occurs regarding the intended, and more easily measured, effects of biochar – on crop yields/productivity, water retention (in sandy soils),and drainage (in clay soils). Whilst crop yield changes from -16% to +100% have been reported within a single study[193], a meta-analysis[194] has indicated a mean yield increase of 14% in acidic soils, and an overall mean of10% in all soil types. Agronomic benefits usually relate to the first year of treatment, and may subsequently show a marked decline[195].

115. 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[196]. Significant reductions in the soil emissions of other greenhouse gases, specifically methane (CH_4)[197,198] and nitrous oxide (N_2O)[199,200,201], and both[202,203], have been also been reported – with the scale of the response dependent on biochar properties and other treatment conditions.

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116. Treatment conditions also, not surprisingly, strongly influence the impacts of biochar on soil biology. Microbial activity is generally enhanced[204,205], and there can be both positive and negative effects on soil fauna[206,207]. Further study would seem necessary: a recent review of this topic[208] concluded that “Elucidating the impacts of soil fauna directly and indirectly on biochar stability is a top research priority”. Other important knowledge gaps relate to:

- The consequences of loss of applied biochar through erosion and run-off[209,210], with implications for water quality and wider environmental impacts;
- The interactions of biochar with other crop treatments and pollutants; for example, biochar might reduce the effectiveness of pre-emergent herbicides[211], whilst remediating the toxic impacts of heavy metals[212,213;]
- The wider consequences for biodiversity, including effects of large-scale requirements for biochar feedstocks.

117. Under large-scale deployment conditions for biochar, climatically-undesirable albedo impacts[214,215] could also become important, notwithstanding that 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. Other scaling issues for biochar have both similarities and differences to those for BECCS, with the main difference being that biochar production is expected to focus on crop residues and other biowaste, rather than dedicated energy crops. The global production of crop residues currently totals ~2.5 Gt C yr^{-1} (around a quarter of fossil fuel emissions), with estimated[216]

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potential for 'net removal' by biochar of ~1.8 Gt C yr^{-1}. The value for 'net removal' does, however, depend on the assumptions made regarding life cycle assessments and related issues – not only for the biochar production process[217,218], but also relating to the persistence of biochar in soil, the timeframe under consideration, and whether there is considered to 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/nationally) .

118. A life cycle assessment has been carried out for straw-based biochar, in comparison to using the straw for building purposes[219]. 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). The removed straw contained 0.5% nitrogen and 0.1% phosphorus; for sustainable biochar production, these nutrients would need to be replaced, by fertilizer or (for nitrogen) by nitrogen-fixing cover crops.

119. Whilst life cycle assessments (LCAs) are an extremely valuable tool for decision-making, their uncertainties also need to be recognized – through consequential, rather than attributional, techniques[220].

3.5 Ocean fertilization and other processes to enhance ocean productivity

120. 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.

121. Two recent reviews of research on ocean fertilization[221,222] 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 unintended 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[223] and

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[223] National Academy of Sciences (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

EuTRACE[224] 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".

122. Recent topic-specific studies on enhanced ocean productivity have provide 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 study; 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[225].

123. **Characterization of natural iron fertilization** and its impacts has been greatly improved, relating to the supply of iron from seafloor sediments around islands[226,227], from wind-blown dust[228,229], and from volcanic eruptions on land[230,231] and undersea[232]. In the Southern Ocean, the export of particulate organic carbon is generally ~3 times higher under conditions of natural iron fertilization[233]; however, effects on CO_2 drawdown depend on the ratio of organic /inorganic carbon in sinking particles[234]. Light levels (determined by mixing depth) can also be important in determining the effectiveness of natural iron fertilization[235].

124. Additional **modelling studies of ocean iron fertilization** have been carried out at global, regional and local scales. A global study[236] 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. The

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Southern Ocean modelling study[237] 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[238]. This effect means that direct scaling-up from iron fertilization experiments to operational CDR deployment is likely to over-estimate sequestration rates and efficiencies.

125. 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[239]. A database for all iron fertilization studies has been compiled[240]

126. A private sector, **unregulated ocean iron addition study** was carried out in July 2012 in the north east Pacific, for the main purpose of fishery enhancement[241]. This project attracted considerable interest[242,243] by the media and NGOs. Although initially seeming to have support from local indigenous peoples, formal endorsement was later repudiated (statement by Council of the Haida Nation, 18 October 2012). Although scientific analyses of this project have been limited, a satellite-based study[244] and plankton surveys[245] indicated that phytoplankton and subsequently zooplankton abundances were enhanced. Whilst effects on carbon drawdown are uncertain, the intended benefits for the salmon fishery may indeed have been achieved[246], replicating the apparent effects of natural ocean fertilization a few years earlier[247].

127. To enhance the **effectiveness of iron delivery to the upper ocean**, a method has been proposed using risk-husks coated with slow release minerals[248]. 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.

128. 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[249], and contrasting cost

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[245] Batten SD & Gower JFR (2014) Did the iron fertilization near Haida Gwaii in 2012 affect the pelagic lower trophic level ecosystem? *Journal Plankton Research* 36, 925-932; doi: 10.1093/plankt/fbu049

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[249] Lawrence MW (2014) Efficiency of carbon sequestration by adding reactive nitrogen in ocean fertilization. *International Journal of Global Warming* 6, 15-33

estimates of US$ 457 per tonne CO_2 removed by iron fertilization[250] and US$ 20 per tonne CO_2 removed by adding nitrogen (as ammonium hydroxide)[251]. 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; longterm monitoring costs; and future hydrographic conditions (affecting mixing and persistence of sequestration).

129. **Ocean macro-algal "afforestation"** has recently been proposed as an alternative approach[252], 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 socio-economic implications. Nevertheless, the feasibility, cost-effectiveness and impacts of a more modest application of this method warrant further attention, to better assess its potential as a CDR technique.

130. 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 unintended release of CO_2 (also from the deeper water). Nevertheless, modelling studies at the regional[253] and global[254] 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[255]. 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[256].

3.6 Enhanced weathering and ocean alkalinization

131. 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[257], also in other recent reviews[258,259,260,261]. Carbon dioxide removal is usually achieved through the reaction of

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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 suited to industrial development[262,263,264]; 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[265]. In CBD (2012),such potential was noted; however, concern was also expressed regarding the bulk of material required to be processed, the potential for unintended effects, and uncertainties regarding overall cost-effectiveness. The NAC/NRC report reached similar conclusions, whilst 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 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.

132. Recent relevant research on the use of silicate rock flour for enhanced weathering has included a budget[266] 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[267] these were estimated at between \$24 -578 per tonne CO_2 sequestered, depending on rock type and other assumptions.

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[261] Schuiling RD (2014) A natural strategy against climate change. *Journal of Chemical Engineering & Chemistry Research* 1, 413-419

[262] Rau GH, Carroll SA, Bourcier WL Singleton MJ et al. (2013) Direct electrolytic dissolution of silicate minerals for air CO_2 mitigation and carbon-negative H_2 production. *Proceedings of the National Academy of Sciences*,110, 10095-10100

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[265] Cressey D (2014) Rock's power to mop up carbon revisited. *Nature* 505, 464.

[266] Moosdorf N, Renforth P & Hartmann J (2014) Carbon dioxide efficiency of terrestrial enhanced weathering. *Environmental Science & Technology* 48, 4809-4816

[267] Renforth P (2012) The potential for enhanced weathering in the UK. *International Journal of Greenhouse Gas Control* 10, 229-243

133. 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[268]. 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[269]. The potential for mycorrhizal fungi of forest trees[270] 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[271] – for both climatic and geotechnical geoengineering.

134. The large-scale application of olivine to the land surface would increase the alkalinity and pH of natural waters, with implications for rivers, coastal waters and potentially the open ocean[272]. Two additional, potentially-beneficial outcomes have been identified: a reduction in ocean acidification in the affected waters, favouring calcifying organisms, and the enhancement of Si availability, favouring diatoms. Increased marine diatom abundance is expected to strengthen the biological carbon pump, thereby providing a second mechanism for removing CO_2 from the atmosphere (and with a land-based 'enhanced weathering' CDR method also then becoming a technique for 'enhancing ocean productivity').

135. The direct addition of olivine to open ocean surface waters[273] and coastal areas[274] has also been proposed. Whilst 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[275]. 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.

136. Scenarios for global-scale ocean alkalinization have been investigated in models[276,277] simulating the addition of quicklime (CaO), lime ($Ca(OH)_2$) and limestone ($CaCO_3$) to the open ocean. Very large

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[268] ten Berge HFM, van der Meer HG, Steenhuizen JW, Goedhart PW et al. (2012) Olivine weathering in soil, and its effects on growth and nutrient uptake in ryegrass (*Lolium perenne* L): a pot experiment. PLoS ONE 7, e42098; doi: 10.1371/journal.pone.0042098

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[272] Hartmann J, West AJ, Renforth P, Kohler P et al. (2013) Enhanced chemical weathering as a geoengineering strategy to reduce atmospheric carbon dioxide, supply nutrients, and mitigate ocean acidification. *Reviews of Geophysics* 51, 113-149.

[273] Köhler P., Abrams J.F., Völker C., Hauck J. & Wolf-Gladrow D.A. (2013) Geoengineering impact of open ocean dissolution of olivine on atmospheric CO_2, surface ocean pH and marine biology. *Environ. Res. Lett.* 8, Article 014009; doi: 10.1088/1748-9326/8/1/014009

[274] Schuiling RD & de Boer PL (2013) Six commercially viable ways to remove CO_2 from the atmosphere and/or reduce CO_2 emissions. *Environmental Sciences Europe* 25, 35

[275] Schuiling RD & de Boer PL (2011) Rolling stones; fast weathering of olivine in shallow seas for cost-effective CO_2 capture and mitigation of global warming and ocean acidification. *Earth System Dynamics Discussions* 2, 551-568

[276] Paquay, F.S. & Zeebe, R.E. (2013) Assessing possible consequences of ocean liming on ocean pH, atmospheric CO_2 concentration and associated costs. *International Journal of Greenhouse Gas Control* 17, 183-188.

[277] Keller DP, Feng EY & Oschlies (2014) Potential climate engineering effectiveness and side effects during a high carbon dioxide-emission scenario. *Nature Communications* 5, 3304; doi: 10.1038/ncomms4304

quantities of alkalinity (in ratio 2:1 with respect to emitted CO_2)[278] 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

137. 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[279,280], 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[281]; more recent estimates have been substantially less, e.g. US$ 60-100 /t CO_2[282,283], although it is not clear if those costs are fully comparable (e.g. capture only, or capture, regeneration and storage). Moisture-swing sorbents[284,285] are now considered the preferred DAC process: they absorb CO_2 when wet, releasing it when dry.

138. 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.

3.8 Removal of greenhouse gases other than CO_2

139. 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 (CH_4 and N_2O respectively)[286].

140. Methane has, however, received some attention, because of its global warming potential (~25 times greater than CO_2) 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[287]. Whilst the scale

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[278] Ilyina, T, Wolf-Gladrow D, Munhoven G & Heinze C (2013) Assessing the potential of calcium-based artificial ocean alkalinization to mitigate rising atmospheric CO_2 and ocean acidification. *Geophysical Research Letters* 40, 5909-5914; doi: 10.1002/2013gl057981

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[283] Holmes G & Keith DW (2012) An air-liquid contactor for large-scale capture of CO_2 from air. *Philosophical Transactions Royal Society A*, 370, 4380-4403

[284] Wang T, Lackner KS & Wright AB (2013) Moisture-swing sorption for carbon dioxide capture from ambient air: a thermodynamic analysis. *Physical Chemistry Chemical Physics* 15, 504-514

[285] Wang T, Liu J, Fang M & Luo Z (2013) A moisture swing sorbent for direct air capture of carbon dioxide: thermodynamic and kinetic analysis. *Energy Procedia* 37, 6096-6104

[286] O Boucher & Folberth GA (2010) New directions: Atmospheric methane removal as a way to mitigate climate change? *Atmospheric Environment* 44,3343-3345

[287] Howarth RW (2014) A bridge to nowhere: methane emissions and the greenhouse gas footprint of natural gas. *Energy Science & Engineering* 2, 47-60

of future CH_4 emissions from thawing permafrost[288] , sub-sea methane clathrates[289] and sub-glacial sources[290] is uncertain[291], the risk of dramatic flux increases cannot be ruled out – and techniques that might address that problem would seem highly desirable[292]. Both biological[293,294] and chemical[295] removal approaches have received attention, but are not yet sufficiently developed for large-scale field application. Boreal vegetation can itself be a sink for CH_4[296]: however, relatively little is known regarding the scale of this effect, and its potential for manipulation.

141. 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[297]. As noted above, the application of biochar may also be able to achieve significant N_2O mitigation.

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[288] Whiteman G, Hope C & Wadhams P (2013) Climate change: Vast costs of Arctic change. *Nature* 499, 401-403

[289] Ruppel CD (2011) Methane hydrates and contemporary climate change. *Nature Education Knowledge* 3, 29

[290] Wadham JL, Arndt S, Tulaczyk S, Stibal M et al. (2012) Potential methane reservoirs beneath Antarctica. *Nature* 488, 633-637

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[295] Kim J, Maitui A, Lin L-C, Stolaroff JK et al. (2013) New materials for methane capture from dilute and medium-concentration sources. Nature Communications 4, 1694

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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

142. 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).

143. 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 (unintended 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. Whilst 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.

144. Three main comparisons are possible to assess SRM effects in models, in relation to: (i) the climatic scenarios arising from current emission trajectories or similar (i.e. the unmitigated IPCC scenario RCP 8.5, or quadrupled CO_2); (ii) moderate-to-strong conventional mitigation (RCP 6.0, RCP 4.5) that still would result in 'dangerous' climate change; or (iii) 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.

145. Even with the combination of an exceptionally-high rate of decarbonisation of energy generation[298], rapid cessation of greenhouse emissions from all other sources, and application of at least some CDR techniques it would seem extremely challenging to have any confidence of staying within 1.5°C of warming[299,300]. That goal might, however, be achievable if SRM were included in the portfolio of climate policies[301], with its deployment based on a "temporary, moderate and responsive scenario"[302]. Furthermore, SRM might be used to slow, rather than fully counteract temperature change under RCP 4.5 or RCP 6.0 scenarios[303]. The associated ethical principles (and governance issues) then become of even greater importance, as considered here in Chapter 5.

146. 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

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[298] Myhrvold NP & Caldeira K (2012) Greenhouse gases, climate change and the transition from coal to low-carbon electricity. *Environmental Research Letters* 7, 014019; doi: 10.1088/1748-9326/7/1/014019

[299] Anderson K & Bows A (2011) Beyond 'dangerous' climate change: emission scenarios for a new world. *Philosophical Transactions of the Royal Society A* 369, 20-44; doi: 10.1098/rsta.2010.0290

[300] Anderson K & Bows A (2012) A new paradigm for climate change. *Nature Climate Change* 2, 639-640; doi: 10.1038/nclimate1646

[301] Bahn O, Chesney M, Gheyssens , Knutti R & Pana AC (2015) Is there room for geoengineering in the optimal climate policy mix? *Environmental Science & Policy* 48, 67-76

[302] Keith DW & MacMartin DG (2015) A temporary, moderate and responsive scenario for solar geoengineering. *Nature Climate Change* 5, 201-206.

[303] MacMartin DG, Caldeira K & Keith DW (2014) Solar geoengineering to limit the rate of temperature change. *Philosophical Transactions of the Royal Society A* 372, art 20140134; doi: 10.1098/rsta.2014.0134.

reports[304,305], and ~40% longer in the EuTRACE report[306], although both emphasised SRM's high risks and uncertainties. SRM has also been the main theme of at least six recent books on climate geoengineering[307,308,309,310,311,312] and is the overwhelming concern of governance and acceptability discussions, reflected in many commentaries questioning the desirability of such an approach[313,314,315]. 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 have that meaning (see Annex 2).

147. Comparative studies between different SRM methods are limited. Whilst 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 intended and unintended climatic consequences. An intercomparison[316] 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), whilst 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.

148. 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[317]; and ii) soil moisture may be a

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[304] National Academy of Sciences (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

[305] National Academy of Sciences (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

[306] Schäfer S, Lawrence M, Stelzer H, Born W et al.(2015) *The European Transdisciplinary Assessment of Climate Engineering (EuTRACE): Removing Greenhouse Gases from the Atmosphere and Reflecting Sunlight away from Earth*. 169 pp; http://www.iass-potsdam.de/de/publikationen/projektberichte

[307] Keith D (2013) *A Case for Climate Engineering.* MIT Press, Cambridge MA, USA. 112 pp

[308] Burns WCG & Strauss AL (2013) *Climate Change Geoengineering. Philosophical Perspectives, Legal Issues and Governance Frameworks.* Cambridge University Press, Cambridge UK. 325 pp

[309] Stilgoe J (2015) *Experiment Earth. Responsible Innovation in Geoengineering*. Routledge, Abingdon, UK.240 pp

[310] Preston CJ (2013) *Engineering the Climate: The Ethics of Solar Radiation Management*. Lexington Books/Rowman & Littlefield, Lanham MD. 278pp

[311] Hulme M (2014) *Can Science Fix Climate Change? A Case against Climate Engineering*. Polity Press, Cambridge UK, 144pp

[312] Hamilton C (2013) Earthmasters: Playing God with the Climate. Allen & Unwin, Australia. 172 pp

[313] Hamilton C (2013) No, we should not just 'at least do the research'. *Nature*, 496, 139

[314] Sillmann J, Lenton TM, Leverman A, Ott K et al. (2015) Climate emergencies do not justify engineering the climate. *Nature Climate Change* 6, 290-292

[315] ETC Group: Mooney P, Wetter KJ & Bronson D (2012) Darken the sky and whiten the earth – The dangers of geoengineering. *Development Dialogue No 61; What Next Volume IIII: Climate Development & Equity;* 210-237

[316] Jackson LS, Crook JA, Osprey SM & Forster P (2014) A comparison of geoengineering methods: assessment of precipitation side effects. AGU Fall Meeting 2014, abstract #GC13I-0779; http://adabs.harvard.edu/abs/2014AGUFMGC13I0779J

[317] Keith DW & MacMartin DG (2015) A temporary, moderate and responsive scenario for solar geoengineering. *Nature Climate Change* 5, 201-206.

more important parameter than precipitation in determining terrestrial productivity, noting that water use efficiency is expected to increase in response to elevated CO_2[318].

149. 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. Whilst there have been research studies[319,320] 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)

Key message (text originally in bold; re-numbered)	Comments
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.	Central issue remains whether SRM should be considered 'lesser of two evils' - and whether it might ever be possible to have sufficient knowledge (and legitimacy) for such a decision to be made.
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.	Statement valid, but 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.	SRM cooling would affect the dynamics of the global carbon cycle, reducing biospheric CO_2 release. Indirect effects on ocean acidification (and other CO_2-driven impacts) may therefore occur.
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 confirmed, but 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.	Effects of solar shading on marine productivity simulated in models.
7. Cloud brightening is a more localised SRM proposal, with its application likely to be limited to specific ocean areas. The predictability of its climatic impacts is currently uncertain	Further modelling of global/regional impacts, and potential for regional-scale application; also identification of additional uncertainties
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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[318] Leakey ADB, Ainsworth EA, Bernacchi CJ, Roges A et al. (2009) Elevated CO_2 effects on plant carbon, nitrogen and water relations: Six important lessons from FACE. *Journal of Experimental Botany* 60, 2859-2876

[319] Bewick R, Sanchez JP & McInnes CR (2012) Gravitationally bound geoengineering dust shade at the inner Lagrange point. *Advances in Space Research*, 50, 1405-1410

[320] Bewick R, Sanchez JP & McInnes CR (2012) The feasibility of using an L 1 positioned dust cloud as a method of space-based geoengineering. *Advances in Space Research*, 49, 1212-1228

4.2 Stratospheric aerosol injection (SAI)

150. 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.

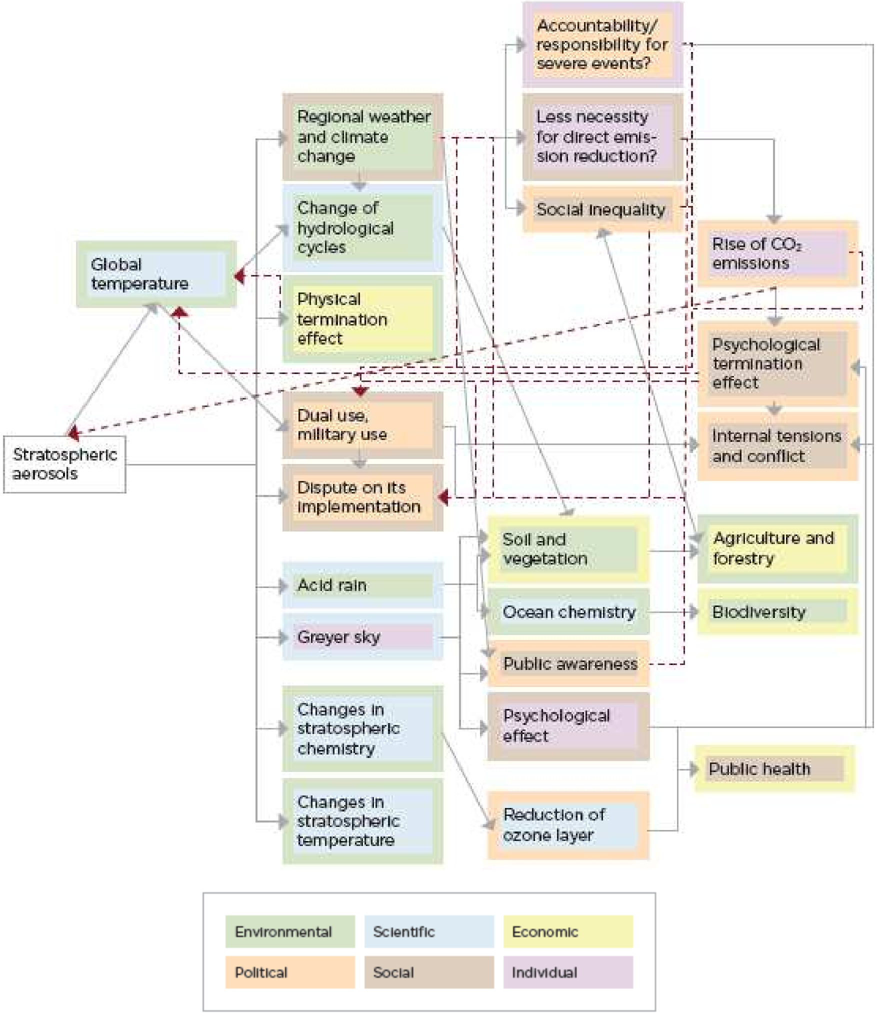

Figure 4.1 Schematic overview of possible implications and impacts of SRM using stratospheric aerosol injection (SAI). Grey arrows, plausible consequences; red arrows, feedbacks. Colour coding key relates to main (in box) and secondary (surrounding border) nature of consequences. Source: JSA Link & J Scheffran; ref[321]. *In the process of obtaining permission to re-use this figure.*

151. 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 longterm 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)[322] is a sub-project of CMIP 5, using simulations from the larger project as controls for solar geoengineering model experiments, including SAI. Whilst 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.

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[321] Schäfer S, Lawrence M, Stelzer H, Born W et al.(2015) *The European Transdisciplinary Assessment of Climate Engineering (EuTRACE): Removing Greenhouse Gases from the Atmosphere and Reflecting Sunlight away from Earth*. 169 pp; http://www.iass-potsdam.de/de/publikationen/projektberichte

[322] Kravitz B, Robock A, Forster PM, Haywood JM et al. (2013) An overview of the Geoengineering Model Intercomparison Project (GeoMIP). *Journal of Physical Research – Atmospheres* 118, 13103-13107; doi: 10.1002/2013JD020569

152. 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 S yr^{-1} (similar to the effect of the Mt Pinatubo eruption) for the period 2020-2070 in the context of an RCP 4.5 warming scenario. Important outcomes from these studies included:

- 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[323].
- Space-based solar dimming and SAI have different regional-scale consequences for temperature and precipitation[324], an effect observed in other comparisons between the two techniques[325,326].
- 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[327].
- 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[328].

153. 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[329], 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[330], an imagined (and simplified) decision-making process was simulated by a predictive control regime[331] 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.

154. 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. Whilst 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-

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[323] Irvine PJ, Boucher O, Kravitz B, Alterskjaer K et al. (2014) Key factors governing uncertainty in the response to sunshade geoengineering from a comparison of the GeoMIP ensemble and a perturbed parameter ensemble. *Journal of Physical Research – Atmospheres* 119, art. 2013JD020716; doi: 10.1002/2013JD020716

[324] Yu XY, Moore JC, Cui XF, Rinke A et al. (2015) Impacts, effectiveness and regional inequalities of the GeoMIP G1 to G4 solar radiation management scenarios. *Global & Planetary Change* 129, 10-22; doi: 10.1016/j.gloplacha.2015.01.010

[325] Kalidindi S, Bala G, Modak A & Caldeira K (2015) Modeling of solar radiation management: a comparison of simulations usinf reduced solar constant and stratospheric sulphate aerosols. *Climate Dynamics* 44, 2909-2925

[326] Ferraro AJ, Highwood EJ & Charlton-Perez AJ (2014) Weakened tropical circulation and reduced precipitation in response to geoengineering. *Environmental Research Letters* 9, 014001; doi: 10.1088/1748-9326/9/1/014001

[327] Pitari G, Aquila V, Kravitz B, Robock A et al. (2014) *Journal of Physical Research – Atmospheres* 119, 2629-2653; doi: 10.1002/2013JD020566

[328] Berdahl M, Robock A, Ji DY, Moore JC et al. (2014) *Journal of Physical Research – Atmospheres* 119,1308-1321; doi: 10.1002/2013JD020627

[329] Tilmes S, Jahn A, Kay JE, Holland M & Lamarque J-F (2014) Can regional climate engineering save the summer Arctic sea ice? *Geophysical Research Letters* 41, 880–885, doi: 10.1002/2013GL058731

[330] Jackson LS, Crook JA, Jarvis A, Leedal D et al. (2015) Assessing the controllability of Arctic sea ice extent by sulfate aerosol geoengineering. *Geophysical Research Letters* 42,1223-1231, doi: 10.1002/2014GL062240

[331] MacMartin DG, Kravitz B, Keith DW & Jarvis A (2013) Dynamics of the coupled human-climate system resulting from closed-loop control of solar geoengineering. *Climate Dynamics* doi: 10.1007/s00382-013-1822-9a

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[332], with potentially catastrophic regional-scale ecological and socio-economic consequences. The implications of northern hemisphere-only SAI are the most serious; Figure 4.2.

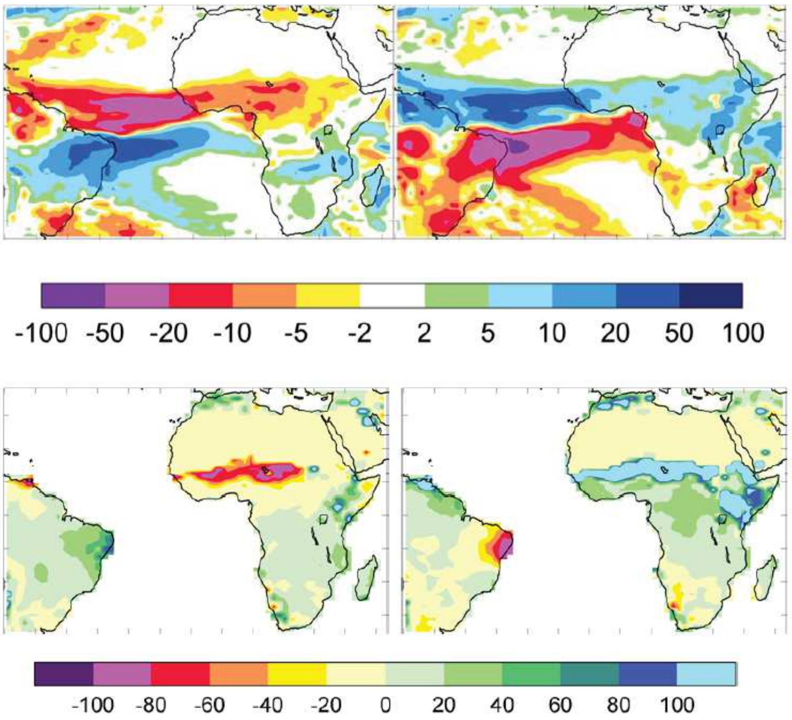

Figure 4.2 Modelled effect of hemispherically asymmetric aerosol sulphate injection. *Upper maps*: Change in mean precipitation (mm/month) for the period 2020-2070 when SO_2 is injected into the northern hemisphere only (left) or southern hemisphere only (right) in comparison to RCP 4.5 scenario. *Lower maps:* Percentage change in net primary production under the same conditions. From ref. cited in Fn. 331.

155. A global framework for **regional risk assessment** arising from SAI deployment has been developed[333]. 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[334] 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.

156. 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[335,336] with candidate materials including alumina, silica oxides and

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[332] Haywood JM, Jones A, Bellouin N & Stephenson D (2013) Asymmetric forcing from stratospheric aerosols impacts Sahelian rainfall. *Nature Climate Change* 3, 660-665; doi: 10.1038/nclimate1857.

[333] Ferraro AJ, Charlton-Perez AJ & EJ Highwood (2014) A risk-based framework for assessing the effectiveness of stratospheric aerosol engineering. *PLoS ONE* 9, e88849; doi: 10.371/journal.plone.0088849

[334] Kravitz B, MacMartin DG, Robock A, Rasch PJ et al (2014) A multi-model assessment of regional climate disparities caused by solar geoengineering. *Environmental Research Letters* 9, 074013

[335] Pope FD, Braesicke P, Grainger RG, Kalberer M. *et al* (2012) Stratospheric aerosol particles and solar-radiation management. *Nature Climate Change* 2, 713-719; doi: 10.1038/nclimate1528

[336] Weisenstein DK & Keith DW (2015) Solar geoengineering using solid aerosol in the stratosphere. *Atmospheric Chemistry & Physics Discussions* 15, 117999-11851

diamond particles. Their advantages would be less mass required for the same radiative effect; also less ozone loss, and less stratospheric heating.

157. 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. Additional analyses confirm that large-scale SAI would cause sky brightening (increase in white light), likely to be discernible in rural areas[337]. Comparable global dimming of 2-3% (and regionally higher, up to 10-15%)[338] was, however, societally-tolerated – and largely unnoticed – in the period 1960-1990 due to tropospheric pollution, primarily by SO_2 and black carbon. Although the quantity of photosynthetically active radiation would decrease under SAI, that effect would be countered by diffuse light increasing the net efficiency of carbon fixation for most terrestrial vegetation. A recent modelling study[339] indicates that similar re-balancing, but by different mechanisms, may also occur for marine ecosystems: modelled reductions of surface irradiance by 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, upper movement of production and biomass was indicated.

158. 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 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)[340]. The magnitude of that effect on ocean acidification has been estimated as an increase in the mean surface ocean pH of 0.05 units by 2100 relative to IPCC A2 scenario[341] and an increase of 0.09 units relative to RCP 8.5[342]. The latter study showed that net pH changes relative to present-day values would, however, still be negative, since the decrease under RCP 8.5 pH (without SRM) would be 0.35. That study also showed that the comparable pH increase achieved by model-simulated large-scale ocean alkalinization – a 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 in the same study.

159. Model simulations show that SRM cooling could reduce the occurrence of temperature-driven bleaching for warm-water corals. However, ocean acidification effects are also involved, since aragonite saturation state and calcification rates are temperature-dependent: at lower temperatures, ocean acidification stress is likely to be more severe[343].

160. 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

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[337] Kravitz B, MacMartin DG & Caldeira K (2012) Geoengineering: Whiter skies? *Geophysical Research Letters* 39, L11801; doi: 10.1029/2012GL051652

[338] Wild M, Gilgen H, Roesch A, Ohmura A et al. (2005) From dimming to brightening: Decadal changes in solar radiation at the Earth's surface. *Science* 308, 847-850

[339] Hardman-Mountford NJ, Polimene L, Hirata T, Brewin RJW & Aiken J (2013) Impacts of light shading and nutrient enrichment geo-engineering approaches on the productivity of a stratified oligotrophic ocean ecosystem. *Journal Royal Society Interface* 10, 20130701

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[342] Keller DP, Feng EY & Oschlies (2014) Potential climate engineering effectiveness and side effects during a high carbon dioxide-emission scenario. *Nature Communications* 5, 3304; doi: 10.1038/ncomms4304

[343] Kwiatkowski L, Cox P, Halloran PR, Mumby PJ & Wiltshire AJ (2015) Coral bleaching under unconventional scenarios of climate warming and ocean acidification. *Nature Climate Change* 5; doi 10.1038/nclimate2655

century) SAI deployment[344] that would greatly reduce **SRMI termination risks.** However, the alternative – that greenhouse gas levels continue to rise – would be highly risky, since very rapid temperature increases would occur if SAI were to be started, then subsequently discontinued. The environmental consequences of such an effect were discussed in CBD (2012); its occurrence has since been confirmed by single-model[345] and multi-model[346] studies.

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[347], and with likely linkage to extreme weather in mid-latitudes[348.] 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)[349]. Sea ice cover is of very great importance to the entire Arctic ecosystem[350], 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[351].

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[352]. 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 socio-economics 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[353].

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[344] Keith DW & MacMartin DG (2015) A temporary, moderate and responsive scenario for solar geoengineering. *Nature Climate Change* 5, 201-206.

[345] McCusker KE, Armour KC, Bitz CM & Battiosti DS (2014) Rapid and extensive warming following cessation of solar radiation management. *Environmental Research Letters* 9, 024005; doi: 10.1088/1748-9326/9/2/024005

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4.3 Marine cloud brightening (MCB)

161. This proposed technique would involve the large-scale addition of cloud condensation nuclei (CCN) to the lower atmosphere, mostly to areas that are currently relatively cloud-free, to enhance the production and longevity of stratocumulus clouds. Sea salt particles would provide the CCN, by finely spraying seawater; the technique is also known as sea-salt climate geoeengineering. 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.

162. 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[354] research needs relating to technical viability, effectiveness and unintended 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.

163. Global modelling studies in the GeoMIP context (based on three Earth system models, and RCP 4.5 scenario) showed that MCB could stabilise top-of-the-atmosphere radiative forcing, i.e. maintain global mean temperatures at 2020 levels[355,356]. Cloud formation was enhanced in low latitudes over both ocean and land, and whilst the localized cooling decreased precipitation over the ocean it increased precipitation over low-latitude land regions. Another multi-model study[357] 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.

164. Other studies have shown the sensitivity of the response to whether CCN are added to maximise direct effects (cloud formation) in clear skies, or whether to maximise indirect effects (cloud brightness and longevity) on existing low clouds[358]; 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[359]. It has been proposed[360] that greater specificity in the areas where MCB is applied might provide specific

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[354] Latham J, Bower K, Choularton T, Coe H et al. (2012) Marine cloud brightening. *Philosophical Transactions of the Royal Society A* 370, 4217-4262

[355] Kravitz B, Forster PM, Jones A, Robock A et al. (2013) Sea spray engineering experiments in the geoengineering model intercomparison project (GeoMIP): Experimental design and preliminary results. *J. Geophys. Res. Atmos.*, 118, 11175-11186; doi: 10.1002/jgrd.50856

[356] Alterskjær K., Kristjánsson J.E., Boucher O., Muri H. *et al* (2013) Sea-salt injections into the low-latitude marine boundary layer: The transient response in three Earth system models. *J. Geophys. Res. Atmos.*, 118, 12,195–12,206, doi: 10.1002/2013JD020432.

[357] Muri H, Niemeier U & Kristjánsson (2015) Tropical rainforest response to marine sky brightening climate engineering. *Geophysical Research Letters* 42, 2951-2960; doi: 10.1002/2015GL063363

[358] Jones A. & Haywood J. M. (2012) Sea-spray geoengineering in the HadGEM2-ES Earth-system model: radiative impact and climate response, *Atmos. Chem. Phys.*, 12, 10887-10898, doi: 10.5194/acp-12-10887-2012.

[359] Baughman E., Gnanadesikan A., Degaetano A. & Adcroft A. (2012) Investigation of the surface and circulation impacts of cloud-brightening geoengineering. *J. Climate* 25, 7527-7543; doi: 10.1175/JCLI-D-11-00282.1

[360] Latham J, Gadian A, Fournier, Parkes B et al. (2014) Marine cloud brightening: regional applications. *Philosophical Transactions of the Royal Society A*, 372, 20140053; doi: 10.1098/rsta.2014.0053

regional benefits; in particular, to reduce coral bleaching[361] and weaken hurricanes[362], and potentially to stabilise the West Antarctic ice sheet, and prevent the loss of Arctic sea-ice. The effectiveness of the technique may be reduced in polar regions (since existing cloud cover and CCN concentrations can be 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[363].

165. Technical issues that need to be resolved for MCB include those relating to optimum particle size distributions[364,365], cloud droplet number[366]; the modelling of aerosol water[367,368], and effects of timing and injection rate[369]. Variability in meteorological conditions (wind speed and boundary layer stability) may greatly reduce the effectiveness of the technique[370,371]. 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[372]. The impacts of the 2-6 fold increase in atmospheric salt loading over tropical land areas is an additional factor requiring consideration[373], since salt stress on vegetation can have significant socio-economic implications[374].

4.4 Surface albedo modification

166. **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[375], whilst 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

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[361] Latham J, Kleypas J, Hauser R, Parkes B & Gadian A (2013) Can marine cloud brightening reduce coral bleaching? *Atmospheric Science Letters* 24, 214-219; doi: 10.1002/asl2.442

[362] Latham J, Parkes B, Gadian A & Salter S (2012) Weakening of hurricanes via marine cloud brightening (MCB). *Atmospheric Science Letters.*, 13, 231-237 ; doi: 10.1002/asl.402

[363] Kravitz B, Wang HL, Rasch PJ, Morrison H & Solomon AB (2014) Process-model simulations of cloud-albedo enhancement by aerosols in the Arctic. *Philosophical Transactions of the Royal Society A*, 372, 20140052; doi: 10.1098/rsta.2014.0052

[364] Alterskjær K. & Kristjánsson J.E. (2013) The sign of the radiative forcing from marine cloud brightening depends on both particle size and injection amount. *Geophyical Research Letters*, 40, 210-215; doi: 10.1002/grl.50117.

[365] Connolly PJ, McFiggans GB, Wood R & Tssiamis A (2014) Factors determining the most efficient spray distribution for marine cloud brightening. *Philosophical Transactions of the Royal Society A*, 372, 20140056; doi: 10.1098/rsta.2014.0056

[366] Pringle KJ, Carslaw KS, Fan T, Mann GW et al. (2012) A multi-model assessment of the impact of sea spray geoengineering on cloud droplet number. *Atmospheric Chemistry & Physics*, 12, 11647-11663.

[367] Jenkins A.K.L. & Forster P.M. (2013) The inclusion of water with the injected aerosol reduces the simulated effectiveness of marine cloud brightening. *Atmospheric Science Letters* 14, 164-9

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[370] Alterskjær K., Kristjánsson J.E. & Seland Ø. (2012) Sensitivity to deliberate sea salt seeding of marine clouds – observations and model simulations. *Atmospheric Chemistry &. Physics* 12, 2795-2807.

[371] Stuart G.S., Stevens R.G., Partanen A.-I. *et al* (2013) Reduced efficacy of marine cloud brightening geoengineering due to in-plume aerosol coagulation: parameterization and global implications. *Atmospheric Chemistry &. Physics* 13, 10385-10396

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[373] Muri H, Niemeier U & Kristjánsson (2015) Tropical rainforest response to marine sky brightening climate engineering. *Geophysical Research Letters* 42, 2951-2960; doi: 10.1002/2015GL063363

[374] Qadir M, Quillérou E, Nangia V, Murtaza G et al. (2014) Economics of salt-induced land degradation and restoration. *Natural Resources Forum*,38, 282-295

[375] Jackson LS, Crook JA, Osprey SM & Forster P (2014) A comparison of geoengineering methods: assessment of precipitation side effects. AGU Fall Meeting 2014, abstract #GC13I-0779; http://adabs.harvard.edu/abs/2014AGUFMGC13I0779J

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)[376]. Worldwide white-roof conversion could have a greater effect on climate through an increase in energy demand than through albedo cooling[377]; however, if restricted to areas where more energy is used for cooling (air conditioning) than domestic heating, a minor net benefit could be achieved for urban areas, by reducing the "heat island" effect in cities.

167. **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[378]. Whilst 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).

168. 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[379]. 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

169. 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.

170. 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[380]. Potential global cooling of ~1.4°C has been estimated[381] 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; whilst under-

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[376] Bala G & Nag B (2012) Albedo enhancement over land to counteract global warming: impacts on hydrological cycle. *Climate Dynamics* 39, 1527-1542

[377] Jacobson MZ & Ten Hoeve JE (2012) Effects of urban surfaces and white roofs on global and regional climate. *Journal of Climate* 25, 1028-1044

[378] Aziz A, Hailes HC, Ward JM & Evans JRG (2014) Long-term stabilization of reflective foams in sea water. *RSC Advances* 4, 53028-53036

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[380] Mitchell DL & Finnegan W (2009*)*, Modification of cirrus clouds to reduce global warming, Environ. Res. Lett. 4, doi:10.1088/1748-9326/4/4/045102

[381] Sorelvmo T, Boos WR & Herger N (2014) Cirrus cloud seeding: a climate engineering mechanism with reduced side effects? *Philosophical Transactions of the Royal Society A*, 372, 20140116; doi: 10.1098/rsta.2014.0116

seeding would have no effect, over-seeding could prolong cirrus lifetime and accelerate global warming[382].

171. Proposed seeding materials include mineral dust particles and bismuth tri-iodide (BiI3), a non-toxic and relatively inexpensive compound previously considered as an ice nucleant for weather modification[383]. 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[384]. However, the environmental implications of this technique have yet to be assessed.

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[382] Storelvmo T, Kristjansson JE, Muri H, Pfeffer M *et al.* (2013) Cirrus cloud seeding has potential to cool climate. *Geophysical Research Letters*, 40, 178-182; doi: 10.1029/2012 GL054201

[383] Mitchell DL & Finnegan W (2009), Modification of cirrus clouds to reduce global warming, *Environmental Research Letters* 4, doi:10.1088/1748-9326/4/4/045102

[384] Jackson LS, Crook JA, Osprey SM & Forster P (2014) A comparison of geoengineering methods: assessment of precipitation side effects. AGU Fall Meeting 2014, abstract #GC13I-0779; http://adabs.harvard.edu/abs/2014AGUFMGC13I0779J

Chapter 5. SOCIO-ECONOMIC AND CULTURAL CONSIDERATIONS RELATING TO CLIMATE GEOENGINEERING

5.1 Introduction

172. 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 around 200 recent publications identified. Only representative papers are cited here; a more comprehensive listing is provided in Annex 1.

173. Despite that apparent wealth of information and analyses, four imbalances should be noted, with 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). When carbon dioxide removal (CDR) is given attention, it is usually in terms of ocean fertilization. The spectrum of other approaches, particularly those involving land-based carbon dioxide removal – also with societally-important issues regarding ethics, equity, governance and economics – has been relatively neglected.

- 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[385,386]. A truly global perspective on relevant values and cultural considerations is therefore lacking, with the discussion process "… riddled with Euro-American biases about legitimate decision-making procedures, management strategies and knowledge"[387]. Only limited effort has been made to stimulate full international dialogue in this topic area[388], and, at times, the voice of indigenous peoples, can be misrepresented[389].

- 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[390]. Whilst life cycle assessments have also used to provide a more holistic approach, these do not necessarily take account of all associated risks and uncertainties[391].

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[385] Belter CW & Seidel DJ (2013) A bibliometric analysis of climate engineering research. *Wiley Interdisciplinary Reviews: Climate Change* 4, 417-427; doi: 10.1002/wcc.229

[386] Oldham P, Szerszynski B, Stilgoe J, Brown C, Eacott B & Yuille A (2014) Mapping the landscape of climate engineering. *Philosophical Transactions of the Royal Society A*, 372, article 20140065; doi: 10.1098/rsta.2014.0065.

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[389] Buck HJ (2014) *Village Science Meets Global Discourse: The Haida Salmon Restoration Corporation's Ocean Iron Fertilization Experiment*. Case Study, Geoengineering Our Climate Working Paper and Opinion Article Series. http://wp.me/p2zsRk-9M

[390] Schäfer S, Maas A & Irvine PJ (2013) Bridging the gaps in interdisciplinary research on solar radiation management. *Gaia Ecological Perspectives for Science & Society* 22, 242-247

[391] Plevin RJ, Delucchi MA & Creutzig F (2013) Using attributional life cycle assessment to estimate climate-change mitigation benefits misleads policy makers. *Journal of Industrial Ecology* 18, 73-83

- With a few exceptions[392], social science research on geoengineering has developed in isolation from natural science studies, resulting in polarization of views rather than a transdisciplinary[393] approach to problem-solving.

The seven key messages relating to socio-economic 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, with additional comments.

Key message (text originally in bold; re-numbered)	Comments
1. The consideration of geoengineering as a potential option raises many socio-economic, cultural and ethical issues, regardless of the specific geoengineering approach.	Main issues remain global justice, the unequal spatial distribution of impacts and benefits, and intergenerational equity.
2. Humanity is now the major force altering the planetary environment.	IPCC AR5 has confirmed the unprecedented scale of human pressures on natural systems
3. The 'moral hazard' of geoengineering is that it is perceived as a technological fallback, possibly reducing effort on mitigation.	Geoengineering and mitigation no longer considered as alternatives: both now seem necessary to avert dangerous climate change.
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.	Direct air capture of CO_2 would seem to have low environmental risks and socio-political consequences – the problem is its cost.
5. An additional issue is the possibility of technological, political and social "lock in",	Current 'lock in' is to dangerous climate change.
6. Geoengineering raises a number of questions regarding the distribution of resources and impacts within and among societies and across time	These risks undoubtedly exist for both CDR and SRM techniques, yet also occur for climate change itself.
7. In cases in which geoengineering experimentation or interventions might have transboundary effects or impacts on areas beyond national jurisdiction, geopolitical tensions could arise	International regulation and oversight recognized as necessary for all activities that might have significant risk of adverse transboundary impacts.

5.2 Framing and discourse analysis

174. 'Epistemological responsibility' has as much meaning to a natural scientist as 'drop-volume-dependent-parametrization' does to a social scientist. Disciplinary backgrounds determine vocabularies; they also shape thinking, values and interpretation. 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. Different frames are used, knowingly or unknowingly, by researchers, politicians and the media as storylines to "amplify different priorities and values"[394] : an understanding of their assumptions and cultural context is therefore not just an academic exercise, but has fundamental implications for communications and decision-making in this controversial policy area[395,396]. Many framings are possible, with emphases on different aspects; Table 5.1 summarises a recent review[397], with focus on considerations given greatest attention by social scientists.

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[392] Schäfer S, Lawrence M, Stelzer H, Born W et al.(2015) *The European Transdisciplinary Assessment of Climate Engineering (EuTRACE): Removing Greenhouse Gases from the Atmosphere and Reflecting Sunlight away from Earth*. 169 pp; http://www.iass-potsdam.de/de/publikationen/projektberichte

[393] Lang DJ, Wiek A, Bergmann M, Stauffacher et al (2012) Transdisciplinary research in sustainability science. Practice, principles and challenges. *Sustainability Science* 7, 25-43; doi: 10.1007/s11625-011-0149-x

[394] Porter KE & Hulme M (2013) the emergence of the geoengineering debate in the UK print media: a frame analysis. *The Geographical Journal* 179, 342-355

[395] Cairns R & Stirling A (2014) 'Maintaining planetary systems' or 'concentrating global power'? High stakes in contending framings of climate geoengineering. *Global Environmental Change* 25-38.

Table 5.1 Framing for generic climate geoengineering, based on Kreuter (2015) (where 'climate engineering' was used instead of geoengineering). Note that aspects discussed are most applicable to atmospheric SRM.

Frame	Comments
1. Solution to the political problem of climate change (over-arching framing)	Policy option framing, either as directly equivalent to mitigation and adaptation, or more frequently, providing an imperfect substitute for emissions reductions, i.e. an 'insufficient mitigation' scenario. [As now indicated by IPCC AR5: without geoengineering, dangerous climate change is (near-) inevitable].
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, as "lesser of two evils"
3. Source of detrimental societal impacts	'Moral hazard' framing: attention given to geoengineering reduces effort on mitigation and adaptation, whilst 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"[398]
4. Driver of transboundary conflict	Danger of unequal distribution of unintended side effects and/or unilateral action threatens international security
5. Arena of political interactions, both between states and within societies	Geoengineering provides opportunities for political advantage in a "global thermostat game"[399], and for personal gain by "special interests, including private corporations, conservative think tanks and scientists affiliated with both"[400]
6. Technology framing	Idea of technofix: "the consistent application of science and technology is humanity's greatest hope for improving human life"[401] – 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"[402]
7. Moral consideration	Ethical questions involving arguments of right and wrong, in context of respect, beneficence and justice. Geoengineering is widely considered by 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

175. Discourse analyses of geoengineering in the news media have examined the use of metaphors (war, controllability and health)[403] and a wider range of frames (innovation, risk, governance and accountability, economics, morality, security and justice)[404]; they have also identified an opening-up of the debate in English-language newspapers[405]. A recent analysis[406] of 114 policy documents relating to

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[396] Huttunen S & Hildén M (2014) Framing the controversial: Geoengineering in academic literature. *Science Communication* 36, 3-29

[397] Kreuter J (2015) *Technofix, Plan B or Ultima Ratio? A Review of the Social Science Literature on Climate Engineering Technologies*. Occasional Paper #2, Institute for Science, Innovation and Society, University of Oxford. http://dev.cam.ox.ac.uk/fileadmin/InSIS/Newsletter/CE_Literature_Review_Judith_Kreuter.pdf

[398] Szerszynski B, Kearnes M, Macnaghten P, Owen R & Stilgoe J (2013) Why solar radiation management geoengineering and democracy won't mix. *Environment & Planning A* 45, 2809-2816

[399] Ricke K, Moreno-Cruz J & Caldeira K (2013) Strategic incentives for climate geoengineering coalitions to exclude broad participation. *Environment Research Letters* 8, 1-8

[400] Sikka T (2012a) A critical discourse analysis of geoengineering advocacy. *Critical Discourse Studies* 9, 163-175

[401] Scott D (2013) *Philosophy of Technology and Geoengineering*. Geoengineering Our Climate Working Paper and Opinion Article Series. Online at: http://wp.mep2zsRk-66

[402] Sikka T (2012b) A critical theory of technology applied to the public discussion of geoengineering. *Technology in Society* 34, 109-117

[403] Luokkanen M., Huttunen S. & Hildén M. (2013) Geoengineering, news media and metaphors: Framing the controversial. *Public Understanding of Science*. doi: 10.1177/0963662513475966.

[404] Porter K. E. & M. Hulme (2013) The emergence of the geoengineering debate in the UK print media: a frame analysis. *Geographical Journal*, 179, 342-355; doi: 10.1111/geoj.12003

[405] Scholte S., Vasileiadou E. & Petersen A.C. (2013) Opening up the societal debate on climate engineering: how newspaper frames are changing. *J. Integrative Environ. Sci.*, 10, 1-16. doi: 10.1080/1943815x.2012.759593.

geoengineering published between 1997 and 2013 showed that concerns were dominated by technical and risk-related issues; hopes related to new solutions to climate change; and action proposals emphasized the need for further research.

176. 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, climate intervention as either unworkable[407], unethical[408], naive[409], overly profit-driven[410] or undemocratic[411]. The question has been also raised as whether social science expertise should be influencing public opinion, rather than reflecting it[412].

177. Framing based on tipping points and climate emergencies has attracted particular interest[413,414] – and criticism by some, who reject the concept of 'exceptionalism' in the context of climate change[415]. 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[416]. 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.

178. Nevertheless, the Earth's climate system is susceptible to threshold behaviour[417]: abrupt changes can occur in response to gradual forcing[418], and post-AR5 analyses of the (in)stability of the Greenland[419] and East Antarctic ice sheets[420] give cause for concern – justifying the concept of exceptionalism with regard to the current and projected rates of climate change, at least within the past 10,000 years[421]. .

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[406] Huttunen S, Skytén E & Hildén M (2015) Emerging policy perspectives on geoengineering: an international comparison. *The Anthropocene Review* 2, 14-32

[407] Hulme M (2014) *Can Science fix Climate Change? A Case against Climate Engineering*. Polity Press, Cambridge

[408] Gardiner SM (2013) The desperation argument for geoengineering. *Political Science and Politics* 46, 28-33

[409] Hamilton C (2013) No, we should not just 'at least do the research'. *Nature* 139, 139

[410] Sikka T (2012a) A critical discourse analysis of geoengineering advocacy. *Critical Discourse Studies* 9, 163-175

[411] Macnaghten P & Szerszynski B (2013) Living the global social experiment: An analysis of public discourse on solar radiation management and its implications for governance. *Global Environmental Change* 23, 465-474.

[412] Heyward C & Rayner S (2013) *A Curious Asymmetry: Social Science Expertise and Geoengineering*. Climate Geoengineering Governance Working Paper Series 007; online at http://geoengineeringgovernanceresearch.org

[413] Markusson N, Ginn F, Ghaleigh NS & Scott V (2013) 'In case of emergency, press here': framing geoengineering as a response to dangerous climate change. *Wiley Interdisciplinary Reviews: Climate Change* 5, 281-290; doi: 10.1002/wcc.263

[414] Barrett S, Lenton TM, Millner A, Tavoni A et al (2014) Climate engineering reconsidered. *Nature Climate Change* 4, 527-529; doi: 10.1038/nclimate2278

[415] A critical discourse analysis of geoengineering advocacy. *Critical Discourse Studies* 9, 163-175

[416] Sillmann J, Lenton TM, Levermann, Ott K et al. (2015) Climate emergencies do not justify engineering the climate. *Nature Climate Change* 5, 290-292

[417] Good P, Lowe J, Ridley J, Bamber J et al. (2014) *Post-AR5 An Updated view of Tipping Points and the Relevance for Long-term Climate Goals.* AVOID2 programme on avoiding dangerous climate change. AVOID2 WPA Report 1; DECC, London. 61 pp. http://www.avoid.uk.net/downloads/avoid2/AVOID2_WPA5_v2_final.pdf

[418] Weber ME, Clark PU, Kuhn G, Timmerman A et al (2014) Millennial-scale variability in Antarctic ice-sheet discharge during the last deglaciation. *Nature* 510, 134-138; doi: 10.1038/nature13397

[419] Enderlin EM, Howat IM, Jeong S, Noh M-J et al (2014) An improved mass budget for the Greenland ice sheet. *Geophysical Research Letters* 41, 866-872

[420] Favier L, Durand G, Cornford SL, Gudmundsson et al. (2014) Retreat of Pine Island Glacier controlled by marine ice-sheet instability. *Nature Climate Change* 4, 117-121

[421] McNeall D, Halloran PR, Good P & Betts RA (2011) Analyzing abrupt and nonlinear climate changes and their impacts. *Wiley Interdisciplinary Reviews: Climate Change* 2, 663-686

5.3 Public engagement

179. The technological nature of geoengineering, particularly atmospheric SRM, is considered by some to make it inherently undemocratic[422]. Public engagement addresses that concern, as it includes affected parties in democratic decision-making processes[423]. It also contributes to the improved dialogue and trust between scientists and public; ensures that decisions about geoengineering research and possible deployment are informed by a broad set of societal interests, values and framings; and contributes to a 'collective experimentation' approach to geoengineering governance[424].

180. Recent public surveys and more structured dialogues have been carried out in the US[425], UK[426,427,428] Germany[429] and Australia and New Zealand[430]. The geographical and cultural bias in that coverage is obvious – yet it is necessary for those engaged in those discourses to know something about what is being discussed in order to have views and opinions. In many cases, additional information is presented, raising concerns that authors' framing may, in some cases, have unduly shaped public responses. Nevertheless, there was relatively consistency in results from all those surveys: i) an overall negative evaluation of geoengineering as a policy response to climate change; and ii) the perceived naturalness of a technique (that may depend on the way it is described) strongly influences its acceptability, with CDR favoured over SRM.

181. The 'cultural cognition' theory is relevant here: 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[431] to be less likely to be sceptical 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 citizens with hierarchical and individualistic values were made aware of geoengineering research, they reacted less dismissively to the climate change study; i.e. the opposite of the 'moral hazard' argument[432] that has been used to suggest that consideration of geoengineering as a climate policy option reduces the credibility of more direct mitigation action.

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[422] Szerszynski B, Kearnes M, Macnaghten P, Owen R & Stilgoe J (2013) Why solar radiation management geoengineering and democracy won't mix. *Environment & Planning A* 45, 2809-2816

[423] Carr WA, Preston CJ, Yung L, Szerszynski B et al. (2013) Public engagement on solar radiation management and why it needs to happen now. *Climatic Change* 121, 567-577

[424] Stilgoe J (2015) Geoengineering as collective experimentation. *Science & Engineering Ethics* (online) doi: 10.1007/s11948-015-9646-0

[425] Borick C. & Rabe B.G. (2012) Americans cool on geoengineering approaches to addressing climate change. *Issues in Governance Studies* 47, 1-6

[426] Corner A., Parkhill K. Pidgeon N. & Vaughan N.E. (2013) Messing with nature? Exploring public perceptions of geoengineering in the UK. *Global Environ. Change* 23, 938-947; doi: 10.1016/ j.gloenvcha.2013

[427] Bellamy R (2015) A sociotechnical framework for governing climate engineering. *Science, Technology & Human Values* (online) doi: 10.1177/0162243915591855

[428] Macnaghten P & Szerszynski B (2013) Living the global social experiment: An analysis of public discourse on solar radiation management and its implications for governance. *Global Environmental Change* 1, 59-68

[429] Merk C, Pönitzsch G, Kniebes C, Rehdanz K & Schmidt U (2015) Exploring public perceptions of stratospheric sulfate injection. *Climatic Change* (online); doi: 10.1007/s10584-014-1317-7

[430] Wright M. J., Teagle D. A. H. & Feetham P. M. (2014) A quantitative evaluation of the public response to climate engineering. *Nature Climate Change*, 4, 106-110. doi: 10.1038/nclimate2087

431 Kahan DM, Jenkins-Smith HC, Tarantola T, Silva CL & Braman D (2015) Geoengineering and climate change polarization: testing a two-channel model of science communication. *Annals of American Academy of Political and Social Science*, 658, 193-222

[432] Hale B (2012) The world that would have been: moral hazard arguments against geoengineering. In: *Engineering the Climate: The Ethics of Solar Radiation Management* (Ed C.J. Preston), Chapter 7, p 113-131. Lexington Books/Rowman & Littlefield, Lanham MD

Chapter 6. REGULATORY FRAMEWORK

6.1 Regulatory status at the time of the previous CBD report on geoengineering

182. 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 **10th meeting of the CBD Conference of the Parties (COP-10)** had, in decision X/33, addressed the broader concept of geoengineering at an international regulatory level.

183. 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. Research was 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. 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

184. Since the publication of CBD (2012), an important recent development relates to the London Convention and 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[433]. 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.

185. 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 45

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[433] On the amendment see e.g. Ginzky and Frost (2014) and Schäfer et al (2015) p. 86-88; for the regulatory history and broader regulatory context see Scott (2013), Regulating ocean fertilization, p. 116

Contracting Parties to the London Protocol[434] have deposited an instrument of acceptance of the amendment with the International Maritime Organization. As of 14 July 2015, the amendment has not received any ratification and has not entered into force[435]. 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.

186. The **2007 amendment to the OSPAR Convention** which allows storage of carbon dioxide in geological formations under the seabed of the North-East Atlantic[436] entered into force in July 2011 and is currently in force for 11 of the 16 OSPAR parties[437].

6.2.2 11th CBD Conference of the Parties (COP-11)

187. 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[438]. This is the first clear statement by the CBD COP, in the context of geoengineering, that conventional mitigation action should be the priority.

188. 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[439]. 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.

189. In decision X/33 Parties were also invited to report on measures undertaken in accordance with paragraph 8(w) of that decision. The Executive Secretary was requested to make available the information through the CBD clearing-house mechanism[440]. So far only few submissions were received[441].

6.2.3 Intergovernmental Panel on Climate Change and UNFCCC

190. The publication of **IPCC AR5** was a further important development, as it also touched upon governance issues relating to geoengineering[442]. It briefly lists some existing international instruments that “may be relevant” to geoengineering, albeit without analysis or assessment[443]. In this respect it does not add to or call into question the findings of the original CBD (2012) report.

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[434] 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 14 July 2015; http://www.imo.org/en/About/Conventions/StatusOfConventions/Pages/Default.aspx.

[435] 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 14 July 2015; http://www.imo.org/en/About/Conventions/StatusOfConventions/Pages/Default.aspx.

[436] See CBD (2012), key message 17 and p. 133-134.

[437] The amendment is currently in force for Norway, Germany, United Kingdom, Spain, European Union, Luxembourg, Denmark, Netherlands, Finland, Sweden and France. On developments relating to CCS under the London Protocol see Dixon et al (2014).

[438] CBD COP decision XI/20 para 4.

[439] CBD COP decision XI/20 para 8.

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

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

[442] In particular WGIII p. 487-490 and 1022-1023. On geoengineering in the IPCC see Petersen (2014).

[443] IPCC AR5 WGIII p. 1023.

191. 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[444]. The spatial and temporal redistribution of risks raises additional issues of intra-generational and inter-generational justice[445], 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[446].

192. 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 CO2 concentrations[447]. 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[448].

193. Under the **UNFCCC**, a technical paper by the Secretariat noted that many of the IPCC’S AR5 scenarios rely on CDR, and the findings on AR5 regarding BECCS[449]. This has so far not been specifically taken up in the deliberations of other UNFCCC bodies. However, in the negotiations towards a new climate agreement, envisaged to be adopted at COP21 in Paris at the end of 2015, there are options in the negotiating text for including obligations regarding “negative emissions”: One option specifies an obligation for all parties to take action towards an emission pathway consistent with staying below 2 or 1.5°C. This obligation would specifically entail: “Ensuring significant and rapid global greenhouse gas emission reductions of at least 70-95 per cent below 2010 levels by 2050 and negative emissions of CO_2 and other long-lived greenhouse gases before 2080”[450]. Another option specifies that differentiated efforts by parties would take the form of a long-term zero emission sustainable development pathway “[c]onsistent with carbon neutrality / net zero emissions by 2050, or full decarbonization by 2050 and/or negative emissions by 2100 [for developed countries][451]. While terminology is not used consistently, these options presumably refer to the IPCC’s concept of “net negative emissions”[452] and could thus refer to CDR.

6.2.4 Other recent reports and literature

194. Recent reports and literature[453] suggest that a one-size-fits-all approach to geoengineering governance is neither desirable nor feasible. Instead, regulatory mechanisms should follow a **functional**

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[444] IPCC AR5 Synthesis report p. 89; WGIII p. 1023.

[445] IPCC AR5 Synthesis report p. 89; WGIII p. 488.

[446] IPCC AR5 WGIII p. 489.

[447] IPCC AR5 Synthesis report p. 89, 123.

[448] IPCC AR5 Synthesis report p. 89, 123

[449] 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).

[450] Geneva negotiating text, FCCC/ADP/2015/1 of 25 February 2015, para 5.1 option (d). Also contained in the informal Streamlined and consolidated text Version of 11 June 2015 @ 16:30, available at http://unfccc.int/meetings/bonn_jun_2015/session/8857.php, last accessed on 7 July 2015.

[451] Geneva negotiating text, FCCC/ADP/2015/1 of 25 February 2015, para 5.1 option (d). Also contained in the informal Streamlined and consolidated text Version of 11 June 2015 @ 16:30, available at http://unfccc.int/meetings/bonn_jun_2015/session/8857.php, last accessed on 7 July 2015.

[452] Defined by IPCC AR5 as “A situation of net negative emissions is achieved when, as result of human activities, more greenhouse gases (GHGs) are sequestered or stored than are released into the atmosphere”, IPCC AR5, Synthesis report, p. 125.

[453] See for instance the draft bibliography on geoengineering governance at http://dcgeoconsortium.org/ce-governance-bibliography/;

approach that takes into account the significant differences in the geoengineering activities proposed[454]. In addition, not all issues would be suitable for, or need to be addressed at the *international* level[455]. One commonly accepted function for international regulatory mechanisms and governance would be to address activities that have the potential to cause significant transboundary harm[456]. There has also been a interest in the explicit or underlying political functions addressed by geoengineering governance, for instance by distinguishing scientific input from political decision-making[457]. 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"[458].

195. 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[459]. 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 regulatory issues at the international level. However most statements on governance in IPCC AR5 specifically address SRM, while simply noting governance implications of large scale CDR[460]. The governance implications of potential international issues arising from large-scale BECCS[461] have so far not been specifically addressed by the international regulatory framework[462] or in literature.

196. 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[463],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[464]. Some authors argue in favour of the UNFCCC as the main or even sole forum for addressing geoengineering[465], as it has a more direct mandate regarding climate change, and because of 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

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[454] Bodle et al (2014), section 6.3 and p.151; also p. 176-185; Keith (2014); Armeni and Redgwell (2015), International legal and regulatory issues; p. 4; Schäfer et al (2015) p. 89-90; see also Rayner et al (2013) in the context of the function of the "Oxford Principles".

[455] Bracmort et al (2013) p. 29; Bodle et al (2014) p. 126, 136. On the Canadian domestic regulatory framework in relation to the "HSRC" ocean fertilisation experiment see e.g. Craik et al (2013); Wilson (2014).

[456] CBD decision XI/20; Brent and McGee (2012) p. 11; Chalecki and Ferrari (2012) p.126; Bodle et al (2014) p.127; Galaz (2012), 28; see also Owen (2014) p. 230 on shortcomings of the focus on physical risk; Lin (2015) specifically on research.

[457] Bodle (2013); Winickoff et al (2015); US National Academy of Sciences (2015), p. 12.

[458] Markusson et al (2014); Sillmann et al (2015).

[459] Cf. Ricke et al (2013); Owen (2014); Keith (2014) p. 5; Bodle et al (2014); US National Academy of Sciences (2015) p. 13.

[460] See e.g. WGIII p. 1022-1023.

[461] See Schäfer et al (2015) p. 116.

[462] Cf. Bodle et al (2014), p. 102-103 and Schäfer et al (2015) p. 84-85 and 117 for an overview of existing international governance for land use and land use change, which under the UNFCCC is mainly addressed through accounting rules.

[463] See discussion of recent proposals in Barret (2014); Bracmort et al (2013) p. 29; Bodansky (2013); Garg (2014); Kuokkanen and Yamineva (2013) p. 165; Schäfer et al (2015) p. 89-90.

[464] Armeni and Redgwell (2015), International legal and regulatory issues, p. 6; cf. CBD (2012) p. 147.

[465] Lin (2009), p.18; Scott (2013), International law in the anthropocene, p. 355; Rickels et al (2011); Honegger et al (2013); Branson (2014). 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, IPCC AR5 WG III p. 103.

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 fertilisation[466]. However, they could be regarded as less suitable fora for broader debates[467].

197. Against this background, there is **no clear "centre of gravity"** in the existing international governance[468] - but there might also be no need for it if the regulatory landscape functions as a "patchwork quilt"[469]. 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[470]. However, this approach has limitations[471], and gaps in the regulatory framework would remain.

198. 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[472]. Arguments in favour include that experiments could pose physical risks and that research has wider, including political implications[473]. It has also been argued that governance can have an enabling function for "safe and useful" research[474]. The London Protocol's concept of "legitimate scientific research" underlying the 2013 amendment[475] can be seen in this context. Proposals have been put forward for tiered approaches to governing research activities according to their nature and scale[476].

199. Apart from general principles[477], **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[478]. One potentially emerging lesson could be that traditional environmental assessments might be unsuitable to address the challenges posed by geoengineering activities[479]. 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[480]. In

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[466] Markus & Ginzky (2011); Williamson (2012) p. 484; Schäfer et al (2015) p. 90. On ocean upwelling see Proelss and Chang (2012).

[467] Scott (2013), Regulating ocean fertilizaton, p. 116.

[468] Bodle et al (2014).

[469] Armeni and Redgwell (2015), International legal and regulatory issues; p. 6.

[470] Schäfer et al (2015) p. 90 and 114.

[471] Kuokkanen and Yamineva (2013) p. 165-166.

[472] See e.g. Dilling and Hauser (2012); IPCC AR5 WGIII p. 61, 489; Bodle et al (2014) p. 140-143; Gosh (2014); Parker (2014); Parson and Keith (2013) with response by Hamilton (2013); Keith et al (2014); Reynolds (2014); Armeni and Redgwell (2015), International legal and regulatory issues; p. 32; Healey and Rayner (2015), p. 18; Hubert and Reichwein (2015); Lin (2015); US National Academy of Sciences (2015) p. 12.

[473] Parson (2014) section 3.3; See e.g. Bodle et al (2014) p. 141; Lin (2015) p. 14; Schäfer et al (2015) p. 58 et seq. See also Craik et al (2013).

[474] US National Academy of Sciences (2015) p. 12.

[475] See London Protocol resolution LP.4(8) of 18 October 2013, para 3 and new Annex 4, para 1.3.

[476] E.g. Parson and Keith (2013); Parker (2015) p. 13-14; US National Academy of Sciences (2015) p. 12 - in favour of differentiated approach, but without specific proposal.

[477] See overview in Schäfer et al (2015), 108-111.

[478] See e.g. Whyte (2012a); Craik and Moore (2014); Healey (2014); Owen (2014); see also Winickoff and Brown (2013) arguing for a national Government Advisory Committee for Geoengineering Research in the US.

[479] See e.g. Craik et al (2013) p. 124; Blackstock et al (2015).

[480] See e.g. African Academy of Sciences and Solar Radiation Management Governance Initiative (2013), p. v.; Winickoff and Flegal (2015).

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[481].

200. These developments relate to key messages 10, 12, 13, 17, 25 and 26 from the earlier report (CBD, 2012, part II), 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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[481] Hester (2013), Remaking the world; Bracmort et al (2013) for the US; Craik et al (2013) on Canada; Armeni et al (2015) Geoengineering Under National Law: A Case Study Of The United Kingdom, for the UK; Bodle et al (2014) section 5.2-5.3 for EU and Germany; Schäfer et al (2015) p. 82 et seq for the EU; Armeni and Redgwell (2015), Geoengineering Under National Law: A Case Study Of Germany.

Chapter 7. SYNTHESIS AND CONCLUSIONS

201. The 5th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR5) shows beyond doubt that the Earth's climate is warming, and that emissions of greenhouse gases from human activities are responsible. Unless action is taken to limit future emissions, global surface temperature are expected to increase by around 4°C within our children's lifetimes, with longterm future sea level being several metres higher than it is today. Those changes will have very many extremely serious consequences for the habitability of the planet, affecting all life on land and in the ocean.

202. To avert such dangers, there is international agreement that future global temperature increase should be no greater than 2°C, recognising that an increase of ~1.5°C would also present many risks. The former goal requires extremely challenging emission reductions, by all countries, as a matter of urgency; furthermore, even with such emissions reductions and safeguarding of natural carbon sinks, it now seems highly likely that active removal of greenhouse gases from the atmosphere would also be required[482], i.e. a form of climate geoengineering.

203. The geoengineering method proposed in IPCC AR5 is large-scale bioenergy with carbon capture and storage (BECCS). That technique would provide 'negative emissions' of CO_2, considered by IPCC to be a form of mitigation. The large-scale BECCS deployment envisaged by IPCC 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 reducing the cost of their phase-out. IPPC AR5 considered – in considerable detail – the impacts of climate change (Working Group II report). What it did not do was to similarly consider the impacts of large-scale BECCS, particularly with regard to land-use change and biodiversity.

204. The information currently available indicates that the proposed large-scale BECCS deployment would be extremely damaging for terrestrial biodiversity, due to its very large land use requirements. Furthermore, many of the assumptions regarding the effectiveness and scalability of BECCS are highly uncertain.

205. Under such circumstances it would seem necessary that appropriate national and international effort should be made to:

- Achieve faster global-scale transformation to zero-carbon energy than currently envisaged
- Urgently re-assess the planetary limits (including implications for land-use, biodiversity and food and water security, as well as socio-economic consequences) for sustainable BECCS deployment
- Carry out research to develop alternative means of greenhouse gas removal, *inter alia* investigating the quantitative scope and impacts of carbon sequestration through biochar and enhanced weathering techniques, and for improvements in the cost-effectiveness of direct air capture.

206. The above research recommendations are considered consistent with the recent European[483] and US reports[484,485] on climate geoengineering. Research will, however, need to carried out in accordance with CBD decision XI/20, without risk of significant transboundary impacts, and with emphasis on:

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[482] Gasser T, Guivarch C, Tachiiri K, Jones CD & Ciais P (2015) Negative emissions physically needed to keep global warming below 2˚C. *Nature Communications* 6, 7958; doi: 10.1038/ncomms8958

[483] Schäfer S, Lawrence M, Stelzer H, Born W et al. (2015) *The European Transdisciplinary Assessment of Climate Engineering (EuTRACE): Removing Greenhouse Gases from the Atmosphere and Reflecting Sunlight away from Earth*. 169 pp; http://www.iass-potsdam.de/de/publikationen/projektberichte

[484] National Academy of Sciences (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

- How biodiversity and ecosystem services are likely to be affected by and respond to geoengineering activities (such as those described above) at different geographic scales
- The intended and unintended effects of different possible geoengineering technique (at a technique specific level) on biodiversity
- The socio-economic, cultural and ethical issues associated with possible geoengineering techniques, including the unequal spatial and temporal distribution of impacts.

207. Research issues (rather than research topics) that will require further careful consideration are summarised in Box 7.1.

Box 7.1 Suggested rationale for, and concerns with, geoengineering research. Summary of Section 5.2 from EuTRACE report, See Fn. 483.

Rationale for research	Concerns
• **Information requirements**. Research on geoengineering provides the information needed for sound climate change policy at national and international levels • **Knowledge provision**. Broader knowledge is required for scientific 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' • **Premature implementation avoidance**. 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.** Geoengineering research provides wider insights and understanding	• '**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. • **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 safedguards) need to be transparently demonstrated to avoid adverse responses, that might have implications for other unrelated studies

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[485] National Academy of Sciences (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

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Annex 1: Additional bibliography (since 2012) for socio-economic and governance aspects of climate geoengineering

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Annex 2. Issues relating to definition of climate geoengineering

As noted in Section 1.3 of the main report, CBD COP, in decision XI/20 (Box 1.1) noted four definitions for climate geoengineering. Whilst similar, these options differ in important regards, with potential for ambiguities to arise when Parties implement this decision and others relating to geoengineering. It is therefore timely to here provide further discussion on their relative merits, noting that the overall need is no 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)[486]. 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[487]:

> "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."

Whilst 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. minimise climate alteration); ii) uncertainties remain regarding the 'fuzzy boundary' with weather modification and ecological engineering (both of which could also have substantive unintended 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 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

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[486] 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.

[487] 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.

> 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)[488]. 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 summarised as "geoengineering comprises SRM, CDR and other methods" and the latter as "not all CDR methods are geoengineering"; iii) whilst 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 CO2 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: 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.

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[488] 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.

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'[489] or 'climate interventions'. The latter switch was made by the US Committee on Geoengineering Climate: Technical Evaluation and Discussion of Impacts, in its two recent reports[490,491] 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.

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[489] 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

[490] National Academy of Science (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

[491] 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

Although most media coverage of the NAS/NRC reports still used geoengineering or climate engineering[492], 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 socio-ecological one… The reports' switch to a language that allows us to better conceptualise coupled and interdependent socio-ecological 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"[493].

The CBD may therefore wish to consider taking forward its future discussions on geoengineering within a climate intervention framework, with greater emphasis on the differences between the two main groups of approaches. There are, however, issues relating to interactions between GGR/CDR and SRM[494]; important insights to be gained from comparative studies[495]; and the potential for additivity, complementarity or competition between different geoengineering techniques should be better understood[496].

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[492] Svoboda M (2015) Geoengineering: neither geo-, nor engineering? Yale Climate Connections; http://www.yaleclimateconnections.org/2015/03/geoengineering-neither-geo-nor-engineering/

[493] Comment by H Buck within http://dcgeoconsortium.org/nas-responses (Forum for Climate Engineering Assessment: Unpacking the social and political implications of climate engineering)

[494] Vaughan NE & Lenton TM (2012) Interactions between reducing CO_2 emissions, CO_2 removal and solar radiation management. *Philosophical Transactions of the Royal Society A* 370, 4343-4364

[495] Keller DP, Feng EY & Oschlies (2014) Potential climate engineering effectiveness and side effects during a high carbon dioxide-emission scenario. *Nature Communications* 5, 3304; doi: 10.1038/ncomms4304

[496] Jones C, Williamson P, Haywood J, Lowe J *et al* (2013) *LWEC Geoengineering Report. A forward look for UK research on climate impacts of geoengineering*. Living With Environmental Change (LWEC), UK; 36 pp. http://www.lwec.org.uk/publications/lwec-geoengineering-report-forward-look-uk-research-climate-impacts-geoengineering