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INTERIM UPDATE OF INFORMATION ON THE POTENTIAL IMPACTS OF CLIMATE GEOENGINEERING ON BIODIVERSITY AND THE REGULATORY FRAMEWORK RELEVANT TO THE CONVENTION ON BIOLOGICAL DIVERSITY

I. INTRODUCTION

1. The eleventh meeting of the Conference of the Parties (COP-11) to the Convention on Biological Diversity (CBD) discussed and noted reports on technical and regulatory matters relating to climate geoengineering arising from the sixteenth meeting of the Subsidiary Body on Scientific, Technical and Technological Advice (SBSTTA-16). These reports were published in September 2012 as [CBD Technical Series No. 66](#), *Geoengineering in Relation to the Convention on Biological Diversity: Technical and Regulatory Matters* (hereafter CBD, 2012).
2. At COP-11, Parties requested the Executive Secretary, subject to the availability of resources, to prepare for a future meeting of the Subsidiary Body 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” (decision XI/20, paragraph 16 (a)).
3. That mandate cannot be fully addressed for SBSTTA-18, since (i) the Synthesis of the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR5) is not available until September 2014; and (ii) the detailed contributions of IPCC Working Groups II and III have only been completed in late March and mid-April 2014 respectively. For these reasons, an interim update is provided here, comprising a bibliography of around 300 peer-reviewed scientific papers and other relevant reports published since the preparation of CBD (2012), together with a brief analysis of their key features. In addition, the most relevant excerpts of the Summaries for Policymakers of the reports of Working Groups I and III are contained in annex II.
4. This interim update has been prepared by the CBD Secretariat with the assistance of the lead author¹ of CBD (2012) and other members of the CBD Expert Group on Geoengineering. It has not yet been peer-reviewed. 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. Further attention could then also be given to the publications identified in annex I, together with other emerging scientific and technical evidence on climate change and its impacts on biodiversity; the potential risks and benefits of geoengineering approaches that might be considered as policy responses; associated research gaps; and the suitability of existing and proposed regulatory mechanisms.

* UNEP/CBD/SBSTTA/18/1.

¹ Phillip Williamson, acting in an independent capacity with support from the UK Natural Environment Research Council.

5. For the purposes of this update, the following definition of geo-engineering is used, consistent with CBD (2012), “deliberate intervention in the planetary environment of a nature and scale intended to counteract anthropogenic climate change and/or its impacts”. This definition includes techniques intended to increase the Earth’s energy loss (primarily by long-term removal of greenhouse gases from the atmosphere) or decrease the Earth’s energy gain (primarily by increasing atmospheric or surface reflectivity), but excludes actions taken to reduce anthropogenic emissions.

6. This definition was developed by the Expert Group on the basis of wider usage, clarity, purpose, brevity and etymological consistency.² It avoids ambiguities relating to ‘carbon sequestration’ and focuses on functional aspects; i.e. the purpose of geoengineering, rather than the methods by which it might be achieved or its potential for indirect effects. A relatively wide spectrum of approaches is covered by the above definition; thus additional, second order information, specifying the technique(s) under consideration, is likely to be needed when the term geoengineering is used for most practical purposes – not only for scientific research on effectiveness and impacts, but also for consideration of ethical and justice issues, public engagement, economic assessments, policy development, and the establishment of appropriate regulatory frameworks at national and international levels.

7. Discussions at COP-11 included consideration of four definition options without prejudice to future deliberations on this issue (decision XI/20, paragraphs 5 (a) – (d)), including the definition used in CBD (2012) as option (b). Subsequent to CBD (2012), the term ‘climate engineering’ has increased in prominence in the scientific literature, as a synonym for “climate-related geoengineering. In due course, SBSTTA may consider a definitive recommendation on the definition of geoengineering, or on alternative terminology. Until such issues have been resolved, there will continue to be undesirable confusion as to what is intended by COP decisions in this area; for example, the request to Parties to report on their geoengineering-related activities.

II. BIBLIOGRAPHY

8. Following the final editing of CBD (2012), the CBD Secretariat and Expert Group members have maintained their awareness of new scientific papers and reports relevant to the continued consideration of geoengineering in the context of the Convention, with focus on peer-reviewed literature that is available online and included in databases such as the Web of Science. The main outcome is given here (annex I) as a bibliography of more than 300 publications from 2012³ to early 2014. These publications are provided in two main groups, Parts 1 and 2, respectively covering (i) impacts of climate geoengineering on biodiversity and (ii) the regulatory framework for climate geoengineering relevant to the Convention on Biological Diversity. Thus the two groups match the COP-11 request for an update covering those two areas, and also match Part I and Part II of CBD (2012).

9. Within the bibliography for Part 1 in annex I, four sub-groups are distinguished, matching the following four chapters of Part I of CBD (2012):

- *Chapter 3: Overview of climate change and ocean acidification and of their impacts on biodiversity.* Here covered by “Context of climate change and ocean acidification”. Publications cited in this sub-group are selective, with focus on reviews and those with greatest applicability to considerations under the CBD. The main topic area for each publication is individually indicated, acknowledging that there may be overlap between topic areas, established here for ‘working purposes’ (sub-headings in Sections 3 - 6 below); other typologies could be equally valid.
- *Chapter 4: Potential impacts on biodiversity of climate geoengineering achieved by sunlight reflection methods.* Here covered by “Sunlight reflection methods (SRM)”. This group of techniques is also known as solar radiation management. The main topic area is identified for each publication, with the same caveats as above.
- *Chapter 5: Potential impacts on biodiversity of carbon dioxide removal geoengineering techniques.* Here covered by “Greenhouse gas removal (GGR) methods”, with the change of wording giving

² Additional discussion on the definition of geoengineering is given in annex II (p 83-84) of Part I of CBD (2012)

³ Around 20 publications from 2012 that were fully cited in Technical Series No. 66 are not re-included in the bibliography given in annex I.

greater flexibility in what might be covered by such approaches. An alternative title “Negative emissions techniques” was considered, since that term is now widely used in the scientific literature; e.g. relating to IPCC scenarios. However, negative emissions is a contradiction in terms and its use can cause confusion. The main topic area is identified for each publication, with the same caveats as above. Note that several publications in the GGR category relate to land management, or CO₂ storage primarily developed for pre-emission carbon capture and storage, rather than necessarily being geoengineering-directed.

- *Chapter 6: Social, economic, cultural and ethical considerations of climate-related geoengineering.* Here covered by “Socio-economic, cultural and ethical aspects”. Policy and governance-related issues are included, with some overlap with Part 2. The main topic area is identified for each publication, with the same caveats as above.

10. The numbering of the publications is consecutive within each Part of the bibliography. In cases where a publication is considered relevant to more than one of the four sub-groups of Part 1, it is repeated in the list, with the number remaining as allocated on first mention. The statistics given in Table 1 provide an indication of relative research activity in sub-groups and topic areas of geoengineering research during the past two years, acknowledging that there may be uncontrolled factors affecting initial identification of publications (e.g. searching efficiency via keywords) and unintentional bias in allocation to topic areas. There are also differences in publication behaviour between natural and social scientists; e.g. more multi-author publications by the former. A peer-reviewed bibliometric analysis of geoengineering literature (covering > 500 publications in the period 1984-2011) discusses some of these issues (ref 43).

Table 1. Distribution of recent geoengineering-related publications between different topic categories, based on the bibliography given in annex I. Numbers within sub-group 1.1 are bracketed, since very many publications in these topic areas were not included in the list. There may also be biases or incomplete coverage for other groups, as discussed in the text. The overall total for Part 1 publications (332) is less than the sum of the sub-totals (373) due to overlap between sub-groups.

Part 1: Impacts of geoengineering on biodiversity								Part 2:	
1.1 Context of climate change & ocean acidification		1.2. Sunlight reflection methods (SRM)		1.3. Greenhouse gas removal (GGR) methods		1.4 Socio-economic, cultural & ethical aspects		Regulatory Framework	
Climate driver	(5.5)	Space SRM	3	Biochar	34	Ethics & values	51	No sub-groups or topic areas	
Climate trend/projection	(4.5)	Stratospheric SRM	46	BECCS	7	Policy & governance	40		
Climate impact: Land (12.5) , Ocean (9.5)	(22)	Tropospheric SRM	23	Biomass storage: Land 3, Ocean 2	5	Discourse analysis	11		
		Surface albedo: Land 3, Ocean 1	4			Economics	4		
		Direct air capture	5	Multi-topic	23				
Ocean acidification	(2)	Multi-technique	23	Enhanced weathering: Land 3.5, Ocean 4.5	8	SUB-TOTAL	129		TOTAL 35
SUB-TOTAL	(34)	SUB-TOTAL	99	CO ₂ storage: Land 1, Ocean 6	7				
				Ocean fertilization	9				
				Multi-technique	36				
				SUB-TOTAL	111				

III. CONTEXT OF CLIMATE CHANGE AND OCEAN ACIDIFICATION

11. The IPCC AR5 WG I report (ref 16) is the main information source providing the climate context for proposed geoengineering techniques and their potential impacts. As noted above (para 3), AR5 WG II and WG III reports (refs 17, 18) are also highly relevant, but were not available in time for consideration by this interim update, and IPCC’s overall synthesis has yet to be published. However, relevant paragraphs from the Summaries for Policy Makers of AR5 WG II and WG III are included in annex II. Key findings from the WG I report, that focuses on climate trends, climate dynamics and model-based projections of future conditions, include the following:

- Warming of the climate system is now unequivocal, driven by anthropogenic greenhouse gas emissions (primarily CO₂). Many aspects of climate change would continue even if emissions could be immediately stopped.

- Climate models have improved since the previous IPCC assessment [AR4, used to provide climate change context for CBD (2012)]. There is therefore greater confidence in their projections, based on radiative forcing scenarios; however, uncertainties still remain.
- Future warming will be greater in the Arctic than the global mean, and greater over land than over the ocean. Warming will continue to exhibit interannual-to-decadal and regional variability.
- Ocean acidification will intensify, with greatest changes in the upper ocean, driven by increases in atmospheric CO₂.
- The threshold for loss of the Greenland ice sheet is likely to be in the range 1-4°C of global warming; if that occurs, global mean sea level would rise by up to 7m over several centuries.

IPCC WG I climate projections for four policy-dependent and emission-related scenarios are summarized in Table 2. The scenarios are defined in terms of Representative Concentration Pathways (RCPs), quantifying the additional radiative forcing (due to greenhouse gases) in year 2100 relative to 1750, as a global mean: 2.6 W m⁻² for RCP 2.6, 4.5 W m⁻² for RCP 4.5, 6.0 W m⁻² for RCP 6.0 and 8.5 W m⁻² for RCP 8.5.

Table 2. Summary outcomes of IPCC WG I multi-model comparisons, based on four scenarios, for likely end of century (2081-2100) atmospheric CO₂; increase in global mean temperature; increase in global mean sea level; and increase in ocean acidity. The increases in temperature and sea level are relative to 1986-2005. Note that: i) there is expected to be considerable regional variability in these changes, ii) atmospheric CO₂ values are currently ~390 ppm, compared to a value of ~280 ppm in 1750; and iii) there has already been a global temperature increase of ~0.7°C, a global sea level increase of ~20 cm, and a global mean pH fall of 0.075 (representing a 26% increase in acidity) since 1850.

Scenario		Projections for end of 21st century			
		Atmospheric CO ₂	Increase in global mean temperature	Increase in global mean sea level	Increase in ocean acidity (pH fall)
RCP 2.6	Strong mitigation (low emissions), also CO ₂ removal from atmosphere; radiative forcing peaks then declines	~420 ppm	0.3 -1.7°C	26-55 cm	-0.065
RCP 4.5	Strong mitigation (low emissions); radiative forcing stabilizes by 2100	~540 ppm	1.1-2.6°C	32-63 cm	-0.150
RCP 6.0	Moderate mitigation (moderate emissions); radiative forcing still increasing in 2100,	~670 ppm	1.4-3.1°C	33-63 cm	-0.225
RCP 8.5	Low mitigation (high emissions; current trend); radiative forcing still increasing in 2100	~940 ppm	2.6-4.8°C	45-82 cm	-0.350

12. The IPCC scenarios RCP 4.5, 6.0 and 8.5 provide the ‘controls’ against which the climatic impacts of different geoengineering techniques, simulated at different scales within models, can be assessed. Whilst the present day (or pre-industrial) climatic conditions can also be used for comparative purposes, it is not valid to ascribe the difference between present day and projected future geoengineered climatic conditions (however achieved) as a ‘geoengineering impact’. Instead that impact is the difference between the non-geoengineered and geo-engineered projected future climate, expected to be climatically beneficial if the geoengineering is effective. There may, however, be regional differences in those effects, also additional, unintended non-climatic impacts due to the geoengineering. As discussed in CBD (2012), the unintended impacts are more likely to be adverse than beneficial.⁴

13. Scenario RCP 2.6 does not provide a non-geoengineered ‘control’, since that pathway is only achievable through active removal of CO₂ (cumulative total in range 100-500 Pg, assumed to be via BECCS) from the atmosphere. Such action is regarded by IPCC AR5 – and here – as geoengineering. The linkage between mitigation and geoengineering is considered further in section 8 below.

14. The IPCC WG I report includes assessments of the climatic consequences of geoengineering through greenhouse gas removal and sunlight reflection methods; key aspects are briefly summarised in Sections 4 and 5 below. Wider impacts of projected climate change on natural systems and society are considered in the WG II report, not discussed here. A selection of other recent publications since CBD

⁴ Additional details on RCP 2.6 scenario are contained in IPCC Working Group III.

(2012) on climate change and its impacts are identified in Part 1.1 of the annex I bibliography, from which the following preliminary conclusions can be drawn:

- Species' range shifts, that are already underway, show wide variability between different groups (affecting community structure), and between marine and terrestrial habitats (refs 4, 25).
- The rates of projected climate change are likely to exceed climatic niche evolution by vertebrates (ref 29) and overall biodiversity loss is likely to accelerate as warming intensifies (ref 30). However, temperature increase *per se* may not be the main factor causing extinctions during conditions of rapid climate change (refs 1, 5, 24).
- Experimental studies and models are now being developed to take account of multiple stressors associated with climate change in the marine environment, including ocean acidification effects (refs 3, 8, 20, 25).
- When the criteria for 'dangerous' climate change is adjusted to take account of multiple impacts, allowable carbon emissions are much reduced (ref 28).
- For land plants, experimentally-induced phenological responses to warming may underestimate observed responses (ref 33).

IV. SUNLIGHT REFLECTION METHODS (SRM)

15. There have been around 100 publications on sunlight reflection methods (solar radiation management) in the past two years, with nearly half of these addressing *stratospheric SRM*, based on increasing the concentration of aerosols in the upper atmosphere. This topic area is covered in Chapter 7 of the IPCC WG I report. Recent advances in understanding, based on both these sources, include:

- Model intercomparisons (GeoMIP) and other studies confirm that stratospheric aerosol injection (e.g. by SO₂) could offset the global temperature increases of RCP 4.5 (refs 90, 119), but major hydrological effects are likely to remain (refs 66, 89, 125). Overall consequences could, in theory, be optimized (refs 85, 98, 99).
- Regional climatic responses to stratospheric SRM would be affected by the latitude, altitude and season of the aerosol injection (refs 68, 129). If aerosols are only added to the northern hemisphere, models show less rainfall in the Sahel but more in Brazil: if only added to the southern hemisphere, the opposite effect occurs. Observations from hemispherically asymmetric volcanic eruptions confirm these results (ref 68).
- The potential for regionally-targeted stratospheric SRM, to limit Arctic sea ice-melt, has been simulated (ref 126); this requires very strong local radiation reduction, and could cause other regional climate changes.
- As indicated by earlier studies, the cessation of stratospheric SRM is near-certain to produce very rapid warming, with potentially severe environmental consequences (refs 42, 79, 101).

16. The scientific literature on *tropospheric SRM* (cloud brightening) has greatly increased, from <10 papers in CBD (2012) to >20 in the past two years. Model-based studies generally confirm the theoretical potential of the approach (ref 35, 80), although its effectiveness is likely to be a function of particle size, micro-physical processes, injection amount and diurnal timing (refs 36, 37, 77, 78, 108, 124). Proposals for field-testing have been developed (ref 130); these may need to be on a relatively large-scale for satellite-based detection of albedo changes (ref 120).

17. The limited numbers of additional studies on *surface albedo changes* (refs 75, 109, 122, 127), *space SRM* (refs 45, 46, 47) and cirrus cloud manipulation (ref 123) do not indicate that these techniques have high potential for further development.

V. GREENHOUSE GAS REMOVAL (GGR)

18. Chapter 6 of the IPCC WG I report gives detailed attention to carbon dioxide removal (CDR), recognising that there may also be potential for removal of other greenhouse gases (e.g. methane, ref 214) and that the more general term of negative emissions is also used for this category of geoengineering, particularly by climate modellers. Key WG I messages relate to the relative slowness

of GGR (decadal to century) in providing climatic benefits, the scale of the effort required, and potential conflicts with food production for biologically-based, terrestrial GGR.

19. The WG I report also emphasises the importance of carbon cycle dynamics when assessing GGR effectiveness. In the same way that anthropogenic emissions of CO₂ do not increase the longterm atmospheric content by the same amount (because of uptake by the ocean and land systems), its removal is partly offset by outgassing from natural sources. Recent papers on this issue include refs 138, 178 and 219.

20. There are many (> 30) publications on *biochar* listed in annex I; these cover its use as a soil improver as well as its potential for carbon sequestration. Effects of biochar on soil greenhouse gas emissions (N₂O and CH₄) are generally considered favourable (refs 142, 149, 167, 207, 211, 220, 223, 224) although dependent on treatment conditions (refs 177, 188) and with negative albedo impacts (refs 187, 217).

21. As identified by CBD (2012), the scope for large-scale CO₂ removal by *BECCS* (bioenergy with carbon capture and storage) and *land biomass storage* is closely linked to land availability (refs 135, 173, 194, 195, 225). Cost-effective carbon capture and storage is also crucial for the former, and remains an issue for direct air capture (refs 163, 190). Recent papers cover leakage risks from both *land and ocean CO₂ storage* reservoirs (refs 133, 148, 159, 191): there is much more extensive literature on pre-emission CCS, geological considerations and ocean acidification impacts that is not included here.

22. The feasibility of *enhanced weathering* on land and in the ocean has been further investigated (refs 200 and 165, 172, 193, 201 respectively) and reviewed (ref 162). Unresolved issues for geoengineering application relate to the cost and energy requirements of material processing and transport, also the environmental consequences of raising silicate levels and pH in rivers and/or coastal seas. Whilst the latter could counteract ocean acidification, very large alkalinity additions (in a ratio of 2:1 with respect to emitted CO₂) are likely to be needed to achieve this effect on a global scale (ref 165).

23. The topic of *ocean fertilization* has attracted recent interest due to an unauthorized iron addition experiment in the Gulf of Alaska (ref 222), primarily justified on the basis of fishery enhancement. Whilst further research in this topic area has been advocated (ref 158), limitations on overall effectiveness and feasibility have also been identified (ref 221).

VI. SOCIO-ECONOMIC, CULTURAL AND ETHICAL ASPECTS

24. Annex I includes around 130 recent publications covering the human dimensions of climate geoengineering, mostly relating to stratospheric SRM. Additional categorization on a technique-specific basis was not considered helpful; instead, the topic areas identified in annex I, and discussed briefly below, relate to the main focus or perspective of the texts. There is, however, a continuum between these topics, and other groupings would be possible.

25. Several of the 51 recent papers in the *ethics and values* topic area can be considered ‘non-research’ (ref 43), in that they provide comment or overviews, rather than novel analyses. Nevertheless, the majority make significant contributions to the debate on two key moral dilemmas: whether it could ever be acceptable to implement geoengineering without the informed consent of all groups affected; and whether research on geoengineering might increase or reduce the likelihood of subsequent implementation. These questions are examined through surveys of public attitudes and perceptions (refs 236, 246, 249, 250, 274, 301, 331) and consideration of psychological (refs 226, 255), gender (ref 242), religious (ref 248) and equity issues (ref 244, 290). There is clear disquiet amongst social scientists that a simplistic cost-benefit or ‘public good’ approach might be used for policy development in this area (refs 239, 251, 262, 264, 293).

26. The 40 recent contributions to the literature in the area of *policy and governance* connect public consent (also considered above) with political legitimacy and specific regulatory mechanisms (also considered below). They also cover issues of ‘self regulation’ by the research community (refs 232, 307). The relatively undeveloped status of the field is exemplified by five publications including “?” in their titles (refs 238, 256, 257, 270, 328) and one with “!” (ref 326). A multi-topic and multi-group paper on climate engineering categorization (ref 49) is also relevant here, since it distinguishes between territorial/domestic actions, and those with potentially significant trans-territorial impacts,

either on climate at the regional or global scale, or on common resources. There is obvious benefit if those involved in governance issues have a well-developed appreciation of the full range of geoengineering techniques; as discussed in CBD (2012) and above, the impacts and implications of different techniques are very different.

27. The *discourse analysis* topic area considers framing and perspective issues, in academic and public discussion (refs 277, 288, 314, 315) and in the media (refs 241, 286, 303, 313). Such considerations provide additional insights into how attitudes and values develop, and, ultimately, how policy decisions are reached at the national and international level. Only four recent publications address the *economics* of geoengineering (refs 48, 100, 184, 280).

VII. REGULATORY FRAMEWORK

28. Regarding the international regulatory framework of geoengineering relevant to the CBD, an important recent development relates to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter 1972 (London Convention) and its 1996 Protocol (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. The amendment is structured to allow other marine geoengineering activities to be considered and listed in a new annex in the future if they fall within the scope of the London Protocol and have the potential to harm the marine environment. The amendment will enter into force 60 days after two thirds of the Contracting Parties to the London Protocol have deposited an instrument of acceptance of the amendment with the International Maritime Organization. As of April 2014, the amendment has not received any ratification (ref 278).

29. This amendment, once entered into force, will strengthen the regulatory framework for ocean fertilization activities and provide a framework for the further regulation of other marine geoengineering activities. However, this recent development, so far, has not changed the validity of the key messages from the earlier report (CBD, 2012, part II), including that “the current regulatory mechanisms that could apply to climate-related geoengineering relevant to the Convention do not constitute a framework for geoengineering as a whole that meets the criteria of being science-based, global, transparent and effective” and that “with the possible exceptions of ocean fertilization experiments and CO₂ 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.”

30. Other recent literature relevant to the international regulatory framework is contained in refs 272, 283, 299, 308, 328, 329, 335, 337, 340 and 343; and for climate change more generally in refs 14 and 19. Relevant issues regarding national legislation are covered in refs 339 and 341.

VIII. SYNTHESIS: INTERDISCIPLINARITY AND INTEGRATION

31. Overall, the key messages identified in the report reviewed at the sixteenth meeting of the Subsidiary Body on Scientific, Technical and Technological Advice (UNEP/CBD/SBSTTA/16/10) and published in [CBD Technical Series No. 66](#) remain valid and are consistent with the recent scientific literature and information contained in the Summary for Policy Makers of the three Working Group reports of the IPCC’s fifth Assessment.

32. The grouping of the annex I publications to match the main chapters and parts of CBD (2012) has comparative benefits for updating purposes. However, that compartmentalization does risk missing an important development within the past two years: the increased attention that has been given to a more interdisciplinary, integrated approach to address not only the problem of climate change but also potential solutions. Thus there is now greater appreciation of the commonalities and interactions, rather than the boundaries, between the natural sciences, socio-economic systems and legal domains when considering the complexities and uncertainties of climate change responses.

33. That approach has, in part, been stimulated by the IPCC AR5 scenarios. As noted in Section 3, RCP 2.6 – the pathway to avoid ‘dangerous’ climate change – is only achievable within emission-based climate models if, in addition to emission reductions of ~50% by 2050, there is active removal of greenhouse gases from the atmosphere. IPCC WG I considers such removal of CO₂ (and potentially

other greenhouse gases) to be a geoengineering action, although with overlap to mitigation. The need to consider both inputs and outputs to the atmosphere was recognised by COP-11: "... climate change should primarily be addressed by reducing anthropogenic emissions by sources and by increasing removals by sinks of greenhouse gases ..." (Decision XI/20, paragraph 4). Recent publications in annex I that are relevant to the interaction of geoengineering and mitigation include refs 19, 22, 28, 31, 49, 81, 82, 128, 150, 153, 237 and 273.

34. Taken together, annex I publications indicate that there is now greater knowledge of the limitations of a range of geoengineering approaches, both in terms of their acceptability, governance and risks (SRM), and their costs, scalability and unintended impacts (GGR). Such considerations would support the view that most, if not all, forms of geoengineering are an inappropriate potential response to climate change, justifying strong international regulation to limit geoengineering research and/or applications (refs 57, 248, 259, 267). The counterargument is that the past two years have also delivered greater knowledge of the scale and dangers of future climate change, that may become unstoppable (Part 1 ref 14), with reduced abilities for emission reductions to diminish its potentially catastrophic consequences for biodiversity and humanity. Evidence for that position is presented in the IPPC AR5 WG I, WG II and WG III reports and many additional analyses, including those that take account of the combined effects of multiple stressors on species and ecosystems (Part 1 refs 3, 23, 28, 29). On that basis, geoengineering research – to continue to investigate whether or not some techniques might provide an environmentally and politically viable future policy option - may now be a higher priority than it was two years ago.

Annex 1

BIBLIOGRAPHY OF RECENT PUBLICATIONS RELEVANT TO CLIMATE-RELATED GEOENGINEERING

Part 1. Impacts of climate geoengineering on biological diversity

The four sub-groups 1.1 -1.4 below correspond to Chapters 3-6 in CBD Technical Series No. 66 (CBD, 2012), as explained in the main text. However there is not an exact match between the Chapter titles and the headings used below, since some of the latter have been shortened or amended. Publications are limited to those dated 2012, 2013 and 2014 (to 31 March), excluding those cited in CBD (2012).

1.1 Context of climate change and ocean acidification. This listing is highly selective. Publications have been allocated to the following topic areas: climate driver; climate trend/ projection; climate impact (separated into land and ocean); and ocean acidification.

	Authors (date)	Publication title; <i>journal/book details</i>	Topic area
1	Bellard C., Bertelsmeier C., Leadley P., Thuiller W. & Courchamp F. (2012)	Impacts of climate change on the future of biodiversity. <i>Ecol. Lett.</i> , 15, 365-377; doi: 10.1111/j.1461-0248.2011.01736.x	<i>Climate impact: land & ocean</i>
2	Bony S., Bellon G., Klocke D., Sherwood S. <i>et al</i> (2013)	Robust direct effect of carbon dioxide on tropical circulation and regional precipitation. <i>Nature Geoscience</i> , 6, 447-451 (2013); doi: 10.1038/NGEO1799	<i>Climate trend/projection</i>
3	Bopp L., Resplandy L., Orr J.C., Doney S.C. <i>et al</i> (2013)	Multiple stressors of ocean ecosystems in the 21 st century: projections with CMIP5 models. <i>Biogeosciences</i> , 10, 6225-6245.	<i>Climate impact: ocean</i>
4	Burrows M.T., Schoeman D.S., Richardson A.J., Molinos J.G. <i>et al</i> (2014)	Geographical limits to species-range shifts are suggested by climate velocity. <i>Nature</i> 507, 492-495; doi: 10.1038/nature12976	<i>Climate impact: land & ocean</i>
5	Cahill A.E., Aiello-Lammens M.E., Fisher-Reid M.C., Hua X. <i>et al</i> (2013)	How does climate change cause extinction? <i>Proc. Roy. Soc. B</i> , 280, 20121890.	<i>Climate impact: land & ocean</i>
6	Cernusak L.A., Winter K., Dalling J.W., Holtum J.A.M. <i>et al.</i> (2013)	Tropical forest responses to increasing atmospheric CO ₂ : current knowledge and opportunities for future research. <i>Functional Plant Biol.</i> , 40, 531-551.	<i>Climate impact: land</i>
7	Cleland E.E., Collins S.L., Dickson T.L., Farrer E.C. <i>et al</i> (2013)	Sensitivity of grassland plant community composition to spatial vs. temporal variation in precipitation. <i>Ecology</i> , 94, 1687-1696.	<i>Climate impact: land</i>
8	Cocco V., Joos F., Steinacher M., Frolicher T.L. <i>et al</i> (2013)	Oxygen and indicators of stress for marine life in multi-model global warming projections. <i>Biogeosciences</i> , 10, 1849-1868; doi: 10.5194/bg-10-1849-2013	<i>Climate impact: ocean</i>
9	Cook B.I., Wolkovich E.M., Davies T.J., Ault T.R. <i>et al</i> (2012)	Sensitivity of spring phenology to warming across temporal and spatial climate gradients in two independent databases. <i>Ecosystems</i> , 15, 1283-1294.	<i>Climate impact: land</i>
10	De Frenne P., Rodríguez-Sánchez F., Coomes D.A., Baeten L. <i>et al</i> (2013)	Microclimate moderates plant responses to macroclimate warming. <i>Proc. Natl. Acad. Sci. USA</i> , 110, 18561-18565.	<i>Climate impact: land</i>
11	de Vries P., Tamis J.E., Foekema E.M. <i>et al</i> (2013)	Towards quantitative ecological risk assessment of elevated carbon dioxide levels in the marine environment. <i>Mar Poll. Bull.</i> , 73 (special issue), SI 516-523	<i>Climate impact: ocean</i>
12	Doney S.C., Ruckelshaus M., Duffy J.E., Barry J.P. <i>et al</i> (2012)	CLIMATE CHANGE IMPACTS ON MARINE ECOSYSTEMS. <i>ANN. REV. MAR. SCI.</i> , 4, 11-37; DOI: 10.1146/ANNUREV-MARINE-041911-111611	<i>Climate impact: ocean</i>
13	Donohue R.J., Roderick M.J.M., McVicar T.R. & Farquhar, G.D. (2013)	Impact of CO ₂ fertilization on maximum foliage cover across the globe's warm, dry environments. <i>Geophys. Res. Lett.</i> , 40, 3031-3035.	<i>Climate impact: land</i>
14	Goldblatt C. & Watson A.J. (2012)	The runaway greenhouse: implications for future climate change, geoengineering and planetary atmospheres. <i>Phil. Trans. Roy. Soc. A</i> , 370, 4197-4216.	<i>Climate trend/projection</i>
15	Higgins S.I. & Scheiter S. (2012)	Atmospheric CO ₂ forces abrupt vegetation shifts locally, but not globally. <i>Nature</i> , 488, 209-212.	<i>Climate impact: land</i>

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16	IPCC (2013)	<i>Climate Change 2013: The Physical Science Basis</i> . Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. http://www.ipcc.ch	Climate driver; climate trend/ projection
17	IPCC (2014a)	<i>Climate Change 2014: Impacts, Adaptation and Vulnerability</i> . Working Group II Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. http://www.ipcc.ch	Climate impact: land & ocean
18	IPCC (2014b)	<i>Climate Change 2014: Mitigation of Climate Change</i> . Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. http://www.ipcc.ch	Climate driver
19	Jones C., Robertson E., Arora V., Friedlingstein P. <i>et al.</i> (2013)	Twenty-first-century compatible CO ₂ emissions and airborne fraction simulated by CMIP5 Earth System Models under four representative concentration pathways. <i>J. Climate</i> , 26, 4398–4413; doi: 10.1175/JCLI-D-12-00554.1	Climate driver
20	Kroeker K. J., Kordas R. C., Crim R., Hendriks I.E. <i>et al.</i> (2013)	Impacts of ocean acidification on marine organisms: quantifying sensitivities and interaction with warming. <i>Global Change Biol.</i> , 19, 1884–1896.	Ocean acidification
21	Le Quéré C., Peters G. P., Andres R. J., Andrew R. M., Boden T. <i>et al.</i> (2013)	Global carbon budget 2013. <i>Earth System Sci. Data Discuss.</i> doi: 10.5194/essdd-6-689-2013	Climate driver
22	Luderer G., Bertram C., Calvin K., De Cian E. & Kriegler E. (2013)	Implication of weak near-term climate policies on longterm mitigation pathways. <i>Clim. Change</i> , doi: 10.1007/s10584-013-0899-9	Climate driver
23	Mora C., Wei C.L., Rollo A., Amaro T. <i>et al.</i> (2013)	Biotic and human vulnerability to projected changes in ocean biogeochemistry over the 21st century. <i>PLOS Biology</i> , 11, e1001682; doi: 10.1371/journal.pbio.1001682	Climate impact: ocean
24	Moritz C. & Agudo R. (2013)	The future of species under climate change: resilience or decline? <i>Science</i> , 341, 504–508; doi: 10.1126/science.1237190	Climate impact: land
25	Poloczanska E.S., Brown C.J., Sydeman W.J., Kiessling W. <i>et al.</i> (2013)	Global change imprint on marine life. <i>Nature Climate Change</i> 3, 919–925; doi: 10.1038/nclimate1958	Climate impact: ocean
26	Pörtner H.O. (2012)	Integrating climate-related stressor effects on marine organisms: unifying principles linking molecule to ecosystem-level changes. <i>Mar. Ecol. Prog. Ser.</i> , 470, 273–290.	Climate impact: ocean
27	Seneviratne S.I., Donat M.G., Mueller B. & Alexander L.V. (2014)	No pause in the increase of hot temperature extremes. <i>Nature Climate Change</i> , 4, 161–163; doi: 10.1038/nclimate2145	Climate trend/ projection
28	Steinacher M., Joos F. & Stocker T.F. (2013)	Allowable carbon emissions lowered by multiple climate targets. <i>Nature</i> 499, 197–201	Climate driver; climate impact: land & ocean
29	Quintero I. & Wiens J.J. (2013)	Rates of projected climate change dramatically exceed past rates of climatic niche evolution among vertebrate species. <i>Ecology Letters</i> , 16, 1095–1103.	Climate trend/ projection
30	Warren R., VanDerWal J., Price J., Walbergen J.A. <i>et al.</i> (2013)	Quantifying the benefit of early climate change mitigation in avoiding biodiversity loss. <i>Nature Climate Change</i> , 3, 678–682; doi: 10.1038/nclimate1887.	Climate driver; climate impact: land & ocean
31	Wiltshire A.J., Gornall J., Booth B.B.B., Dennis E. <i>et al.</i> (2013)	The importance of population, climate change and CO ₂ plant physiological forcing in determining future global water stress. <i>Global Environ. Change</i> , 23, 1083–1097.	Climate impact: land
32	Wiltshire A.J., Kay G., Gornall J.L. & Betts R.A. (2013)	The impact of climate, CO ₂ and population on regional food and water resources in the 2050s. <i>Sustainability</i> , 5, 2129–2151; doi:10.3390/su5052129	Climate impact: land
33	Wittmann A.C. & H.O. Pörtner (2013)	Sensitivities of extant animal taxa to ocean acidification. <i>Nature Climate Change</i> 3, 995–1001	Ocean acidification
34	Wolkovich E.M., Cook B.I., Allen J.M., Crimmins T.M. <i>et al.</i> (2012)	WARMING EXPERIMENTS UNDERPREDICT PLANT PHENOLOGICAL RESPONSES TO CLIMATE CHANGE. <i>NATURE</i> , 485, 494–497;doi: 10.1038/nature11014	Climate impact: land

1.2 Sunlight reflection methods (SRM). Publications have been allocated to the following topic areas: space SRM; stratospheric SRM; tropospheric SRM; surface albedo (separated into land and ocean); and multi-technique. Publications with reference numbers in brackets have already been listed in Part 1.1.

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- 37 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. *Tropospheric SRM*
- 38 Andrejczuk M., Gadian A. & Blyth A. (2014) Numerical simulations of stratocumulus cloud response to aerosol perturbation. *Atmos. Res.*, doi: 10.1016/j.atmosres.2014.01.006 *Tropospheric SRM*
- 39 Andrews T., Gregory J.M., Webb M.J., Gregory J.M. & Forster P.M. (2012) Cloud adjustment and its role in CO₂ radiative forcing and climate sensitivity: a review. *Surveys in Geophysics*, 33, 619-635. *Tropospheric SRM*
- 40 Aquila V., Garfinkel C.I., Newman P.A., Oman L.D. & Waugh D.W. (2014) Modifications of the quasi-biennial oscillation by a geoengineering perturbation of the stratospheric aerosol layer. *Geophys. Res. Lett.*, doi: 10.1002/2013GL058818 *Stratospheric SRM*
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- 46 Bewick R., Sanchez J.P. & McInnes C.R. (2012) Gravitationally bound geoengineering dust shade at the inner Lagrange point. *Advances in Space Research*, 50, 1405-1410 *Space SRM*
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60	ETC Group (2013)	The artificial intelligence of geoengineering. <i>ETC Communiqué 109</i> (8pp)	<i>Multi-technique</i>
61	Ferraro A.J., Highwood E.J. & Charlton-Perez A.J. (2014)	Weakened tropical circulation and reduced precipitation in response to geoengineering. <i>Environ. Res. Lett.</i> 9, 014001; doi:10.1088/1748-9326/9/1/014001	<i>Stratospheric SRM</i>
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68	Haywood J.M., Jones A., Bellouin N. & Stephenson D.B. (2013)	Asymmetric forcing from stratospheric aerosols impacts Sahelian rainfall. <i>Nature Climate Change</i> , 3, 660-665; doi: 10.1038/nclimate1857.	<i>Stratospheric SRM</i>
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70	Hommel R. & Graf H.-F. (2012)	Modelling the size distribution of geoengineered stratospheric aerosols. <i>Atmos. Sci. Lett.</i> , 12, 168-175.	<i>Stratospheric SRM</i>
71	Honegger M., Michaelowa A. & Butzengeiger-Geyer S. (2012)	<i>Climate Engineering: Avoiding Pandora's Box through Research and Governance</i> . FIN Climate Policy Perspectives 5 (8pp)	<i>Multi-technique</i>
72	Hulme M. (2012)	Climate change: climate engineering through stratospheric aerosol injection. <i>Prog. Phys. Geog.</i> 36, 694-705	<i>Stratospheric SRM</i>
(16)	IPCC (2013)	<i>Climate Change 2013: The Physical Science Basis</i> . Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. http: www.ipcc.ch .	<i>Multi-technique</i>
(17)	IPCC (2014a)	<i>Climate Change 2014: Impacts, Adaptation and Vulnerability</i> . Working Group II Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. http: www.ipcc.ch .	<i>Multi-technique</i>
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129	Volodin, E. M., Kostykin, S. V., & Ryaboshapko, A. G. (2012).	Climate response to aerosol injection at different stratospheric locations. <i>Atmos. Sci. Lett.</i> , 12, 381-385.	Stratospheric SRM
130	Wood R. & Ackerman T.P. (2013)	Defining success and limits of field experiments to test geoengineering by marine cloud brightening. <i>Clim. Change</i> , 121, 459-472	Tropospheric SRM
131	Wood R., Gardiner S. & Hartzell-Nichols L. (2013).	Climatic Change special issue: geoengineering research and its limitations. <i>Clim. Change</i> , 121, 427-430.	Multi-technique

1.3 Greenhouse gas removal (GGR) methods. Publications have been allocated to the following topic areas: biochar; BECCS (bioenergy with carbon capture and storage); biomass storage (separated into land and ocean); direct air capture; enhanced weathering (separated into land and ocean, the latter including ocean alkalization); CO₂ storage (separated into land and ocean); ocean fertilization; and multi-technique. Publications with reference numbers in brackets have already been listed above.

	Authors (date)	Publication title; <i>journal</i>	Topic area
132	Achterberg E.P., Moore C.M, Henson S. A., Steigenberger S. <i>et al</i> (2013)	Natural iron fertilization by the Eyjafjallajökull volcanic eruption. <i>Geophys. Res. Lett.</i> , 40, 921-926; doi: 10.1002/grl.5022	Ocean fertilization
133	Al-Traboulsi M., Sjoegersten S., Colls J. <i>et al.</i> (2013)	Potential impact of CO ₂ leakage from Carbon Capture and Storage (CCS) systems on growth and yield in maize. <i>Plant & Soil</i> , 365, 267-281	CO ₂ storage: land
134	Ameloot N., Graber E.R., Verheijen F.G.A. <i>et al.</i> (2013)	Interactions between biochar stability and soil organisms: review and research needs. <i>Europ. J. Soil Sci.</i> , 64, 379-390	Biochar
135	Azar C., Johansson D.J.A. & Mattsson N. (2013)	Meeting global temperature targets—the role of bioenergy with carbon capture and storage. <i>Environ. Res. Lett.</i> , 8, 034004; doi:10.1088/1748-9326/8/3/034004	BECCS
(43)	Belter C.W. & Seidel, D.J. (2013)	A bibliometric analysis of climate engineering research, <i>WIREs Clim. Change</i> , 4, 417-427; doi: 10.1002/wcc.229.	Multi-technique
136	Biederman L.A. & Harpole W.S. (2013)	Biochar and its effects on plant productivity and nutrient cycling: a meta-analysis. <i>Glob. Change Biol. Bioenergy</i> , 5, 202-214	Biochar
137	Boucher J. F., Tremblay P., Gaboury S. & Villeneuve C. (2013)	Can boreal afforestation help offset incompressible GHG emissions from Canadian industries? <i>Process Safety and Environmental Protection</i> , 90, 459-466.	Biomass storage: land
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140	Boyd P.W., Bakker D. C. E. & Chandler C. (2012)	A new database to explore the findings from large-scale ocean iron enrichment experiments. <i>Oceanography</i> , 25, 64-71.	Ocean fertilization
(51)	Caldeira K., Govindasamy B. & Cao L. (2013)	The science of geoengineering. <i>Ann. Rev. Earth Planetary Sci.</i> , 41, 231-256.	Multi-technique
141	Case S. D. C., McNamara N. P., Reay D.S. <i>et al.</i> (2014)	Can biochar reduce soil greenhouse gas emissions from a <i>Miscanthus</i> bioenergy crop? <i>Glob. Change Biol. Bioenergy</i> 6, 76-89	Biochar

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208	Schuiling R. D. (2013)	Carbon dioxide sequestration, weathering approaches to. In: <i>Geoengineering Responses to Climate Change</i> (ed: T. M. Lenton & N. E. Vaughan), p 141-167. Springer, New York.	<i>Enhanced weathering: land</i>
209	Schulz H., Dunst G. & Glaser B. (2013)	Positive effects of composted biochar on plant growth and soil fertility. <i>Agronomy Sustainable Development</i> , 33, 817-827	<i>Biochar</i>
210	Shackley S., Sohi S., Ibarrola R., Hammond J. <i>et al.</i> (2013)	Biochar, tool for climate change mitigation and soil management. In: <i>Geoengineering Responses to Climate Change</i> (ed: T. M. Lenton & N. E. Vaughan), p. 73-140. Springer, New York.	<i>Biochar</i>
(121)	Shepherd J.G. (2012)	Geoengineering the climate: an overview and update. <i>Phil. Trans. R. Soc. A</i> , 370, 4166-4175; doi: 10.1098/rsta.2012.0186	<i>Multi-technique</i>
211	Singla A. & Inubushi K. (2014)	Effect of biochar on CH ₄ and N ₂ O emission from soils vegetated with paddy. <i>Paddy Water Environ.</i> , 12, 239-243	<i>Biochar</i>
212	Smith L.J. & Torn M.S. (2013)	Ecological limits to terrestrial biological carbon dioxide removal, <i>Clim. Change</i> , 118, 89-103; doi: 10.1007/s10584-012-0682-3	<i>Multi-technique</i>
213	Stavi I. & Lal R. (2013)	Agroforestry and biochar to offset climate change: a review. <i>Agronomy for Sustainable Development</i> , 33, 81-96	<i>Multi-technique</i>
214	Stolaroff J.K., Bhattacharyya S., Smith C.A., Bourcier W.L. <i>et al.</i> (2012)	Review of methane mitigation technologies with application to rapid release of methane from the Arctic. <i>Environ. Sci. Technol.</i> , 46, 6455-6469.	<i>Multi-technique</i>
215	Tavoni M. & Socolow R. (2013)	Modeling meets science and technology: an introduction to a special issue on negative emissions, <i>Clim. Change</i> , 118, 1-14; doi: 10.1007/s10584-013-0757-9	<i>Multi-technique</i>
216	van Vuuren D.P., Deetman S., van Vleet J., van den Berg M. <i>et al.</i> (2013)	<i>The role of negative CO₂ emissions for reaching 2° C: insights from integrated assessment modelling.</i> <i>Clim. Change</i> , 118, 59-72; doi: 10.1007/s10584-013-0714-7	<i>Multi-technique</i>
(128)	Vaughan N.E. & Lenton T.M. (2012)	Interactions between reducing CO ₂ emissions, CO ₂ removal and solar radiation management. <i>Phil. Trans. R. Soc. A</i> , 370, 4343-4364; doi:10.1098/rsta.2012.0188	<i>Multi-technique</i>
217	Verheijen F.G.A., Jeffery S., van der Velde M. <i>et al.</i> (2013)	Reductions in soil surface albedo as a function of biochar application rate: implications for global radiative forcing. <i>Environ. Res. Lett.</i> , 8, Article 044008	<i>Biochar</i>

218	Verheijen, F. G. A., Montanarella, L., & Bastos, A. C. (2012).	Sustainability, certification, and regulation of biochar. <i>Pesquisa Agropecuaria Brasileira</i> , 47, 649-653.	<i>Biochar</i>
219	Vichi M., Navarra A. & Fogli P. G. (2013).	Adjustment of the natural ocean carbon cycle to negative emission rates. <i>Clim. Change</i> , 118, 105-118; doi: 10.1007/s10584-012-0677-0	<i>Multi-technique</i>
220	Wang J., Pan X., Liu Y., Zhang X. & Xiong Z. (2012)	Effects of biochar amendment in two soils on greenhouse gas emissions and crop production. <i>Plant & Soil</i> , 360, 287-298.	<i>Biochar</i>
221	Williamson P., Wallace D.W.R., Law C.S., Boyd P.W. et al (2012)	Ocean fertilization for geoengineering: a review of effectiveness, environmental impacts and emerging governance. <i>Process Safety Environ. Protection</i> , 90, 475-488.	<i>Ocean fertilization</i>
(131)	Wood R., Gardiner S. & Hartzell-Nichols L. (2013).	Climatic Change special issue: geoengineering research and its limitations. <i>Climatic Change</i> , 121, 427-430.	<i>Multi-technique</i>
222	Xiu P., Thomas A.C. & Chai F. (2014)	Satellite bio-optical and altimeter comparisons of phytoplankton blooms induced by natural and artificial iron addition in the Gulf of Alaska. <i>Remote Sensing of Environment</i> , 145, 38-46	<i>Ocean fertilization</i>
223	Xu G., Lv Y., Sun J. et al. (2012)	Recent advances in biochar applications in agricultural soils: benefits and environmental implications. <i>Clean Soil Air Water</i> , 40, 1093-1098	<i>Biochar</i>
224	Yu L., Tang J., Zhang R. et al. (2013)	Effects of biochar application on soil methane emission at different soil moisture levels. <i>Biology & Fertility of Soils</i> , 49, 119-128.	<i>Biochar</i>
225	Zeng N., King A.W., Zaitchik B., Wullschlegel S.D. et al (2013)	Carbon sequestration via wood harvest and storage: An assessment of its harvest potential. <i>Climatic Change</i> , 118, 245-257; doi: 10.1007/s10584-012-0624-0.	<i>Biomass storage: land</i>

1.4 Socio-economic, cultural and ethical aspects. Publications have been allocated to the following topic areas: ethics and values; policy and governance; discourse analysis; economics; and multi-topic. Publications with reference numbers in brackets have already been listed above.

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(42)	Baum, S. D., Maher T. M. & Haqq-Misra J. (2013)	Double catastrophe: intermittent stratospheric geoengineering induced by societal collapse. <i>Environ. Sys. Decis.</i> , 33, 168-180.	<i>Ethics & values</i>
227	Bellamy R., Chilvers J., Vaughan N.E. & Lenton T.M (2012)	A review of climate geoengineering appraisals. <i>WIRes Clim. Change</i> , 3, 597-615	<i>Ethics & values</i>
228	Bellamy R., Chilvers J., Vaughan N.E. & Lenton T.M. (2013)	'Opening up' geoengineering appraisal: Multi-criteria mapping of options for tackling climate change. <i>Global Environ. Change</i> , 23, (Special Issue) SI 926-937; doi: 10.1016/j.gloenvcha.2013.07.011.	<i>Ethics & values</i>
(43)	Belter C.W. & Seidel, D.J. (2013)	A bibliometric analysis of climate engineering research, <i>WIRes Clim. Change</i> , 4, 417-427; doi: 10.1002/wcc.229.	<i>Multi-topic</i>
229	Betz G. (2012)	The case for climate engineering research: An analysis of the "arm the future" argument. <i>Clim. Change</i> 111, 473-485.	<i>Ethics & values</i>
230	Betz G. & Cacean S. (2012)	<i>Ethical Aspects of Climate Engineering</i> . KIT Scientific Publishing, Karlsruhe. http://digbib.ubka.uni-karlsruhe.de/volltexte/1000028245	<i>Ethics & values</i>
231	Bickel J. E. (2013)	Climate engineering and climate tipping-point scenarios. <i>Environ. Sys. Decis.</i> 33, 152-167; doi: 10.1007/s10669-013-9435-8	<i>Ethics & values</i>
(48)	Bickel J. E. & Agrawal S. (2013).	Re-examining the economics of aerosol geoengineering. <i>Climatic Change</i> 119, 993-1006.	<i>Economics</i>
232	Blackstock, J. (2012)	Researchers can't regulate climate engineering alone. <i>Nature</i> , 486, 159.	<i>Policy & governance</i>
233	Bodansky D. (2013)	The who, what, and wherefore of geoengineering governance. <i>Climatic Change</i> , 121, 539-551	<i>Policy & governance</i>
234	Bodle R. (2013)	Climate law and geoengineering. In: <i>Climate Change and the Law</i> , E. J. Hollo, K. Kulovesi & M. Mehling (eds); 447-471. Dordrecht: Springer.	<i>Policy & governance</i>
235	Borgmann A. (2012)	The setting of the scene: technological fixes and the design of the good life. In: <i>Engineering the Climate: The Ethics of Solar Radiation Management</i> (Ed	<i>Ethics & values</i>

- C.J. Preston), Chapter 11, p 189-200.. Lexington Books/Rowman & Littlefield, Lanham MD
- 236 Borick C. & Rabe B.G. (2012) Americans cool on geoengineering approaches to addressing climate change. *Ethics & values Issues in Governance Studies* 47, 1-6
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Annex II

EXCERPTS FROM THE SUMMARIES FOR POLICYMAKERS OF THE REPORTS OF WORKING GROUPS I AND III OF THE IPCC'S FIFTH ASSESSMENT REPORT THAT DIRECTLY ADDRESS CLIMATE-RELATED GEOENGINEERING

Working Group I

“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 CO₂ 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.”

(IPCC 2013, WG I, Summary for Policymakers, Section E.8.)

Working Group III

“**Scenarios reaching atmospheric concentration levels of about 450 ppm CO₂eq 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 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 GtCO₂eq or below in 2100. In scenarios reaching 500 ppm CO₂eq by 2100, 2050 emissions levels are 25% to 55% lower than in 2010 globally. In scenarios reaching 550 ppm CO₂eq, 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 CO₂eq 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.”

(IPCC 2013, WG III, Summary for Policymakers, Section SPM.4)

“**Mitigation scenarios reaching about 450 ppm CO₂eq in 2100 typically involve temporary overshoot of atmospheric concentrations, as do many scenarios reaching about 500 ppm to 550 ppm CO₂eq in 2100. Depending on the level of the overshoot, overshoot scenarios typically rely on the availability and widespread deployment of BECCS and afforestation in the second half of the century. The availability and scale of these and other Carbon Dioxide Removal (CDR) technologies and methods are uncertain and CDR technologies and methods are, to varying degrees, associated with challenges and risks (see Section SPM 4.2) (high confidence).** CDR is also prevalent in many scenarios without overshoot to compensate for residual emissions from sectors where mitigation is more expensive. There is only limited evidence on the potential for large-scale deployment of BECCS, large-scale afforestation, and other CDR technologies and methods.”

(IPCC 2013, WG III, Summary for Policymakers, Section SPM.4)

“**Carbon dioxide capture and storage (CCS) technologies could reduce the lifecycle GHG emissions of fossil fuel power plants (medium evidence, medium agreement).** While all components of integrated CCS systems exist and are in use today by the fossil fuel extraction and refining industry, CCS has not yet been applied at scale to a large, operational commercial fossil fuel power plant. CCS power plants could be seen in the market if this is incentivized by regulation and/or if they become competitive with their unabated counterparts, if the additional investment and operational costs, caused in part by efficiency reductions, are compensated by sufficiently high carbon prices (or direct financial support). For the large-scale future deployment of CCS, well-defined regulations concerning short- and long-term responsibilities for storage are needed as well as economic incentives. Barriers to large-scale deployment of CCS technologies include concerns about the operational safety and long-term integrity of CO₂ storage as well as transport risks. There is, however, a growing body of literature on how to ensure the integrity of CO₂ wells, on the potential consequences of a pressure build-up within a geologic formation caused

by CO₂ storage (such as induced seismicity), and on the potential human health and environmental impacts from CO₂ that migrates out of the primary injection zone (*limited evidence, medium agreement*).”
(IPCC 2013, WG III, Section SPM.4.2.2)

“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.”
(IPCC 2013, WG III, Section SPM.4.2.2)

“Policies governing agricultural practices and forest conservation and management are more effective when involving both mitigation and adaptation. Some mitigation options in the AFOLU sector (such as soil and forest carbon stocks) may be vulnerable to climate change (*medium evidence, high agreement*). When implemented sustainably, activities to reduce emissions from deforestation and forest degradation (REDD+ is an example designed to be sustainable) are cost-effective policy options for mitigating climate change, with potential economic, social and other environmental and adaptation co-benefits (e.g., conservation of biodiversity and water resources, and reducing soil erosion) (*limited evidence, medium agreement*).”
(IPCC 2013, WG III, Section SPM.4.2.4)

“Bioenergy can play a critical role for mitigation, but there are issues to consider, such as the sustainability of practices and the efficiency of bioenergy systems (*robust evidence, medium agreement*). Barriers to large-scale deployment of bioenergy include concerns about GHG emissions from land, food security, water resources, biodiversity conservation and livelihoods. The scientific debate about the overall climate impact related to land-use competition effects of specific bioenergy pathways remains unresolved (*robust evidence, high agreement*). Bioenergy technologies are diverse and span a wide range of options and technology pathways. Evidence suggests that options with low lifecycle emissions (e.g., sugar cane, 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 cookstoves, 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*).”
(IPCC 2013, WG III, Section SPM.4.2.4)
