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# IMPACTS OF CLIMATE-RELATED GEOENGINEERING ON BIOLOGICAL DIVERSITY

*Note by the Executive Secretary*

1. The Executive Secretary is circulating herewith, for the information of participants in the sixteenth meeting of the Subsidiary Body on Scientific, Technical and Technological Advice, a study on the impacts of climate-related geoengineering on biological diversity.

2. This study compiles and synthesizes available scientific information on the possible impacts of a range of geoengineering techniques on biodiversity, including preliminary information on associated social, economic and cultural considerations. The study also considers definitions and understandings of climate-related geoengineering relevant to the Convention on Biological Diversity (CBD). The study has been prepared in response to paragraph 9 (l) of decision X/33, to address the elements of the mandate from that decision which relate specifically to the impacts of climate-related geoengineering on biodiversity. Related legal and regulatory matters are treated in a separate study (UNEP/CBD/SBSTTA/16/INF/29). In addition, a separate consultation process has been undertaken by the Convention on Biological Diversity in order to seek the views of indigenous peoples and local communities on the possible impacts of geoengineering techniques on biodiversity and associated social, economic and cultural considerations (UNEP/CBD/SBSTTA/16/INF/30).

3. This study has been prepared by a group of experts and the Secretariat of the Convention on Biological Diversity, taking into account comments from two rounds of review by Parties, experts and stakeholders.[3]

4. The key messages are available in all United Nations languages in section II of the note by the Executive Secretary on the technical and regulatory matters on geoengineering in relation to the Convention on Biological Diversity (UNEP/CBD/SBSTTA/16/10).

5. The study has not been formally edited. It will be edited prior to publication in the CBD Technical Series.

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* UNEP/CBD/SBSTTA/16/1.

[1] Reissued to include the Key Messages (as provided in document UNEP/CBD/SBSTTA/16/10) and the table of contents. The rest of the text remains unchanged.

[2] Lead authors are: Phillip Williamson, Robert Watson, Georgina Mace, Paulo Artaxo, Ralph Bodle, Victor Galaz, Andrew Parker, David Santillo, Chris Vivian, David Cooper, Jaime Webbe, Annie Cung and Emma Woods. Others who provided input or comments are listed in annex II.

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# IMPACTS OF CLIMATE-RELATED GEOENGINEERING ON BIOLOGICAL DIVERSITY

## KEY MESSAGES

6. **Biodiversity, ecosystems and their services are critical to human well-being. Protection of biodiversity and ecosystems requires that drivers of biodiversity loss are reduced.** The current main direct drivers of biodiversity loss are habitat conversion, over-exploitation, introduction of invasive species, pollution and climate change. These in turn are being driven by demographic, economic, technological, socio-political and cultural changes. Human-driven climate change due to greenhouse-gas emissions is becoming increasingly important as a driver of biodiversity loss and the degradation of ecosystem services. A rapid transition to a low-carbon economy is the best strategy to reduce such adverse impacts on biodiversity. However, on the basis of current greenhouse-gas emissions, their long atmospheric residence times and the relatively limited action to date to reduce future emissions, the use of geoengineering techniques has also been suggested as an additional means to limit the magnitude of human-induced climate change and its impacts.

*Proposed climate-related geoengineering techniques*

7. **In this report, climate-related geoengineering is defined as a deliberate intervention in the planetary environment of a nature and scale intended to counteract anthropogenic climate change and its impacts.** Geoengineering techniques include increasing the reflectivity of the Earth's surface or atmosphere, and removing greenhouse gases from the atmosphere; other approaches have also been proposed. This definition of geoengineering encompasses a wide spectrum of possible actions to counteract (or remedy) global warming and its associated consequences. The commonality of those actions is that they could produce global cooling, if applied at sufficient scale. Geoengineering can therefore be differentiated from actions that mitigate (reduce or prevent) anthropogenic greenhouse-gas emissions. Carbon capture and storage (CCS) linked to fossil fuel combustion is not here considered as geoengineering, although some geoengineering techniques may involve the same or similar processes of managed carbon storage. Afforestation/reforestation and large scale land-management changes are, however, included, notwithstanding that such measures are already deployed for climate-change mitigation and other purposes, and that they involve minimal use of new technologies. (*Sections 2.1-2.2*)[4]

8. **Sunlight reflection methods (SRM), also known as solar radiation management, aim to counteract warming and associated climatic changes by reducing the incidence and subsequent absorption of short-wave solar radiation, reflecting a small proportion of it back into space.** They are expected to rapidly have an effect once deployed at the appropriate scale, and thus have the potential to reduce surface global temperatures within a few months or years if that were considered desirable. SRM would not address the root cause of human-driven climate change arising from increased greenhouse-gas concentrations in the atmosphere: instead they would mask the warming effect of accumulating greenhouse gases. They would introduce a new dynamic between the warming effects of greenhouse gases and the cooling effects of SRM with uncertain climatic implications, especially at the regional scale. SRM would not directly address ocean acidification. SRM proposals include:

1. *Space-based approaches:* reducing the amount of solar energy reaching the Earth by positioning sun-shields in space with the aim of reflecting or deflecting solar radiation;
2. *Changes in stratospheric aerosols*: injecting sulphates or other types of particles into the upper atmosphere, with the aim of increasing the scattering of sunlight back to space;
3. *Increases in cloud reflectivity:* increasing the concentration of cloud-condensation nuclei in the lower atmosphere, particularly over ocean areas, thereby whitening clouds with the aim of increasing the reflection of solar radiation;
4. *Increases in surface albedo:* modifying land or ocean surfaces with the aim of reflecting more solar radiation out to space.

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[4] Information in parentheses indicates where full details, with references, can be found in the main report.

SRM could be implemented separately or in combination, at a range of scales. (*Section 2.2.1*)

9. **Carbon dioxide removal (CDR) techniques aim to remove $CO_2$, a major greenhouse gas, from the atmosphere**, allowing outgoing long-wave (thermal infra-red) radiation to escape more easily. In principle, other greenhouse gases, such as nitrous oxide ($N_2O$), and methane ($CH_4$), could also be removed from the atmosphere or reduced at source, but such approaches are currently highly speculative. Proposed CDR techniques include:

1. *Ocean fertilization:* the enrichment of nutrients in marine environments with the intention of stimulating plant production, hence $CO_2$ uptake from the atmosphere and the deposition of carbon in the deep ocean;
2. *Enhanced weathering:* artificially increasing the rate by which $CO_2$ is naturally removed from the atmosphere by the weathering (dissolution) of carbonate and silicate rocks;
3. *Increasing carbon sequestration through ecosystem management:* through, for example: afforestation, reforestation, or measures that enhance natural carbon storage in soils and wetlands
4. *Biological carbon capture, using harvested biomass and subsequent carbon storage:* for example, through biochar, the long term storage of crop residues or timber, or bio-energy with carbon capture and storage; and
5. *Direct, chemical capture of carbon from the atmosphere and its subsequent storage*, for example, with storage as liquid $CO_2$ in geological formations or in the deep ocean.

CDR approaches involve two steps: (1) $CO_2$ capture from the atmosphere; and (2) long-term storage (sequestration) of the captured carbon. In the first three techniques, these two steps are very closely linked, although the permanence of the storage may be variable and technique-specific; in the fourth and fifth, capture and storage may be separated in time and space. Ecosystem-based approaches such as afforestation, reforestation or the enhancement of soil carbon are already employed as climate-change mitigation activities, and are not universally regarded as geoengineering technologies. CDR techniques act relatively slowly: to have a significant impact on the climate, such interventions, individually or collectively, would need to involve the removal from the atmosphere of several Gt C/yr (gigatonnes of carbon per year), maintained over decades. This seems unlikely to be achievable for several proposed CDR approaches. (*Section 2.2.2*)

10. **There is no single geoengineering approach that currently meets all three basic criteria for effectiveness, safety and affordability. Different techniques are at different stages of development, mostly theoretical, and many are of doubtful effectiveness.** Few, if any, of the approaches proposed above can be considered well-researched; for most, the practicalities of their implementation have yet to be investigated, and mechanisms for their governance are potentially problematic. Early indications are that several of the techniques, both SRM and CDR, are unlikely to be effective at the global scale. (*Section 2*)

*Climate change and ocean acidification, and their impacts on biodiversity*

11. **The continued increase in $CO_2$ and other atmospheric greenhouse gases not only has profound implications for global and regional average temperatures, but also for precipitation, soil moisture, ice-sheet dynamics, sea-level rise, ocean acidification and the frequency and magnitude of extreme events such as floods, droughts and wildfires.** Future climatic perturbations could be abrupt or irreversible, and potentially extend over millennial time scales; they will inevitably have major consequences for natural and human systems, severely affecting biodiversity and incurring very high socio-economic costs. (*Section 3.1*).

12. **Since 2000, the rate of increase in anthropogenic CO2 emissions has accelerated, averaging ~3.1% per year. Emissions of other greenhouse gases are also increasing. As a result, it will be extremely challenging to limit global warming to the proposed target of 2°C.** In fact, current commitments to limit greenhouse-gas emissions correspond to a 3-5$^{o}$C warmer world. Avoidance of high risk of dangerous climate change therefore requires an urgent and massive effort to reduce greenhouse-gas emissions, as well as protecting existing natural carbon sinks, including through sustainable land management. If such efforts are not made, geoengineering approaches are likely to be increasingly proposed to offset at least some of the impacts of climate change, despite the risks and uncertainties involved (*Section 3.1.2*).

13. **Even with strong climate mitigation policies, further human-driven climate change is inevitable due to lagged responses in the Earth climate system.** Increases in global mean surface

temperature of 0.3 - 2.2°C are projected to occur over several centuries after atmospheric concentrations of greenhouse gases have been stabilized, with associated increases in sea level due to thermally-driven expansion and ice-melt. The seriousness of these changes provides the reason why geoengineering has attracted attention. (*Section 3.1.2*)

14. **Human-driven climate change poses an increasingly severe range of threats to biodiversity and ecosystem services, greatly increasing the risk of species extinctions and local losses.** Temperature, precipitation and other climate attributes strongly influence the distribution and abundance of species, and their interactions. Because species respond to climate change in different ways, ecosystems (and the services they provide) will be disrupted. Projected climate change is not only more rapid than recent naturally-occurring climate change (e.g., during ice age cycles) but now the scope for such adaptive responses is reduced by other anthropogenic pressures, including over-exploitation, habitat loss, fragmentation and degradation, introduction of non-native species, and pollution. Risk of global extinction and local extirpations is therefore increased, since the abundance and genetic diversity of many species are already reduced, and their adaptive capacity is lessened. (*Section 3.2.1*)

15. **The terrestrial impacts of projected climate change are likely to be greatest for montane and polar habitats, for coastal areas affected by sea-level change, and wherever there are major changes in freshwater availability.** Species with limited adaptive capability will be particularly at risk; while insect pests and disease vectors in temperate regions are expected to benefit. Forest ecosystems, and the goods and services they provide, are likely to be affected as much, or more, by changes in hydrological regimes (affecting fire risk) and pest abundance, than by direct effects of temperature change. *(Section 3.2.2)*

16. **Marine species and ecosystems are increasingly subject to ocean acidification as well as changes in temperature.** Climate driven changes in the reproductive success, abundance and distribution of marine organisms are already occurring, more rapidly than on land. The loss of summer sea-ice in the Arctic will have major biodiversity implications. Biological impacts of ocean acidification (an inevitable chemical consequence of the increase in atmospheric $CO_2$) are less certain; nevertheless, an atmospheric $CO_2$ concentration of 450 ppm would decrease surface pH by ~0.2 units, making large-scale and ecologically significant effects likely. Tropical corals seem to be especially at risk, being vulnerable to the combination of ocean acidification, temperature stress (coral bleaching), coastal pollution (eutrophication and increased sediment load), sea-level rise and human exploitation (over-fishing and coral-harvesting). (*Section 3.2.3*)

17. **The biosphere plays a key role in climate processes, especially as part of the carbon and water cycles**. Very large amounts of carbon are naturally circulated and stored by terrestrial and marine ecosystems, through biologically-driven processes. Proportionately small changes in ocean and terrestrial carbon stores, caused by changes in the balance of natural exchange processes, can have climatically-significant implications for atmospheric $CO_2$ levels. Potential tipping points that may cause the rapid release of long-term carbon stores, e.g., as methane, are poorly understood. (*Section 3.3*)

*Potential impacts on biodiversity of SRM geoengineering*

18. **SRM, if effective in abating the magnitude of warming, would reduce several of the climate-change related impacts on biodiversity. Such techniques are also likely to have other, unintended impacts on biodiversity.** Assessment of the totality of those impacts is not straightforward: not only are the effects of specific SRM measures uncertain, but the outcome of the risk assessment will depend on the alternative, non-SRM strategy used as the 'control' for comparisons. Because climate change is projected to occur, climate-change scenarios provide relevant controls for assessing the risks and benefits of geoengineering, including the implications for biodiversity (*Chapter 4; Introduction*)

19. **Model-based analyses and evidence from volcanic eruptions indicate that uniform dimming of sunlight by 1-2% through an unspecified atmospheric SRM measure could, for most areas of the planet, reduce future temperature changes projected under unmitigated greenhouse gas emissions.** Overall, this would reduce several of the adverse impacts of projected climate change on biodiversity. These benefits would vary regionally, and might be negligible or absent for some areas. However, only limited research has been done; uniform dimming is a theoretical concept and may not be achievable; and many uncertainties remain concerning the effects

of different atmospheric SRM measures and their geo-spatial consequences, for the hydrological cycle as well as for heat distribution. It is therefore not yet possible to predict effects with any confidence. (*Section 4.1.1*)

20. **SRM would introduce a new dynamic between the heating effects of greenhouse gases and the cooling due to sunlight reduction**. There are no known palaeo-precedents for the radiative impacts of high greenhouse-gas concentrations to be balanced by reduced light quantity; thus the stability of that combination is uncertain, and it is not clear what specific environmental challenges an “SRM world” might present to individual species and ecosystems, either on a short-term or a long-term basis. (*Section 4.1.3*)

21. **The amount of anthropogenic $CO_2$ in the atmosphere is unaffected by SRM. Thus SRM would have little effect on ocean acidification and its associated impacts on marine biodiversity, nor the impacts (positive or negative) of elevated atmospheric $CO_2$ on terrestrial ecosystems.** Some indirect effects of SRM on atmospheric $CO_2$ are possible; e.g., if such techniques prevent the temperature-driven release of additional $CO_2$ from natural systems. Nevertheless, SRM cannot be considered as an alternative to emission mitigation or CDR in terms of avoiding detrimental effects on the (marine) biosphere. (*Section 4.1.4*)

22. **Rapid termination of SRM, that had been deployed for some time and masking a high degree of warming due to continued greenhouse-gas emissions, would almost certainly have large negative impacts on biodiversity and ecosystem services.** Those adverse consequences would be more severe than those resulting from gradual climate change, since the opportunity for adaptation, including through population migration, would be much reduced. (*Section 4.1.5*)

23. **Stratospheric aerosol injection, using sulphate particles, would affect the overall quantity and quality of light reaching the biosphere; have relatively minor effects on atmospheric acidity; and could also contribute to stratospheric ozone depletion.** All these unintended impacts have implications for biodiversity and ecosystem services. Stratospheric aerosols would decrease the amount of photosynthetically active radiation (PAR) reaching the Earth by 1-2%, but would increase the proportion of diffuse (as opposed to direct) radiation. This would be expected to affect community composition and structure. It may lead to an increase of gross primary productivity (GPP) in forest ecosystems whilst decreasing ocean productivity. However, the magnitude and nature of effects on biodiversity are likely to be mixed, and are currently not well understood. Increased ozone depletion, primarily in the polar regions, would cause an increase in the amount of ultra violet (UV) radiation reaching the Earth, although potentially offset by the UV scattering of the aerosol particles themselves. (*Section 4.2.1*)

24. **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;** nevertheless regional cooling with associated atmospheric and oceanic perturbations are likely, with potentially significant effects on terrestrial and marine biodiversity and ecosystems. Unintended impacts could be positive as well as negative. (*Section 4.2.2*)

25. **Surface albedo changes would need to be deployed over very large land areas (sub-continental scale) or over much of the global ocean to have substantive effects on the global climate, with consequent impacts on ecosystems. Strong localized cooling could have a disruptive effect on regional weather patterns.** For instance, covering deserts with reflective material on a scale large enough to be effective in addressing the impacts of climate change would greatly reduce habitat availability for desert fauna and flora, as well as affecting its customary use. (*Section 4.2.3*)

*Potential impacts on biodiversity of CDR geoengineering techniques*

26. **Carbon dioxide removal techniques, if effective and feasible, would be expected to reduce the negative impacts on biodiversity of climate change and, in most cases, of ocean acidification.** By removing $CO_2$ from the atmosphere, CDR techniques reduce the concentration of the main causal agent of anthropogenic climate change, Acidification of the surface ocean would also be reduced, but the effect of CDR on the ocean as a whole will depend on the location of long-term carbon storage. CDR methods are generally slow in affecting the atmospheric $CO_2$ concentration, with further substantial time-lags in the climatic benefits. Several of the techniques are of doubtful effectiveness, because of limited scalability. (*Section 5.1*)

27. **Individual CDR techniques may have significant unintended impacts on terrestrial, and/or ocean ecosystems, depending on the nature, scale and location of carbon capture and storage.** In some biologically-driven processes (ocean fertilization; afforestation, reforestation and soil carbon enhancement), carbon removal from the atmosphere and its subsequent storage are very closely linked. In these cases, impacts on biodiversity are likely to be limited to marine and terrestrial systems respectively. In other cases, the steps are discrete, and various combinations of capture and storage options are possible. Thus the carbon that is fixed within land biomass, for example, could be either: dumped in the ocean as crop residues; incorporated into the soil as charcoal; or used as fuel with the resultant $CO_2$ chemically removed at source and stored either in sub-surface reservoirs or the deep ocean. In these cases, each step will have different and additive potential impacts on biodiversity, and potentially separate impacts on marine and terrestrial environments. (*Section 5.1*)

28. **Ocean fertilization involves increased biological primary production with associated changes in phytoplankton community structure and species diversity, and implications for the wider food web.** Ocean fertilization may be achieved through the external addition of nutrients (Fe, N or P) or, possibly, by modifying ocean upwelling. If carried out on a climatically significant scale, changes may include an increased risk of harmful algal blooms, and increased benthic biomass. Potential effects on fisheries are uncertain. If Fe is used to stimulate primary production, increases in one region may be offset, to some degree, by decreases elsewhere. Ocean fertilization is expected to increase the midwater production of methane and nitrous oxide; if released to the atmosphere, these greenhouse gases would significantly reduce the effectiveness of the technique. Large-scale ocean fertilization would slow near-surface ocean acidification but increase acidification (and potential anoxia) in mid- and deep-water. The small-scale experiments conducted to date indicate that this is a technique of doubtful effectiveness for geoengineering purposes. (*Section 5.2.1*)

29. **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.** $CO_2$ is naturally removed from the atmosphere by the weathering (dissolution) of carbonate and silicate rocks. This process could be artificially accelerated by techniques that include releasing calcium carbonate or other dissolution products of alkaline minerals into the ocean or spreading abundant silicate minerals such as olivine over agricultural soils. In the ocean, this technique could, in theory, be used to counter ocean acidification; the practicalities have yet to be tested. (*Section 5.2.2*)

30. **The impacts on biodiversity of ecosystem carbon storage through afforestation, reforestation, or the enhancement of soil and wetland carbon depend on the method and scale of implementation.** If managed well, such approaches have the potential to increase or maintain biodiversity. Afforestation, reforestation and land-use change are already being promoted as climate change mitigation options, and are not considered by many to be geoengineering. Much guidance has already been developed, by the Convention on Biological Diversity and others, to maximize the biodiversity benefits of these approaches and minimize the disadvantages (e.g., planting assemblages of native species rather than exotic monocultures). (*Section 5.2.3*)

31. **Production of biomass for carbon sequestration on a scale large enough to be climatically significant is likely to either compete for land with food and other crops or involve large-scale land-use change, with impacts on biodiversity as well as greenhouse-gas emissions that may partially offset (or even exceed) the carbon sequestered as biomass.** The coupling of biomass production with its use as bioenergy in power stations equipped with effective carbon capture at source has the potential to be carbon negative. The net effects on biodiversity and greenhouse-gas emissions would depend on the approaches used. The storage or disposal of biomass may have impacts on biodiversity separate from those involved in its production. Removal of organic matter from agricultural ecosystems is likely to have negative impacts on agricultural productivity and biodiversity, and may increase the need for fertilizer application to maintain soil fertility. (*Section 5.2.4.1*)

32. **The impacts of long-term storage of biochar (charcoal) in different soil types and under different environmental conditions are not well understood.** Important issues that need to be resolved include the stability of carbon in the biochar, and effects on soil water retention, $N_2O$ release, crop yields, mycorrhizal fungi, soil microbial communities and detritivores. (*Section 5.2.4.2.1*)

33. **Ocean storage of terrestrial biomass (e.g., crop residues) is expected to have a negative impact on biodiversity.** The deposition of ballasted bales would likely have significant local physical impacts on the seabed due to the sheer mass of the material. Wider, long-term indirect effects of oxygen depletion and deep-water acidification could be regionally significant if there were cumulative deposition, and subsequent decomposition, of many gigatonnes of organic carbon. (*Section 5.2.4.2.2*)

34. **Chemical capture of $CO_2$ from ambient air would require a large amount of energy. Some proposed processes may also have high demand for freshwater, and potential risk of chemical pollution from sorbent manufacture; otherwise they would have relatively small direct impacts on biodiversity.** Removal of $CO_2$ from the ambient air (where its concentration is 0.04%) is much more difficult and energy intensive than its capture from flue gases of power stations (where levels are about 300 times higher, at ~12%); it is therefore unlikely to be viable without additional carbon-free energy sources. $CO_2$ extracted from the atmosphere would need to be stored either in the ocean or in sub-surface geological reservoirs with additional potential impacts; alternatively, it could be converted to carbonates and bicarbonates. (*Section 5.2.5.1*)

35. **Ocean $CO_2$ storage will necessarily alter the local chemical environment, with a high likelihood of biological effects.** Effects on mid-water and seafloor ecosystems are likely through the exposure of marine invertebrates, fish and microbes to pH reductions of 0.1 - 0.3 units. Near-total destruction of deep seafloor organisms can be expected if lakes of liquid $CO_2$ are created. Chronic effects on ecosystems of direct $CO_2$ injection into the ocean over large ocean areas and long time scales have not yet been studied, and the capacity of ecosystems to compensate or adjust to such $CO_2$ induced shifts is unknown. (*Section 5.2.5.2.1*)

36. **Leakage from $CO_2$ stored in sub-seafloor geological reservoirs, though considered unlikely if sites are well selected, would have biodiversity implications for benthic fauna on a local scale.** $CO_2$ storage in sub-seafloor geological reservoirs is already being implemented at pilot-scale levels. Its effects on lithospheric microbial communities seem likely to be severe, but have not been studied (*Section 5.2.5.2.2*)

*Social, economic, cultural and ethical considerations of climate-related geoengineering*

37. **The consideration of geoengineering as a potential option raises many socio-economic, cultural and ethical issues, regardless of the specific geoengineering approach.** Such issues include global justice, the unequal spatial distribution of impacts and benefits, and intergenerational equity. Confidence in technological solutions, or alternatively risk-aversion, may be both highly differentiated across social groups and highly dynamic. (*Section 6.3*)

38. **Humanity is now the major force altering the planetary environment**. This has important repercussions, not only because it forces society to consider multiple and interacting global environmental changes, but also because it requires difficult discussions on whether it is desirable to move from (1) unintentional modifications of the Earth system, with implications that until a few decades ago we were unaware of; to (2) attempts to reach international agreement to reduce the actions causing the damage; and finally to (3) consideration of actions to deliberately modify global cycles and systems, to try to avoid the worst outcomes of climate change. (*Section 6.3.1*)

39. **The 'moral hazard' of geoengineering is that it is perceived as a technological fallback, possibly reducing effort on mitigation.** However, the opposite may also occur: when there is wider knowledge on geoengineering, and its limitations and uncertainties, increased policy effort might be directed at emission reductions. Other ethical considerations include the question of whether it is acceptable to remediate one pollutant by introducing another. (*Section 6.3.1*)

40. **In addition to limiting the undesirable impacts of climate change, the large-scale application of geoengineering techniques is near-certain to involve unintended side effects and increase socio-political tensions.** While technological innovation has helped to transform societies and improve the quality of life in many ways, it has not always done so in a sustainable manner. Failures to respond to early warnings of unintended consequences of particular technologies have been documented, and it has been questioned whether technological approaches are the best option to address problems created by the application of earlier technologies. (*Section 6.3.2*)

41. **An additional issue is the possibility of technological, political and social "lock in"**, whereby the development of geoengineering technologies might also result in the emergence of vested interests and increasing social momentum. It has been argued that this path of dependency could make

deployment more likely, and/or limit the reversibility of geoengineering techniques. To minimise such risks, research to assess the safety, feasibility and cost-effectiveness of geoengineering must be open-minded and objective, without prejudice to the desirability or otherwise of geoengineering implementation. (*Section 6.3.2*)

42. **Geoengineering raises a number of questions regarding the distribution of resources and impacts within and among societies and across time.** Access to natural resources is needed for some geoengineering techniques. Competition for limited resources can be expected to increase if land-based CDR techniques emerge as a competing activity for land, water and energy use. The distribution of impacts (both positive and negative) of SRM geoengineering is unlikely to be uniform – neither are the impacts of climate change itself. (*Section 6.3.4*)

43. **In cases in which geoengineering experimentation or interventions might have transboundary effects or impacts on areas beyond national jurisdiction, geopolitical tensions could arise** regardless of causation of actual negative impacts, especially in the absence of international agreement. As with climate change, geoengineering could also entail intergenerational issues: future generations might be faced with the need to maintain geoengineering measures in order to avoid termination effects that might be mostly caused by emissions from several decades earlier. (*Section 6.3.5*)

*Synthesis*

44. **The deployment of geoengineering techniques, if feasible and effective, could reduce the magnitude of climate change and its impacts on biodiversity. At the same time, most geoengineering techniques are likely to have unintended impacts on biodiversity, particularly when deployed at a climatically-significant scale, together with significant risks and uncertainties.** The nature of the unintended effects, and their spatial distribution, will vary among techniques; overall outcomes are difficult to predict. For several techniques, there would increases in land use change, and there could also be an increase in other drivers of biodiversity loss. (*Section 7.1*)

45. **There are many areas where knowledge is still very limited**. These include: (1) the overall effectiveness of some of the techniques, based on realistic estimates of their scalability; (2) how the proposed geoengineering techniques can be expected to affect weather and climate regionally and globally; (3) how biodiversity, ecosystems and their services are likely to respond to geoengineered changes in climate; (4) the unintended effects of different proposed geoengineering techniques on biodiversity; and (5) the social and economic implications, particularly with regard to geo-political acceptability, governance and the potential need for international compensation in the event of there being ‘winners and losers’. Targeted research could help fill these gaps (*Section 7.3*)

46. **There is very limited understanding among stakeholders of geoengineering concepts, techniques and their potential positive and negative impacts on biodiversity.** Not only is much less information available on geoengineering than for climate change, but there has been little consideration of the issues by indigenous peoples, local communities and marginalized groups, especially in developing countries. Since these communities play a major role in actively managing ecosystems that deliver key climatic services, the lack of knowledge of their perspective is a major gap that requires further attention (*Section 7.3*)

# CHAPTER 1: MANDATE, CONTEXT AND SCOPE OF WORK

## 1.1 Mandate

At the tenth meeting of the Conference of the Parties (COP-10) to the Convention on Biological Diversity (CBD), Parties adopted a decision on climate-related geoengineering[5] and its impacts on the achievement of the objectives of the CBD as part of its decision on biodiversity and climate change.

Specifically, in paragraph 8 of that decision, the Conference of the Parties:

> Invite[d] Parties and other Governments, according to national circumstances and priorities, as well as relevant organizations and processes, to consider the guidance below on ways to conserve, sustainably use and restore biodiversity and ecosystem services while contributing to climate change mitigation and adaptation to (….)
>
> 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 geo-engineering, and in accordance with the precautionary approach and Article 14 of the Convention, that no climate-related geo-engineering activities[6] 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;
>
> x) Make sure that ocean fertilization activities are addressed in accordance with decision IX/16 C, acknowledging the work of the London Convention/London Protocol."

Further, in paragraph 9 of that decision the Conference of the Parties:

> "Request[ed] the Executive Secretary to:
>
> l) Compile and synthesize available scientific information, and views and experiences of indigenous and local communities and other stakeholders, on the possible impacts of geo-engineering techniques on biodiversity and associated social, economic and cultural considerations, and options on definitions and understandings of climate-related geo-engineering relevant to the Convention on Biological Diversity and make it available for consideration at a meeting of the Subsidiary Body on Scientific, Technical and Technological Advice (SBSTTA) prior to the eleventh meeting of the Conference of the Parties; and
>
> m) Taking into account the possible need for science based global, transparent and effective control and regulatory mechanisms, subject to the availability of financial resources, undertake a study on gaps in such existing mechanisms for climate-related geo-engineering relevant to the Convention on Biological Diversity, bearing in mind that such mechanisms may not be best placed under the Convention on Biological Diversity, for consideration by SBSTTA prior to a future meeting of the Conference of the Parties and to communicate the results to relevant organizations."

Accordingly, this report has been prepared by a group of experts[7] and the CBD Secretariat following discussions of a liaison group convened thanks to financial support from the Government of the United Kingdom of Great Britain and Northern Ireland, and the Government of Norway. The report compiles and synthesizes available scientific information on the possible impacts of geoengineering

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[5] To match wider usage, 'geoengineering' is unhyphenated in this report (except where quoting previous CBD documents)

[6] "Without prejudice to future deliberations on the definition of geo-engineering 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 geo-engineering 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."

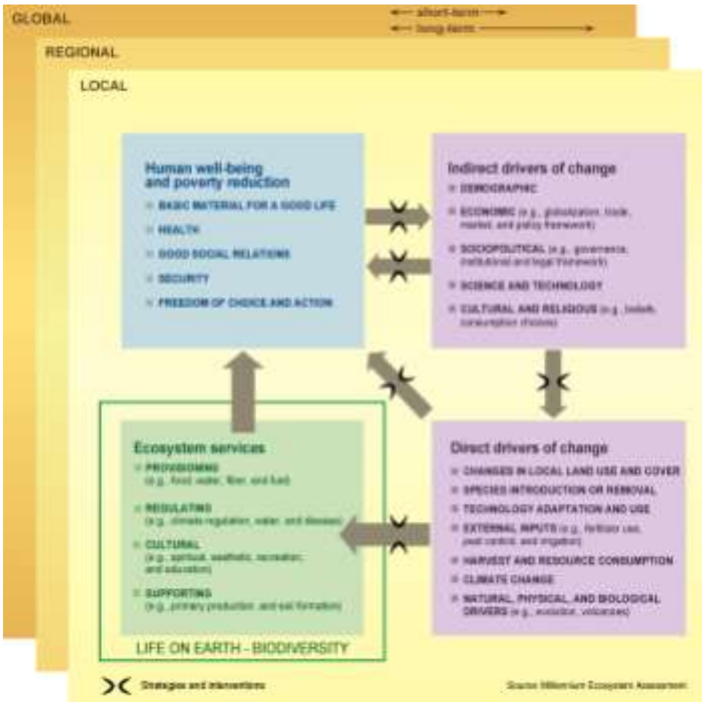
[7] Annex II provides information on expert group members and others who contributed to this report.

techniques on biodiversity, including preliminary information on associated social, economic and cultural considerations. Related legal and regulatory matters are treated in a separate study. In addition, a complementary consultation process was carried out by the CBD to seek the views of indigenous and local communities on the possible impacts of geoengineering techniques on biodiversity and associated social, economic and cultural considerations.

### 1.2 Context for the consideration of potential impacts of geoengineering on biodiversity

Biodiversity, ecosystems and their services (provisioning, regulating, cultural and supporting) are critical to human well-being. They are being directly and adversely affected by habitat conversion, over-exploitation, invasive species, pollution and climate change. These in turn are driven by demographic, economic, technological, socio-political and cultural changes (Figure 1.1). Protection of biodiversity and ecosystems means that we urgently need to address the direct drivers of change, as well as giving further consideration to indirect drivers.

**Figure 1.1. Linkage between biodiversity, ecosystem services, human well-being and direct and indirect drivers of change[8].**




*Climate change is one of several drivers of changes to biodiversity and ecosystem services, operating over local, regional and global spatial scales, and short-term and long-term timescales. Any proposed geoengineering actions are superimposed on this framework.*

Climate change is becoming increasingly important as a driver of biodiversity loss and the degradation of ecosystems and their services. It is best addressed by a rapid and major reduction in global greenhouse-gas emissions, requiring a transition to a low-carbon economy through changes in how energy is produced and used, and in the way the environment is managed. However, international commitment is currently lacking to reduce future greenhouse-gas emissions at the scale required, with two main consequences. First, serious and possibly irreversible climate disruption is now much more likely within the next 50-100 years[9,10]; second, to potentially avoid that outcome, increasing attention has been recently given to a range of climate geoengineering techniques, as a different, and as yet unproven, strategy. The early motivation for exploring such concepts was, at least partly, that they might offer an alternative to strong emission reductions; however, geoengineering is now primarily

[8] Millennium Ecosystem Assessment (2005). *Ecosystems and Human Well-being: Synthesis*, Island Press, Washington DC, 137 pp. Online at www.maweb.org/documents/document.356.aspx.pdf

[9] Anderson K. & Bows A. (2011). Beyond 'dangerous' climate change: emission scenarios for a new world. *Phil. Trans. Roy. Soc. A.* 369, 20-44; doi: 10.1098/rsta.2010.0290

[10] Myhrvold N.P. & Caldeira K. (2012). Greenhouse gases, climate change and the transition from coal to low-carbon electricity. *Environ. Res. Letters*, 7, 014019; doi: 10.1088/1748-9326/7/1/014019; online at stacks.iop.org/ERL/7/014019

considered by its proponents as an additional action, complementing other efforts to limit the magnitude of human-induced climate change.

Assessment of the impact of geoengineering techniques on biodiversity – the mandate for this report – requires an evaluation of their potential for both positive and negative effects, in the context of climate changes that are already occurring and their projected trajectories. Future climate conditions will be largely determined by future anthropogenic greenhouse-gas emissions, in turn largely determined by future mitigation policies agreed at the global level. Since global greenhouse-gas emissions are currently continuing to increase at a rapid rate, the main comparisons made here are in relation to a 2 - 3 fold increase in atmospheric greenhouse gas concentrations compared to pre-industrial levels, with associated projected increases in average global surface temperature of around 3°C - 5°C by 2100. The consequences for biodiversity of such climate change scenarios are summarised in Chapter 3 of this report. Other climate projections, based on other emission pathways, are also possible.

The scale and nature of potential geoengineering impacts on biodiversity will necessarily depend on the 'baseline' comparison made. Such impacts will also closely depend on the effectiveness, feasibility and implementation scenario for the specific techniques under consideration. The timing of deployment may also be important. Thus the impacts for a potentially rapid-acting geoengineering technique might vary according to whether it is deployed in the near future, i.e. under 'present day' climatic conditions, or in (say) 50 or 100 years time, and whether deployment is made slowly or rapidly.

The CBD generic guidance on impact assessment, discussed below, provided a wider framework for this study.

### 1.3 Relevant guidance under the Convention on Biological Diversity

The decision on geoengineering adopted by the Conference of the Parties at its tenth meeting, in paragraph 8(w), refers to the precautionary approach and to Article 14 of the Convention.

The precautionary approach contained in Principle 15 of the Rio Declaration on Environment and Development is an approach to uncertainty, and provides for action to avoid serious or irreversible environmental harm in advance of scientific certainty of such harm. In the context of the Convention, it is referred to in numerous decisions and pieces of guidance, including the Strategic Plan for Biodiversity 2011-2020; the ecosystem approach; the voluntary guidelines on biodiversity-inclusive impact assessment; the Addis Ababa principles and guidelines for the sustainable use of biodiversity; the guiding principles for the prevention, introduction and mitigation of impacts of alien species that threaten ecosystems, habitats or species; the programme of work on marine and coastal biological diversity; the proposals for the design and implementation of incentive measures; the Cartagena Protocol on Biosafety; agricultural biodiversity in the context of Genetic Use Restriction Technologies; and forest biodiversity with regard to genetically modified trees.

In decision X/33, the Conference of the Parties calls for precaution in the absence of an adequate scientific basis on which to justify geoengineering activities and appropriate consideration of the associated risks for the environment and biodiversity, and associated social, economic and cultural impacts. Further consideration of the precautionary approach is provided in the companion study[11] on the regulatory framework of climate-related geoengineering relevant to the Convention on Biological Diversity.

Article 14 of the Convention includes provisions on environmental impact assessment of proposed projects as well as strategic environmental assessment of programmes and policies that are likely to have significant adverse impacts on biodiversity. To assist Parties in this area, a set of voluntary guidelines were developed:

- Voluntary guidelines for biodiversity-inclusive impact assessment, adopted through decision VIII/28;

[11] CBD Secretariat (2012). *Regulatory Framework of Climate-related Geoengineering Relevant to the Convention on Biological Diversity.* Study carried out in line with CBD Decision X/33.

- Additional guidance on biodiversity-inclusive Strategic Environmental Assessment, endorsed through decision VIII/28;
- Akwé: Kon voluntary guidelines for the conduct of cultural, environmental and social impact assessment regarding developments proposed to take place on, or which are likely to impact on, sacred sites and on lands and waters traditionally occupied or used by indigenous and local communities, adopted through decision VII/16;
- Tkarihwaié:ri code of ethical conduct to ensure respect for the cultural and intellectual heritage of indigenous and local communities; and
- Draft voluntary guidelines for the consideration of biodiversity in environmental impact assessments (EIAs) and strategic environmental assessments (SEAs) in marine and coastal areas, including those beyond national jurisdiction.

Article 14 includes further provisions for activities which are likely to have significant adverse effects on the biodiversity of other States or areas beyond the limits of national jurisdiction. Given the large scale of geoengineering interventions, the need for notification, exchange of information and consultation as well as readiness for emergency responses called for in this provision would likely apply to the originator of such geoengineering activities. To date, the Convention has not developed further guidance in this area. Issues of liability and redress, including restoration and compensation for damage to biodiversity caused by activities under the jurisdiction of other States, are still under debate.

The guidelines developed under Article 14 provide useful elements that can inform analysis of the impacts of geoengineering on biodiversity, both at the level of specific activities and at the level of broader assessments, The assessment frameworks of other bodies may also be relevant; e.g., as developed by the London Convention/London Protocol, and the more general requirement of Article 206 of the UN Convention on Law of the Sea (UNCLOS) requiring States to assess the potential effects of activities taking place at sea. Given the broad scope of the present study, the CBD guidelines for strategic environmental assessment would seem particularly useful.  Those guidelines recommend consideration of the following:

i) How the proposed techniques are expected to impact on the various components and levels of biodiversity and across ecosystem types, and the implications for ecosystem services, and for the people who depend on such services;

ii) How the proposed techniques are expected to affect the key direct and indirect drivers of biodiversity change.

Where such information is available, Chapters 3, 4 and 5 provide an assessment of how specific geoengineering techniques might affect the various components of biodiversity for a range of ecosystems, and the implications of those impacts for ecosystem services. However, in many cases, detailed information is lacking. particularly with regard to potential impacts on biodiversity at the genetic level.

At a global scale, the largest driver of terrestrial biodiversity loss has been, and continues to be, land use change. In the ocean, over-exploitation has also been a major cause of biodiversity loss and food-web perturbations. Such changes, on land and in the ocean, can have climatic implications, through effects on greenhouse gases fluxes, and climate change itself is rapidly increasing in importance as a driver of biodiversity loss. However, the importance of different drivers of loss varies among ecosystems and from region to region[12,13]. An overview of the potential impacts of geoengineering and of alternative actions on the drivers of biodiversity loss is provided in Chapter 7.

The CBD guidelines on impacts assessment also highlight, as key principles, stakeholder involvement, transparency and good quality information.

Since good quality information on many aspects of geoengineering is still very limited (and may not be readily available to all stakeholders)[14], this study should be regarded as a first step in assessing its

[12] Millennium Ecosystem Assessment (2005). *Ecosystems and Human Well-being: Synthesis*, Island Press, Washington DC, 137 pp.   Online at www.maweb.org/documents/document.356.aspx.pdf
[13] CBD Secretariat  (2010). *Global Biodiversity Outlook 3*. Montreal, 94 pp.
[14] The number of scientific publications relating to geoeengineering is currently  increasing at a rapid rate, with associated increases in information accessibility.  Nevertheless, it is recognised that much of the relevant literature may not be readily

potential impacts on biodiversity. Key knowledge gaps include: i) the overall effectiveness of many of the geoengineering techniques, based on realistic estimates of their scalability; ii) how the proposed techniques affect weather and climate regionally and globally; iii) how biodiversity, ecosystems and their services might respond to geo-engineered changes in climate; iv) the unintended effects of geoengineering on biodiversity; and v) the social and economic implications of deliberate climate manipulations, in the context of changes to biodiversity and ecosystem services.

With a view to encouraging involvement of stakeholders, a number of consultations have been held[15] and drafts of this report were made available for two rounds of peer review. It is nevertheless recognized that the opportunities for full and effective participation of stakeholders have been limited. To some extent, this is an inevitable consequence of the relative novelty of the issues under discussion. Some indigenous and local communities and stakeholder groups do not consider themselves sufficiently prepared to contribute to such an effort in a full and effective manner. It is hoped that this report, together with related efforts[16], will help to expand information and understanding on geoengineering issues.

### 1.4 Scope of techniques examined in this study

There is a range of views as to what should be considered as climate-related geoengineering relevant to the CBD. Approaches may involve both hardware- or technology-based engineering as well as 'natural' processes[17] that might have a climatically-significant impact at the global scale, depending on the spatial and temporal scale of interventions. Several approaches that may be considered as geoengineering can also be considered as climate change mitigation and/or adaptation; for example, some ecosystem restoration activities.

This study defines geoengineering in a relatively inclusive way, without prejudice to any definition of the term that may subsequently be agreed under the Convention or elsewhere, and recognizing that there is not yet scientific consensus on the scope of the term. Nevertheless, the definition used in this study is considered consistent with COP 10 decision X/33, paragraph 8(w). In particular, it excludes carbon capture from fossil fuels (i.e, preventing the release of $CO_2$ into the atmosphere), whilst recognizing that the carbon storage components of that process are also shared by other climate remediation techniques that are considered as geoengineering and are therefore included.

For some proposed techniques, there is insufficient information to make an evidence-based assessment of potential impacts. The scope of the study is therefore limited, and should not be taken as a comprehensive analysis of all matters related to geoengineering.

### 1.5 Structure of the document

Chapter 2 considers definitions of geoengineering for the purposes of this study, based on a compilation and summary of existing definitions (given in Annex 1). Chapter 2 also provides an overview of the range of techniques here considered as geoengineering.

Chapter 3 provides a summary of projected climate change and the related phenomenon of ocean acidification under commonly-used emission scenarios, together with the expected impacts of those

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available to everyone with interests.

[15] Consultations have involved: 1) Mini-workshop on biodiversity and climate-related geoengineering, 10 June 2011, Bonn, Germany; 2) Liaison Group Meeting on Climate-Related Geoengineering as it relates to the Convention on Biological Diversity, 29 June - 1 July, 2011, London, UK; 3) Informal Dialogue with Indigenous Peoples and Local Communities on Biodiversity Aspects of Geo-engineering the Climate; side event during the Seventh Meeting of the Ad Hoc Open-ended Working Group on Article 8(j) and Related Provisions, 2 November 2011, Montreal, Canada; and 4) Consultation on Climate-related Geo-engineering relevant to the Convention on Biological Diversity; side event during the fifteenth meeting of the Subsidiary Body on Scientific, Technical and Technological Advice (SBSTTA 15), 9 November 2011, Montreal, Canada.

[16] Online discussion on indigenous peoples and local communities and geoengineering, Climate Frontlines - Global forum for indigenous peoples, small islands and vulnerable communities; www.climatefrontlines.org.

[17] The distinction between technological and natural is not clear-cut in the geoengineering context, Thus most proposed geoengineeering techniques involve enhancement or simulation of naturally-occurring processes that already play a major role in climate dynamics, and that are naturally variable on decadal to geological timescales. Furthermore, many natural processes relevant to geoengineering are already subject to significant human manipulation and perturbation, involving technology (= applied science) to some degree.

changes on biodiversity. Such information provides the necessary context for the assessment of the impacts of geoengineering, as discussed in Section 1.2 above,

The potential intended and unintended impacts on biodiversity and ecosystem services (where known) of different geoengineering techniques are reviewed in Chapters 4 and 5, focussing on the potential impacts of sunlight reflection methods (SRM) and carbon dioxide removal (CDR) techniques respectively. Such impacts, that may be positive or negative, are considered for deployment scales intended to reduce solar radiation sufficiently to have a substantive effect on global warming, or to achieve the long-term removal of a climatically significant amount of $CO_2$ from the atmosphere. For smaller-scale deployments, including local trials that might be made for research purposes, the magnitude of effects will necessarily be less, and impacts might either be undetectable or insignificant for biodiversity.

Chapter 6 gives a preliminary review of possible social, economic and cultural impacts associated with the impacts of geoengineering on biodiversity, whilst Chapter 7 presents some general conclusions.

### 1.6 Key sources of information

The study builds on past work on geoengineering, climate change and biodiversity including information available from the Intergovernmental Panel on Climate Change[18]; the Royal Society[19]; the 2011 workshop 'Ecosystem impacts of geoengineering' held by the International Geosphere-Biosphere Programme and associated publication[20]; the Technology Assessment of Climate Engineering by the US Government Accountability Office[21]; relevant CBD Technical Series reports[22,23]; and a range of topic-specific scientific publications, as individually cited. Nevertheless, it should be noted that the peer-reviewed literature on geoengineering is mostly on its intended, climatic effects. Information on unintended impacts (of greatest relevance here) is limited, and mostly of a theoretical nature; many uncertainties remain.

While this study is primarily based on recent literature, the concept of large-scale, deliberate climate modification is not new[24,25]. The main focus of ideas developed in the 1950s and 1960s was, however, to increase, not decrease, temperatures (particularly in the Arctic), or increase rainfall on a regional basis. The first proposals to counteract human-induced changes in the climate (then given the name geoengineering) date from the 1970s. Historical examples of climate control proposals are given in Table 1 below, with a more extensive listing available in the report of the U.S. Government Accountability Office[26].

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[18] IPCC (Intergovernmental Panel on Climate Change) (2007). *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Pachauri, R.K & Reisinger, A. (eds.)]. IPCC, Geneva, Switzerland, 104 pp. Also: IPCC (2005). *Special Report on Carbon Capture and Storage* [B Metz, O. Davidson, H de Coninck, M Loos & L. Meyer (eds)], Cambridge University Press, UK, 431 pp; and IPCC (2000). *Special Report on Land Use, Land-Use Change and Forestry [R.T. Watson, I.R. Noble, B. Bolin, N.H. Ravindranath, D.J. Verardo & D.J. Dokken (eds)].* The IPCC Fifth Assessment Report (AR5) is currently in preparation.

[19] The Royal Society (2009). *Geoengineering the Climate: Science, Governance and Uncertainty*. RS Policy document 10/09. The Royal Society, London, 82 pp

[20] Russell, L.M. & 16 others. (2012). Ecosystem impacts of geoengineering: A review for developing a science plan. *Ambio*, in press.

[21] U.S. Government Accountability Office (2011). *Technology Assessment: Climate engineering. Technical status, future directions, and potential responses*. GAO-11-71. www.gao.gov/new.items/d1171.pdf

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

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

[24] Lamb, H.H. (1977). *Climatic History and the Future, Parts III and IV*. Princeton University Press, 835 pp

[25] Fleming, J.R. (2010). *Fixing the Sky: The Checkered History of Weather and Climate Control*. Columbia University Press, New York, 344 pp

[26] U.S. Government Accountability Office (2011). *Technology Assessment: Climate engineering. Technical status, future directions, and potential tresponses.* GAO-11-71. www.gao.gov/new.items/d1171.pdf

**Table 1: Historical examples of proposals for regional and global-scale climate modifications and control.**

| **Date** | **Author** | **Proposal** |
|---|---|---|
| 1877 | N. Shaler | Re-routing the Pacific's warm Kuroshio Current through the Bering Strait to raise Arctic temperatures by around 15°C |
| 1958 | M. Gorodsky and V. Cherenkov | Placing metallic potassium particles into the Arctic stratosphere with the aim of thawing permafrost in Russia, Canada and Alaska, and melting polar ice |
| 1960s | M. Budyko and others | Melting of Arctic sea-ice by adding soot to its surface |
| 1977 | C. Marchetti | Disposal of liquid $CO_2$ to the deep ocean, via the Mediterranean outflow |
| 1990 | J. Martin | Adding iron to the ocean to enhance ocean $CO_2$ uptake |
| 1992 | US National Academy of Science Committee on Science, Engineering, and Public Policy | Adding aerosols to the stratosphere to increase the reflection of sunlight |

More recently, several professional societies[27] have argued that geoengineering might need to be taken seriously, and have called for further research in this area. At the same time, there has also been considerable public discussion and enunciation of social, economic, cultural and ethical considerations. Concerns have been raised[28] by civil society organizations, indigenous communities and others, and have featured in popular books and in the media. Some reference to this debate is included in Chapter 6 of this report, in the context of CBD-relevant issues. An assessment of the regulation of geoengineering is covered in a separate CBD report[29], as has already been noted, and the governance of research on SRM has recently been reviewed[30].

[27] For example, the American Meteorological Society, the American Geophysical Union and the UK-based Institute of Physics.

[28] For example: ETC Group (2010). *Geopiracy: The Case against Geoengineering*. ETC Group Communique 103. www.etcgroup.org/upload/publication/pdf_file/ETC_geopiracy_4web.pdf.

[29] CBD Secretariat (2012). *Regulatory Framework of Climate-related Geoengineering Relevant to the Convention on Biological Diversity. Study carried out in line with CBD Decision X/33.*

[30] Solar Radiation Management Governance Initiative (SRMGI) (2011). *Solar Radiation Management: the Governance of Research.* Environmentasl Defense Fund, The Royal Society and TWAS. 68 pp, Online at www.srmgi.org/report

# CHAPTER 2: DEFINITION AND FEATURES OF GEOENGINEERING APPROACHES AND TECHNIQUES

## 2.1 Definition of climate-related geoengineering

The term geoengineering has been defined and used in different ways by different authors and bodies (Annex 1). Many of the existing definitions contain common elements but within different formulations. A starting point is the interim definition adopted by the tenth Conference of the Parties to the CBD[31]:

> "Without prejudice to future deliberations on the definition of geo-engineering 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 geo-engineering 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."

Based on the above, and consistent with most of the definitions listed in Annex 1, this report defines climate-related geoengineering as:

> A deliberate intervention in the planetary environment of a nature and scale intended to counteract anthropogenic climate change and its impacts.

This definition is 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[32], 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[33].

Unlike some definitions of geoengineering, the above definition includes the potential removal of greenhouse gases other than $CO_2$, such as methane[34]; it also includes the possibility that cooling might be achieved by enhancing the loss of long-wave radiation from the Earth, through cirrus-cloud manipulations[35]. However both those approaches are currently speculative, with little or no peer-reviewed discussion of their methods and potential impacts: they are therefore not further examined in this report, nor are others of a similar, very preliminary, status.

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

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[31] Footnote to CBD decision X/33, paragraph 8(w)

[32] Geoengineering could also be defined with non-climatic objectives; for example, to counter-act ozone depletion or specifically to address ocean acidification

[33] McLaren D. (2011). *First stop digging. An assessment of the potential for negative emission techniques to contribute safely and fairly to meeting carbon budgets in the 21st century*. McLaren Environmental Research & Consultancy Working Paper 1/11; https://sites.google.com/site/mclarenerc

[34] Boucher O. & Folberth G.A. (2010). New directions: atmospheric methane removal as a way to mitigate climate change? *Atmospheric Environment* 44, 3343-3345,: doi: 10.1016/j.atmosenv.2010.04.032

[35] Mitchell D.L, Mishra S. & Lawson R.P. (2011). Cirrus clouds and climate engineering: new findings on ice nucleation and theoretical basis. In: *Planet Earth 2011- Global Warming Challenges and Opportunities for Policy and Practice*, ed E Carayannis; InTech, p 257- 288; online at www.intechopen.com/articles/show/title/cirrus-clouds-and-climate-engineering-new-findings-on-ice-nucleation-and-theoretical-basis.

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[36].

As noted in Chapter 1, there is currently a range of views concerning whether geoengineering should include or exclude a number of activities involving bio-energy, afforestation and reforestation, and changing land management practices. If such techniques are deployed at sufficient scale to significantly counteract climate change, and are implemented with that intention, then their inclusion within the definition of geoengineering seems logically justified, notwithstanding that such measures are already being used for climate change mitigation and other purposes, and that they may involve minimal use of new technologies[37].

There is also a range of views concerning the inclusion or exclusion of weather modification technologies, such as cloud seeding, within the definition of geoengineering. Proponents of inclusion argue that the history, intention, institutions, technologies themselves, and impacts are closely related to geoengineering. Nevertheless, unless they can be scaled-up sufficiently to achieve (beneficial) climatic effects at the global level, they are considered out of scope for the current study[38].

The above definition is broad in scope, suitable for broad-based analysis such as this study. More specific definitions that are narrower in scope and allow for more precise legal interpretations may be required for some purposes, such as providing policy advice and regulation. Such definitions might be confined to specific techniques, classes of techniques, or environments, and the distinction between regional and global-scale effects may be less important. For example, definitions relating to SRM techniques or CDR techniques that have the potential for significant negative transboundary implications, or the potential to directly affect all or part of the global commons in a negative way, may warrant separate treatment.

### 2.2 Features of proposed geoengineering techniques

Based on the definition of geoengineering given above, this study considers a range of techniques and their potential impacts. They are grouped into sunlight reflection methods (SRM) and carbon dioxide removal (CDR) methods, whilst recognising that other approaches might also be possible.

When considering the potential effectiveness and impacts of such approaches, the report examines the spatial and temporal scales at which the approaches would have to operate in order to offset the projected changes arising from future anthropogenic emissions of greenhouse gases. These projected changes are based on scenarios for anthropogenic emissions of greenhouse gases developed by the Intergovernmental Panel on Climate Change (IPCC) as Special Report Emissions Scenarios (SRES) (see Chapter 3, section 3.1). More recently, alternative scenarios (Representative Concentration Pathways, RCPs) have been developed by IPCC[39], but these have not yet been widely used in the literature.

A conceptual overview showing how SRM and CDR techniques exert their intended and unintended effects is given in Figure 2.1.

**Figure 2.1. Conceptual overview of how greenhouse-gas emission reductions and the two main groups of geoengineering techniques may affect the climate system, ocean acidification, biodiversity, ecosystem services and human well-being.**

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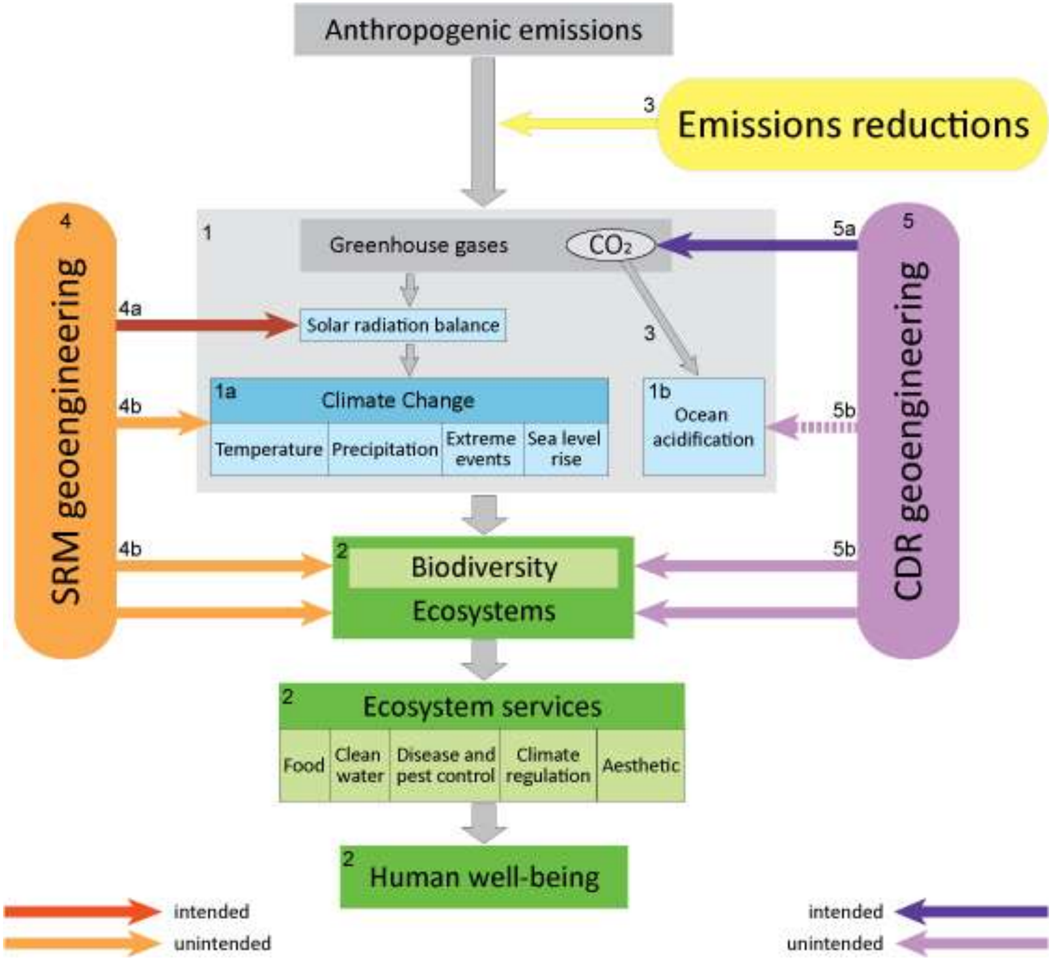
[36] Most CCS techniques involve the storage of $CO_2$ in depleted hydrocarbon reservoirs and saline aquifers. However, it has also been proposed that liquid $CO_2$ could be injected into basaltic rocks, to form calcium and magnesium carbonates – as discussed in Chapter 5.

[37] The expert group considered defining geoengineering on the basis that (novel) technologies were necessarily involved. However, that did not provide a workable definition, since most human activities (including agriculture and forestry) are, to some degree, technological, and 'novel' did not unambiguously define what was in scope.

[38] A similar conclusion (to exclude weather modification) was made by the UK House of Commons Science and Technology Committee (2010). *The regulation of geoengineering.* 5th Report of Session 2009-10, HoC STC; www.publications.parliament.uk/pa/cm200910/cmselect/cmsctech/221/221.pdf

[39] Moss R. & 18 others. (2010). The next generation of scenarios for climate change research and assessment. *Nature* 463, 747-756; doi: 10.1038/nature088232.




*Anthropogenic emissions of greenhouse gases are influencing the balance of solar radiation entering and leaving the atmosphere resulting in global warming and associated climate change phenomena such as changes in temperature, precipitation, sea level rise and increased incidence of extreme events (1a). In addition, increased atmospheric $CO_2$ concentrations leads directly to increased ocean acidification (1b). Climate change and ocean acidification affect biodiversity and ecosystem functioning, with a range of mostly negative impacts on human well-being (2). The impacts of climate change on biodiversity are examined in Chapter 3 of this study. Climate change and ocean acidification are best mitigated by reductions in greenhouse- gas emissions (3). Given the insufficient action to date to reduce such emissions, the use of geoengineering techniques has been suggested to limit the magnitude of human-induced climate change and or its impacts. There are two major broad groups of approaches, as described in Chapter 2 of this study:*

- *Sunlight reflection methods (SRM) aim to counteract warming by reducing the incidence and subsequent absorption of incoming solar radiation (4a).*
- *Carbon dioxide removal (CDR) techniques are aimed at removing $CO_2$ from the atmosphere (5a).*

*However, both groups of techniques are likely to have unintended effects (4b and 5b) with potentially negative impacts on biodiversity. These impacts are examined in Chapters 4 and 5 of this study. Note that this diagram has been simplified for clarity; for example, the feedback linkages between biodiversity, ecosystems and climate are not shown.*

### 2.2.1 *Sunlight reflection methods (SRM)*

#### *2.2.1.1 Description*

Sunlight reflection methods (SRM, also known as solar radiation management) would counteract warming by reducing the incidence and subsequent absorption of incoming solar (short-wave) radiation, often referred to as insolation. This would be achieved by making the Earth more reflective, i.e. increasing the planetary albedo, or using space-based devices to divert incoming solar energy[40]. The resultant cooling effect would counteract the warming influence of increasing

[40] The Royal Society. (2009). *Geoengineering the Climate: Science, Governance and Uncertainty*. RS Policy document 10/09. The Royal Society, London, 82 pp

greenhouse gases. It may be possible to apply some of these techniques so that their effects are greatest within particular regions or latitude bands, with lesser effects elsewhere.

SRM is expected to rapidly have an effect on climate if deployed at the appropriate scale. However, SRM does not treat the root cause of anthropogenic climate change, arising from increasing greenhouse gas concentrations in the atmosphere, nor would it directly address ocean acidification or the $CO_2$ fertilization effect[41,42]. Moreover, it would introduce a new dynamic between the warming effects of greenhouse gases and the cooling effects of SRM with uncertain climatic implications, especially at the regional scale.

Proposed SRM techniques considered in this document comprise four main categories:

i) *Space-based approaches:* reducing the amount of solar energy reaching Earth by positioning sun-shields in space with the aim of reflecting or deflecting solar radiation;

ii) *Changes in stratospheric aerosols*: injecting sulphates or other types of particles into the upper atmosphere, with the aim of increasing the scattering of sunlight back to space[43];

iii) *Increases in cloud reflectivity:* increasing the concentration of cloud-condensation nuclei in the lower atmosphere, particularly over ocean areas, thereby whitening clouds with the aim of increasing the reflection of solar radiation;

iv) *Increases in surface albedo:* modifying land or ocean surfaces, with the aim of reflecting more solar radiation out to space. This could include growing crops with more reflective foliage, painting surfaces in the built environment white, or covering areas (e.g., of desert) with reflective material.

*2.2.1.2 Scope in terms of the scale of the responses*

The aim of SRM is to counteract the positive radiative forcing of greenhouse gases with a negative forcing. To be effective in reducing a rise in global temperature, the reduction in absorbed solar radiation would need to be a significant proportion of the increases in radiative forcing at the top of the atmosphere caused by anthropogenic greenhouse gases. For example, to fully counteract the warming effect of a doubling of the $CO_2$ concentration would require a reduction in total incoming solar radiation by about 2% (at the top of the atmosphere) and a reduction in absorbed heat energy by about 4 W $m^{-2}$ (watts per square meter) as a global average (for both the atmosphere and the Earth's surface).

The impact on radiative forcing of a given SRM method is dependent on altitude (whether the method is applied at the surface, in the atmosphere, or in space), as well as the geographical location of its main deployment site(s). Other factors that need to be taken into account include the negative radiative forcing of other anthropogenic emissions such as sulphate and nitrate aerosols that together may provide a forcing of up to –2.1 W $m^{-2}$ by 2100[44]. Such uncertainties and interactions make it difficult to assess the scale of geoengineering that would be required, although quantitative estimates of the effectiveness of different techniques have been made[45].

### *2.2.2 Carbon dioxide removal (CDR)*

*2.2.2.1 Description*

Carbon dioxide removal (CDR) involves the extraction of $CO_2$, a major greenhouse gas, from the

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[41] $CO_2$ fertilization effect: higher $CO_2$ concentrations in the atmosphere increase productivity in some plant groups under certain conditions.

[42] SRM would not alter anthropogenic $CO_2$ in the atmospheric. However, if it prevented warming, it could reduce additional $CO_2$ releases from the terrestrial biosphere. Such effects are discussed in greater detail in Chapter 4.

[43] Sulphur dioxide emissions into the troposphere (e.g., as currently happening from coal-fired power stations) result in an increase in sulphate aerosol concentration that also reflects solar radiation and therefore has a similar counteracting effect to stratospheric aerosols. However, different physico-chemical reactions occur at different levels of the atmosphere, affecting aerosol processes and removal rates.

[44] IPCC (2007). *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, Pachauri, R.K and Reisinger, A. (eds.)]. IPCC, Geneva, Switzerland, 104 pp

[45] Lenton T.M. & Vaughan N.E. (2009). The radiative forcing potential of different climate geoengineering options. *Atmos. Chem. & Physics*, 9, 5539-5561.

atmosphere, allowing more outgoing long-wave (thermal infra-red) radiation to escape[46]. In principle, other greenhouse gases, such as nitrous oxide ($N_2O$) and methane[47] ($CH_4$), could also be removed from the atmosphere; however, such approaches have yet to be developed.

CDR approaches involve two steps: 1) $CO_2$ capture from the atmosphere; and 2) long-term storage (sequestration) of the captured carbon. In some biologically- and chemically-driven processes, these steps are very closely linked, although the permanence of the storage may be variable and technique-specific. This is the case for ocean fertilization, afforestation, reforestation and soil carbon enhancement. In such cases the whole process, and their unintended impacts on biodiversity, are effectively confined to marine and terrestrial systems respectively.

In other cases, the steps are discrete and various combinations of removal and storage options are possible, separated in time and space. Carbon captured in terrestrial ecosystems as biomass, for example, could be disposed either in the ocean as plant residues or incorporated into the soil as charcoal. It could also be used as fuel with the resultant $CO_2$ (re-)captured at source and stored either in sub-surface reservoirs or the deep ocean. In these cases, each step will have its advantages and disadvantages, and all need to be examined.

Proposed CDR techniques considered in this document (based on the definition of geoengineering used here) include:

i) *Ocean fertilization:* the enrichment of nutrients in the marine environment with the principal intention of stimulating primary productivity in the ocean, and hence $CO_2$ uptake from the atmosphere, and the deposition of carbon in the deep ocean. Two techniques have been proposed with the aim of achieving these effects:

   (a) *Direct ocean fertilization:* the artificial addition of limiting nutrients from external (non-marine) sources. This proposed approach includes addition of the micro-nutrient iron, or the macro-nutrients nitrogen or phosphorus.

   (b) *Upwelling modification:* for the specific purpose of enhancing nutrient supply, and hence biologically-driven carbon transfer to the deep sea. Increased upwelling in one part of the ocean necessarily causes increased downwelling elsewhere, and downwelling modification has itself been proposed as a geoengineering approach (although not involving a fertilization effect).

   For both the above, local-scale activities that are carried out for other purposes (but might cause ocean fertilization as a side effect) are not considered to be geoengineering; for example, nutrient additions as part of conventional aquaculture, or pumping cold, deep water to the surface for cooling or energy-generating purposes.

ii) *Enhanced weathering:* artificially increasing the rate by which $CO_2$ is naturally removed from the atmosphere by the weathering (dissolution) of carbonate and silicate rocks, including:

   (a) *Enhanced ocean alkalinity*: adding alkaline minerals or their dissolution products (e.g., calcium carbonate, bicarbonate or hydroxide) in order to chemically enhance ocean storage of $CO_2$. This process buffers the ocean to decreasing pH, and thereby, in theory, could help to counter ocean acidification.

   (b) *Enhanced weathering of rocks:* the slow natural reaction of silicate rocks with $CO_2$ (to form solid carbonate and silicate minerals) can be accelerated by spreading finely-ground silicate minerals such as olivine over agricultural soils.

iii) *Increasing carbon sequestration through ecosystem management[48]:*

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[46] The Royal Society (2009). *Geoengineering the Climate: Science, Governance and Uncertainty*. RS Policy document 10/09. The Royal Society, London, 82 pp

[47] Boucher, O. & Folberth, G.A. (2010). New directions: atmospheric methane removal as a way to mitigate climate change? *Atmospheric Environment* 44, 3343-3345,: doi: 10.1016/j.atmosenv.2010.04.032

[48] IPCC definitions are used here for afforestation and reforestation, providing consistency with other CBD Reports. Note that for the first commitment period of the Kyoto Protocol, reforestation activities are limited to those occurring on land that did not contain forest on 31 December 1989.

(a) *Afforestation*: direct human-induced conversion of land that has not been forested (for a period of at least 50 years) to forested land through planting, seeding and/or the human-induced promotion of natural seed sources.

(b) *Reforestation*: direct human-induced conversion of non-forested land to forested land through planting, seeding and/or the human-induced promotion of natural seed sources, on land that was previously forested but converted to non-forested land.

(c) *Enhancing soil and wetland carbon*: through improved land management activities including retaining captured $CO_2$ so that it does not reach the atmosphere and enhancing soil carbon via livestock management.

*iv) Biological carbon capture, using harvested biomass and subsequent carbon storage.* This consists of two relatively discrete steps, with various options for the storage step:

(a) *Production of biomass*: This can be done through the use of conventional crops, trees and algae, and possibly also through plants bioengineered to grow faster and take up more carbon in more long-lived forms (wood or roots).

(b) *Bio-energy carbon capture and storage (BECCS):* Bioenergy with $CO_2$ sequestration combining existing technology for bioenergy / biofuels and for carbon capture and storage (geological storage).

(c) *Biochar:* the production of black carbon, most commonly through pyrolysis (heating, in a low- or zero-oxygen environment) and its deliberate application to soils.

(d) *Ocean biomass storage:* depositing crop waste or other terrestrial biomass onto the deep ocean seabed, possibly in high sedimentation areas.

*v) Direct, chemical capture of carbon from the atmosphere and its subsequent storage.* This also consists of two discrete steps with various options for the storage step:

(a) *Direct carbon capture from ambient air* (‘artificial trees’): the capture of $CO_2$ from the air by either its adsorption onto solids, or its absorption into highly alkaline or moderately alkaline solutions (that may involve using a catalyst).

(b) *Sub-surface storage in geological formations*: the subsequent storage of the captured carbon (usually but not necessarily as liquid $CO_2$) in oil or gas fields, un-minable coal beds, deep saline formations or basaltic/peridotite rocks where stable carbonate minerals might be formed.

(c) *Ocean $CO_2$ storage:* ocean storage of liquid $CO_2$ (e.g., as obtained from air capture) into the water column through either a fixed pipeline or a moving ship, or by injecting liquid $CO_2$ into deep sea sediments below 3,000 m depth, or by depositing liquid $CO_2$ via a pipeline onto the sea floor. At depths > 3,000 m, liquid $CO_2$ is denser than water and is expected to form a “lake” that would delay its dispersion into the surrounding environment;

As previously mentioned, there is a range of views as to whether activities such as large-scale afforestation or reforestation should be classified as geoengineering. These approaches are already widely deployed for climate change mitigation as well as other purposes, and involve minimal use of novel technologies. For similar reasons, there is debate over whether biomass-based carbon should be included. However, for the sake of completeness, all of these approaches are discussed in this report without prejudice to any subsequent discussions within the CBD on definitions or policy on geoengineering.

*2.2.2.2 Scope in terms of the scale of the response*

The natural balance of plant growth and decomposition in the terrestrial biosphere currently results in a net uptake of about 2.6 GtC/yr (gigatonnes of carbon) from the atmosphere, although this is partially offset by emissions of about 0.9 GtC/yr from tropical deforestation and other land use changes. In comparison, the current $CO_2$ release rate from fossil fuel burning alone is about 9.1 GtC/yr[49]; so to

[49] Global Carbon Project (2011). *Carbon Budget and Trends 2010*. www.globalcarbonproject.org/carbonbudget, released 4 December 2011.

have a significant positive impact, one or more CDR interventions would need to remove from the atmosphere several GtC/yr, maintained over decades and more probably centuries. It is very unlikely that such approaches could be deployed on a large enough scale to alter the climate quickly; thus they would be of little help if there was a need for 'emergency action' to cool the planet.

### *2.2.3 Comparison between SRM and CDR techniques*

Although described above separately, it is possible that, if geoengineering were to be undertaken, a combination of SRM and CDR techniques could be used, alongside mitigation through emission reductions, with the objective of off-setting at least some of the impacts of changes to the climate system from past or ongoing emissions. While SRM and CDR interventions would both have global effects, since climate operates on a global scale, some of the proposed SRM interventions (such as changing cloud or land surface albedo) could result in strong hemispheric or regional disparities, likely to change the frequency of extreme events and the behaviour of major weather systems, e.g. the South East Asia monsoon. Under conditions of rapid climate change, the unequivocal separation of impact causality between those arising from the SRM intervention and those that would have happened anyway would probably not be possible. Likewise, CDR techniques will ultimately reduce global $CO_2$ concentrations but might also involve regional effects, e.g. if removal is strongly hemispherically biased. Furthermore, climatic conditions for a particular atmospheric $CO_2$ level are likely to be different according to whether global $CO_2$ is increasing or decreasing[50].

In general, SRM can have a relatively rapid impact on the radiation budget once deployed, whereas the effects of many of the CDR processes are relatively slow. Furthermore, while approaches using SRM have the potential to offset the radiative effects of all greenhouse gases, they do not directly alleviate other consequences of changes in atmospheric chemistry, such as ocean acidification. In contrast, CDR techniques do address changes in atmospheric $CO_2$ concentrations, but they do not address the radiative effects of increased atmospheric concentrations of other greenhouse gases (e.g., methane, nitrous oxide, tropospheric ozone, and halocarbons) and black carbon. Whilst CDR techniques would reduce or slow surface ocean acidification to some degree (in relation to their overall effectiveness), that benefit could be compromised if the carbon or $CO_2$ removed from the atmosphere is subsequently added elsewhere to the ocean.

The 2009 Royal Society report[51] provided a generally well-regarded overview of the effectiveness, affordability safety and timeliness of the main SRM and CDR techniques that have been proposed. Several other reviews have since been published[52,53,54,55], including those giving quantitative comparisons of maximum potential effectiveness, in terms of radiative forcing[56,57]. The IPCC Fifth Assessment Report (AR5), currently in preparation, is understood to include assessments of the climatic effectiveness of both SRM and CDR techniques, partly based on an expert group meeting[58].

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[50] Chadwick R., Wu P., Good P. & Andrews T. (2012). Asymmetries in tropical rainfall and circulation patterns in idealised $CO_2$ removal experiments. *Climate Dynamics*, online publication; doi: 10.1007/s00382-012-1287-2

[51] The Royal Society (2009). *Geoengineering the Climate: Science, Governance and Uncertainty*. RS Policy document 10/09. The Royal Society, London, 82 pp

[52] McLaren D. (2011). *First stop digging. An assessment of the potential for negative emission techniques to contribute safely and fairly to meeting carbon budgets in the 21st century*. McLaren Environmental Research & Consultancy Working Paper 1/11; https://sites.google.com/site/mclarenerc

[53] Ginzky H., Harmann F., Kartschall K., Leujak W., Lipsius K., Mäder C., Schwermer S. & Straube G. (2011). *Geoengineering. Effective Climate Protection or Megalomania?* Umweltdbundesamt (German Federal Environment Agency); 48 pp

[54] Rickels W., Klepper G., Dovern J., Betz G., Brachatzek N., Cacean S., Güssow K., Heintzenberg J., Hiller S., Hoose C., Leisner T., Oschlies A., Platt U., Proelß A., Renn O., Schäfer S. & Zürn M. (2011). *Large-Scale Intentional Interventions into the Climate System? Assessing the Climate .Engineering Debate*. Scoping report conducted on behalf of the German Federal Ministry of Education and Research (BMBF), Kiel Earth Institute, Kiel; 161 pp.

[55] Gordon, B. (2010). *Engineering the Climate: Research Needs and Strategies for International Coordination*. Committee on Science and Technology of the Congress of the United States of America, Washington DC.

[56] Lenton T.M. & Vaughan N. (2009). Radiative forcing potential of climate geoengineering. *Atmos. Chem. Phys*. 9, 5539-5561

[57] Vaughan N.E. & Lenton T.M. (2011). A review of climate geoengineering proposals. *Climatic Change*, 109, 745-790

[58] Blackstock J., Boucher O. & Gruber N. (2012). *Summary of the Synthesis Session and Main Outcomes of the IPCC Expert Meeting on Geoengineering; 20-22 June 2011, Lima, Peru*. IPCC (Intergovernmental Panel on Climate Change); in press.

With regard to readiness, the U.S. Government Accountability Office report[59] ranked all geoengineering technologies as immature, with a technology readiness level of 2 or 3 on a scale of 1 to 9.

Clearly, interventions that are deemed to be 'safe' (i.e., low relative risk) are preferable. However, a consistent finding of the reviews that included a safety assessment was that techniques considered low risk did not score highly for effectiveness at scale. Fast reversibility is also an important consideration, even for techniques assessed as 'safe', since if the safety evaluation should prove incorrect, any unintended – and unexpected – adverse consequences could be reversed relatively quickly.

Unless there are also strong emission reductions, the commitment to geoengineering as a means of avoiding dangerous climate change needs to be continued for decadal to century timescales (and potentially for millennia). This 'treadmill' problem is particularly acute for SRM interventions, whose intensity would need to be progressively increased unless other actions are taken to stabilise greenhouse gas concentrations. The cessation of SRM interventions could be a highly risky process, particularly if it were carried out rapidly after being deployed for some time and greenhouse gas levels in the atmosphere were high: the likely result would be a rapid increase in the solar radiation reaching the Earth's surface, causing very rapid increase in surface temperature[60]. Under such circumstances, high reversibility is not necessarily advantageous.

### 2.2.4 Additional speculative techniques

In addition to the SRM and CDR techniques described above, a number of more speculative approaches have been mooted. These have not been evaluated and are not discussed further in this report. They include some approaches based on increasing the rate of loss of long-wave heat radiation. For example, by reducing the amount of cirrus clouds by injection of an appropriate substance to form ice particles as a sink for upper tropospheric water vapour[61]. Another enhanced heat-loss approach is to use icebreakers to open up passages in Arctic ice in autumn and winter, to reduce the insulating effect of the ice (so more heat is transferred from the ocean to the atmosphere), thus thickening adjacent ice and increasing the amount of reflected solar radiation the next spring.

Other proposed (speculative) approaches have included carrying out major geomorphological changes, such as draining seawater into the Qattara Depression (central Sahara) to increase regional moisture levels[62] and slow sea level rise, or fully or partly blocking the Bering Strait to reduce Arctic Ocean circulation and promote the formation of sea ice.

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[59] U.S. Government Accountability Office (2011). *Technology Assessment: Climate Engineering. Technical Status, Future Directions, and Potential Responses.* GAO-11-71. www.gao.gov/new.items/d1171.pdf

[60] In one model simulation, the rate was up to 20 times greater than present-day rates. [Matthews H.D. & Caldeira K. (2007) . Transient climate-carbon simulations of planetary geoengineering. *Proc. Nat. Acad. Sci. USA*, 104, 9949-9954; doi: 10.1073/pnas.0700419104]

[61] Mitchell D.L,, Mishra S. & Lawson R.P. (2011). Cirrus clouds and climate engineering: new findings on ice nucleation and theoretical basis. In: *Planet Earth 2011- Global Warming Challenges and Opportunities for Policy & Practice*, ed E Carayannis; InTech, p 257- 288; online at www.intechopen.com/articles/show/title/cirrus-clouds-and-climate-engineering-new-findings-on-ice-nucleation-and-theoretical-basis

[62] Cathcart R.B. & Badescu V. (2004). Architectural ecology: a tentative Sahara restoration. *Int. J. Environ. Stud.*, 61, 145-160; doi: 10.1080/0020723032000087961

# CHAPTER 3: OVERVIEW OF CLIMATE CHANGE AND OCEAN ACIDIFICATION AND OF THE THEIR IMPACTS ON BIODIVERSITY

Geoengineering techniques are being proposed to counteract some of the negative impacts of climate change, which include impacts on biodiversity. This chapter therefore provides an overview of projected climate change (Section 3.1) and its impacts on biodiversity and ecosystems (Section 3.2), in order to provide context, and a possible baseline which can be taken into account when the impacts of geoengineering techniques are reviewed in subsequent chapters.

## 3.1 Overview of projected climate change and ocean acidification.

Human activities have already increased the concentration of greenhouse gases, such as $CO_2$, in the atmosphere. These changes affect the Earth's energy budget, and are considered to be the main cause of the ~0.8°C average increase in global surface temperature that has been recorded over the last century[63]. The continued increase in atmospheric greenhouse gases has profound implications not only for global and regional average temperatures, but also precipitation, ice-sheet dynamics, sea-level rise, ocean acidification and the frequency and magnitude of extreme events. Future climatic perturbations could be abrupt or irreversible, and are likely to extend over millennial time scales; they will inevitably have major consequences for natural and human systems, severely affecting biodiversity and incurring very high socio-economic costs.

### *3.1.1 Scenarios and models*

Our main comparisons here are based on future scenarios for anthropogenic emissions of greenhouse gases developed and used by the Intergovernmental Panel on Climate Change (IPCC), particularly those given in its Special Report on Emissions Scenarios (SRES)[64]. A new generation of emission scenarios has since been developed[65] for use in the IPCC fifth assessment report (AR5). We make no attempt to pre-empt the AR5 findings; nevertheless, more recent results are discussed below as appropriate, in the context of current emission trajectories.

The SRES scenarios were grouped into four families (A1, A2, B1 and B2) according to assumptions regarding the rates of global economic growth, population growth, and technological development. The A1 family includes three illustrative scenarios relating to dependence on fossil fuels (A1FI, fossil fuel intensive; A1B, balanced; and A1T, non-fossil energy sources); the other families each have only one illustrative member. The B1 scenario assumes the rapid introduction of resource-efficient technologies, together with global population peaking at 8.7 billion in 2050.

The six SRES illustrative scenarios were used in the IPCC's fourth assessment report (AR4) in a suite of climate change models to estimate a range of future global warming of 1.1 to 6.4°C by 2100, with a 'best estimate' range of 1.8 to 4.0°C (Figures 3.1 and 3.2)[66]. A 7$^{th}$ scenario assumed that atmospheric concentrations of greenhouse gases remain constant at year 2000 values. Note in Figure 3.2 the very large regional differences in temperature increase, and between land and ocean areas, with increases of up to 7°C for the Arctic. The projected precipitation changes also have high spatial variability, with both increases and decreases of ~20% in most continents.

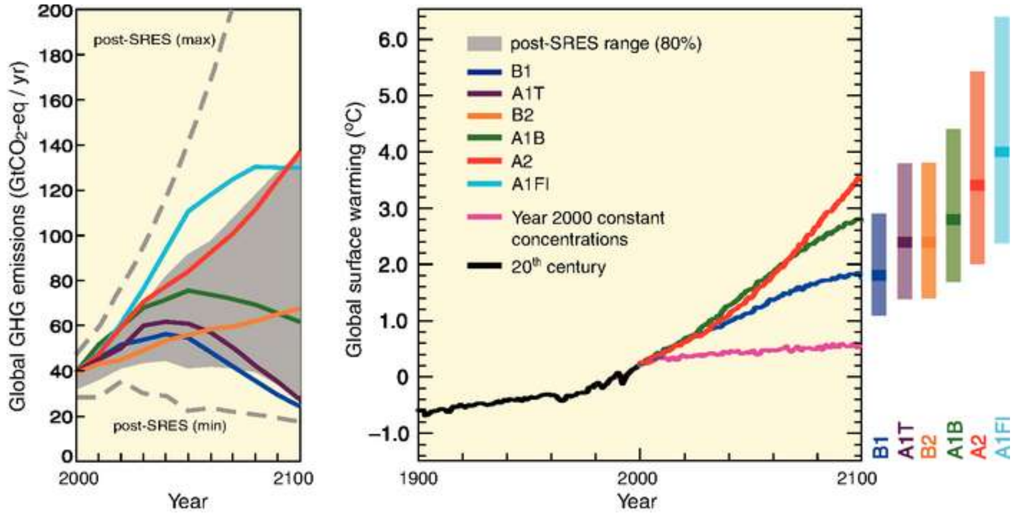
**Figure 3.1: IPCC AR4 scenarios for greenhouse gas annual emissions to 2100.**

[63] Intergovernmental Panel on Climate Change (IPCC) (2008). *Climate Change 2007 – Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Pachauri R.K. & Resinger A. (Eds). IPCC, Geneva, Switzerland, pp 104.

[64] Intergovernmental Panel on Climate Change (IPCC). (2000). *Emissions Scenarios*. Nakicenovic N. & Swart R. (Eds). Cambridge University Press, UK, pp 570.

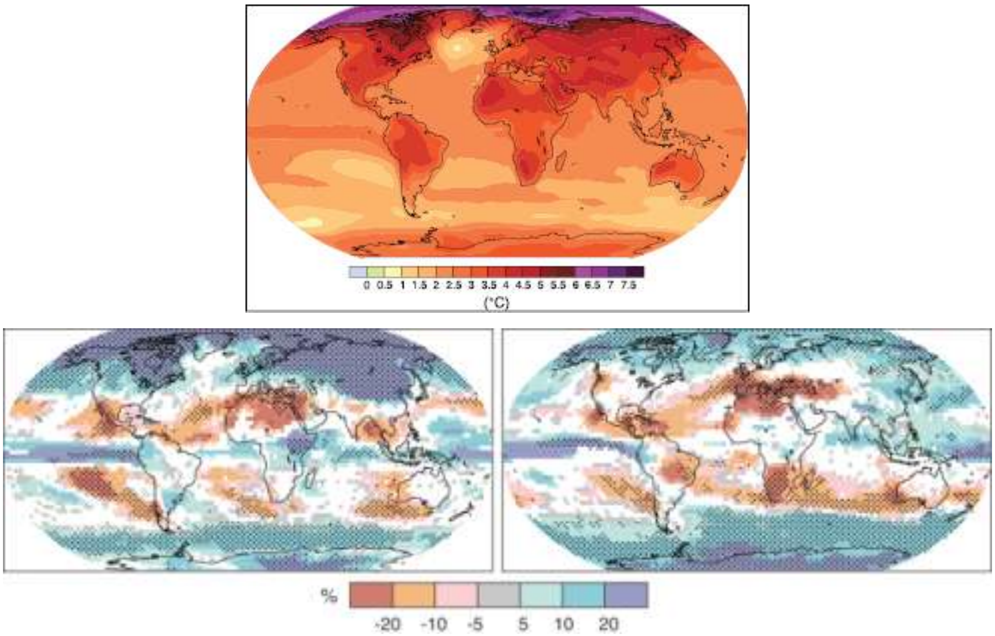
[65] Moss R. & 18 others. (2010). The next generation of scenarios for climate change research and assessment. *Nature* 463, 747-756; doi: 10.1038/nature088232.

[66] Intergovernmental Panel on Climate Change (IPCC). (2008). *Climate Change 2007 – Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Pachauri R.K. & Resinger A. (Eds). IPCC, Geneva, Switzerland, pp 104.




*Left: Six illustrative scenarios for greenhouse gas annual emissions from 2000 to 2100, as gigatonnes of $CO_2$ equivalent. Greenhouse gases include $CO_2$, $CH_4$, $N_2O$ and F-gases. The grey shaded area shows the 80$^{th}$ percentile range of other scenarios published since the IPCC Special Report on Emission Scenarios; the dashed lines [labelled post-SRES (max) and post-SRES (min)] show the full range of post-SRES scenarios. Right: Vertical bars show range of temperature increases and best estimates for IPCC's six illustrative emission scenarios, based on multi-model comparisons between 1980-1999 and 2090-2099. Temporal changes in global surface warming also shown for scenarios A2, A1B and B1 (red, green and dark blue lines respectively), with pink line showing temperature change if atmospheric concentrations of greenhouse gases could be held constant at year 2000 values.*

**Figure 3.2: IPCC AR4 projections of changes in temperature and precipitation to 2100**




*Projected increase in annual mean temperature (upper map) and percentage precipitation change (lower maps; left, December to February; right, June to August) for the SRES A1B scenario, based on multi-model comparisons between 1980-1999 and 2090-2099. Coloured areas on precipitation maps are where >66% of the models agree in the sign of the change; for stippled areas, >90% of the models agree in the sign of the change.*

IPCC AR4 estimated global sea level rise (relative to 1990) to be 0.2 to 0.6 m by 2100; however, those projections excluded ice sheet changes. Taking such effects into account, more recent empirical estimates[67] give projected sea level increases of 0.4 – 2.1 m, with similar values obtained

[67] Rahmstorf S. (2010). A new view on sea level rise. *Nature Reports Climate Change*, 4, 44-45; doi: 10.1038/climate.2010.29

from measurements of ice-sheet mass balance[68], although with large uncertainties relating to current loss rates (particularly for Antarctica)[69]. Future sea level change will not be globally uniform[70]: regional variability may be up to 10-20 cm for a projected global end-of-century rise of around 1 m.

The broad pattern of climate change observed since ~1850 has been consistent with model simulations, with high latitudes warming more than the tropics, land areas warming more than oceans, and the warming trend accelerating over the past 50 years. Over the next 100 years, interactions between changes in temperature and precipitation (Figure 3.2) will become more critical; for example, affecting soil moisture and water availability in both natural and managed ecosystems. These effects are likely to vary across regions and seasons, although with marked differences between model projections. By 2050, water availability may increase by up to 40% in high latitudes and some wet tropical areas, while decreasing by as much as 30% in already dry regions in the mid-latitudes and tropics[71]. Additional analyses[72] of 40 global climate model projections using the SRES A2 scenario indicate that Northern Africa, Southern Europe and parts of Central Asia could warm by 6-8°C by 2100, whilst precipitation decreases by ≥10%.

The IPCC SRES scenarios can be considered inherently optimistic, in that they assume continued improvements in the amounts of energy and carbon needed for future economic growth. Such assumptions have not recently been met[73]; if future improvements in energy efficiency are not achieved, emissions reductions would need to be substantively greater than estimated in AR4.

As noted above, new emission scenarios[74] will be used in the IPCC fifth assessment report (AR5). These will include both baseline and mitigation scenarios, with emphasis on Representative Concentration Pathways (RCPs) and cumulative emissions to achieve stabilization of greenhouse gas concentrations at various target levels, linked to their climatic impacts. For example, stabilization at 450, 550 and 650 ppm $CO_2$eq (carbon dioxide equivalent; taking account of anthropogenic greenhouse gases and aerosols in addition to $CO_2$), is expected to provide around a 50% chance of limiting future global surface temperature increase to 2°C, 3°C and 4°C respectively. Note that anthropogenic sulphate aerosols have a negative $CO_2$eq value; thus if their emissions are reduced, the rate of warming would increase.

### *3.1.2 Current trajectories for climate change*

One of the goals of the United Nations Framework Convention on Climate Change is to prevent dangerous anthropogenic interference in the climate system. This aim is stated in the UNFCCC Objective (Article 2 of the Convention):

"*The ultimate objective of this Convention and any related legal instruments that the Conference of the Parties may adopt is to achieve, in accordance with the relevant provisions of the Convention, stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner*."

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[68] Rignot E., Velicogna I., van den Broeke M.R., Monaghan A. & Lenaerts J. (2011). Acceleration of the contribution of the Greenland and Antarctic ice sheets to sea level rise. *Geophysical Research Letters*, 38, L05503, doi: 10.1029/2011GL046583

[69] Zwally H.J. & Giovinetto M.B. (2011). Overview and assessment of Antarctic ice-sheet mass balance estimates: 1992-2009. *Surveys in Geophysics*, 32, 351-376; doi: 10.1007/s10712-011-9123-5

[70] Milne G.A., Gehrels W.R., Hughes C.W. & Tamisiea M.E. (2009). Identifying the causes of sea level change. *Nature Geosciences* 2, 471-478; doi: 10.1038/ngeo544.

71 Intergovernmental Panel on Climate Change (IPCC). (2008). *Climate Change 2007 – Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Pachauri R.K. & Resinger A. (Eds). IPCC, Geneva, Switzerland, pp 104.

[72] Sanderson M.G, Hemming D.L & Betts R.A. (2011). Regional temperature and precipitation changes under high-end (≥4°C) global warming. *Phil. Trans. R. Soc. A*, 369, 85-98; doi: 10.1098/rsta.2010.0283

[73] Pielke R., Wigley T. & Green C. (2008). Dangerous assumptions. *Nature*, 452, 531-532; doi: 10.1038/452531a

[74] Moss R. & 18 others. (2010). The next generation of scenarios for climate change research and assessment. *Nature* 463, 747-756; doi: 10.1038/nature088232.

However, there are both political and technical difficulties in deciding what 'dangerous' means in terms of equivalent temperature increase and other climate changes (and hence $CO_2$eq stabilization value). The Copenhagen Accord[75] recognized "the scientific view that the increase in global temperature should be below 2°C", which equates to a target of around 400-450 ppm $CO_2$eq. Lower stabilization targets have also been proposed[76,77,78] on the basis that a 2°C temperature increase represents an unacceptable level of climate change[79].

Currently the ensemble of greenhouse gases and aerosols are equivalent to around 495 ppm $CO_2$eq, but cooling by anthropogenic sulphate aerosols offsets around 100 ppm $CO_2$eq. Progress towards achieving emission reduction targets for greenhouse gases has been recently reviewed[80,81].

Since IPCC AR4, much additional evidence has been published showing that the world is warming[82]. Furthermore, the rate of increase in anthropogenic $CO_2$ emissions has accelerated since 2000[83,84], averaging 3.1% per year and reaching 5.9% in 2010 (Figure 3.3). Such emissions match or exceed the rates of the highest IPCC SRES scenarios for that period (A1B, A1FI and A2) despite the Kyoto Protocol and the recent global economic downturn. Emissions (and atmospheric levels) of other greenhouse gases, e.g. methane[85], have also shown recent increases. As a result, it is now very likely that the 450 ppm $CO_2$eq target will be exceeded. For example, for ~50% success in reaching that target, it has been estimated that global greenhouse-gas emissions would need to peak in the period 2015-2020, with an annual reduction of emissions of >5% thereafter[86]. Other recent studies have reached similar conclusions[87]; nevertheless, the inclusion of additional mitigation measures (for methane and carbon black) could substantially reduce the risks of crossing the 2°C threshold[88]. Whilst such changes in greenhouse-gas emissions are not unrealistic for some developed countries, a rapid transition to a low-carbon economy has yet to be agreed at the global level and its implementation is likely to be extremely difficult[89] – primarily because the necessary planning for

[75] UNFCCC (2010). Copenhagen Accord. http://unfccc.int/resource/docs/2009/cop15/eng/107.pdf

[76] Rockström J. & 28 others (2009). Planetary boundaries: exploring the safe operating space for humanity. *Ecology and Society*, 14, Article 32; www.ecologyandsociety.org/vol14/iss2/art32

[77] Hansen J., Sato M., Kharecha P., Beerling D., Berner R., Massson-Delmotte V., Pagani M., Raymo M., Royer D.L. & Zachos J.C. (2008). Target atmospheric $CO_2$: where should humanity aim? *Open Atmos. Sci. J.*, 2, 217-231; doi 10.2174/1874282300802010217

[78] Veron J.E.N., Hoegh-Guldberg O., Lenton T.M., Lough J.M., Obura D.O., Pearce-Kelley P., Sheppard C.R.C., Spalding M., Stafford-Smith M.G. & Rogers A.D. (2009). The coral reef crisis: the critical importance of <350 ppm $CO_2$. *Marine Pollution Bulletin*, 58, 1428-1436; doi: 10.1016/j.marpolbul.2009.09.009

[79] Anderson K. & Bows A. (2011). Beyond 'dangerous' climate change: emission scenarios for a new world. *Phil. Trans. Roy. Soc. A*. 369, 20-44; doi: 10.1098/rsta.2010.0290

[80] UNEP (2011). *Bridging the Emissions Gap*. United Nations Environment Programme (UNEP), 52 pp; www.unep.org/pdf/UNEP_bridging_gap.pdf

[81] IAEA (2011). *Climate Change and Nuclear Power 2011*. International Atomic Energy Authority (IAEA). 40 pp. www.iaea.org/OurWork/ST/NE/Pess?assets/11-43751_ccnp_brochure.pdf

[82] Summary given in: Pope V., Kendon L., Lowe J., Carroll F.& Tempest S. (eds) (2011). *Evidence. The State of the Climate*. UK Met Office/Hadley Centre; 20 pp; www.metoffice.gov.uk/media/pdf/m/6/evidence.pdf

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[88] Shindell D & 23 others (2012). Simultaneously mitigating near-term climate change and improving health and food security. *Science* 335, 183-189; 10.1126/science.1210026.

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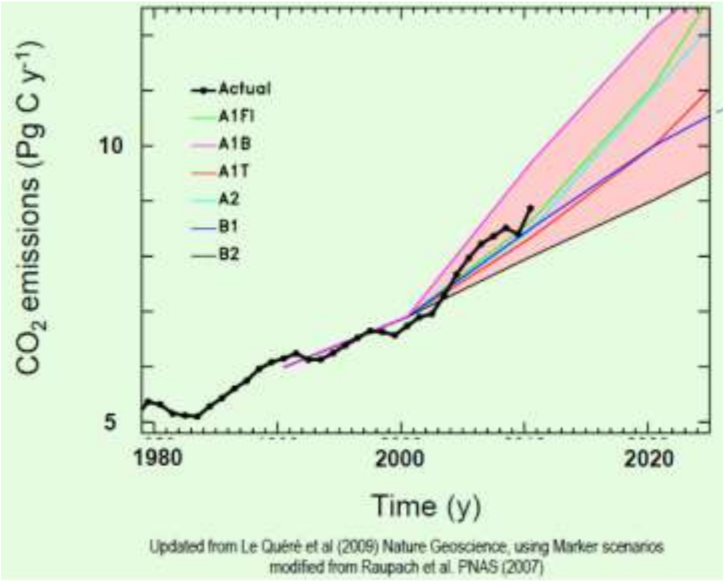
radical changes in energy infrastructure and associated economic development[90,91,92] is not yet in place. If large-scale and rapid mitigation measures are not effected, IPCC AR4 models project a global warming of at least 3-5°C by 2100. In that context, geoengineering approaches have received increasing attention, to counteract at least some of the impacts of such climate change, despite the risks and uncertainties involved.

**Figure 3.3: Global emissions of $CO_2$ for 1980-2010 in comparison to IPCC SRES emission scenarios for 2000-2025[93].**




*The average rate of increase of $CO_2$ emissions since 2000 has been around 3% per year (increasing atmospheric concentrations by ~2 ppm per year), tracking the highest IPCC emission scenarios used for AR4 climate projections. The increase in emissions in 2010 was 5.9%, the highest total annual growth recorded.*

Climate-carbon-cycle feedbacks were not included in all the climate models used for IPCC AR4, but will be included in AR5. Ensemble-based analyses[94] of the A1FI scenario with such feedbacks matched the upper end of the AR4 projections, indicating that an increase of 4°C relative to pre-industrial levels could be reached as soon as the early 2060s. The omission of non-linearities, irreversible changes[95] and tipping points[96] from global climate models makes them more stable than the real world. As a result of that greater stability, models can be poor at simulating previous abrupt climate change due to natural causes[97]. However, the recent improvements in Earth system models (and computing capacity) give increasing confidence in their representations of future climate-ecosystem interactions.

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[91] UNEP (2011). *Bridging the Emissions Gap*. United Nations Environment Programme (UNEP), 52 pp; www.unep.org/pdf/UNEP_bridging_gap.pdf

[92] IAEA. (2011). *Climate Change and Nuclear Power 2011*. International Atomic Energy Authority (IAEA). 40 pp. www.iaea.org/OurWork/ST/NE/Pess?assets/11-43751_ccnp_brochure.pdf

[93] Le Quéré, C. (2011). The response of the carbon sinks to recent climate change, and current and expected emissions in the short term from fossil fuel burning and land use. Presentation at UNFCCC SBSTA Workshop, Bonn 2-3 June 2011; http://unfccc.int/files/methods_and_science/research_and_systematic_observations/application/pdf/15_le_quere_response_of_carbon_sinks.pdf

[94] Betts R.A., Collins M., Hemming D.L., Jones C.D., Lowe J.A. & Sanderson M.G. (2011). When could global warming reach 4°C? *Phil. Trans. R. Soc. A*, 369, 67-84; doi: 10.1098/rsta.2010.0292

[95] Solomon S., Plattner G.-K., Knutti R. & Friedlingstein P. (2009). Irreversible climate change due to carbon dioxide emissions. *Proc. Natl. Acad. Sci U.S.A*, 106, 1704-1709; doi: 10.1073/pnas.0812721106

[96] Lenton T.M., Held H., Kriegler E., Hall J.W., Lucht W., Rahmstorf S. & Schellhuber H.J. (2008). Tipping elements in the Earth's climate system. *Proc. Natl. Acad. Sci. U.S.A.*, 105, 1786-1793; doi:10.1073/pnas.0705414105

[97] Valdes P. (2011). Built for stability. *Nature Geosciences* 4, 414-416; doi: 10.1038/ngeo1200

Even with strong climate mitigation policies, further climate change is inevitable due to lagged responses in the Earth climate system (so-called unrealized warming). Increases in global mean surface temperature of 0.3 - 2.2$^{o}$C are projected to occur over several centuries after atmospheric concentrations of greenhouse gases have been stabilized[98], with associated increases in sea level due to thermally-driven expansion and ice-melt. Due to the long residence time of $CO_2$ in the atmosphere, it is an extremely slow and difficult process to return to a $CO_2$ stabilisation target once this has been exceeded. For other short-lived greenhouse gases, climate system behaviour also prolongs their warming effects[99].

Such lag effects have particular importance for ocean acidification. Thus, changes in surface ocean pH (due to the solubility of $CO_2$, and the formation of carbonic acid) closely follow the changes in atmospheric $CO_2$. The penetration of such pH changes to the ocean interior is, however, very much slower, depending on the century-to-millennium timescale of ocean mixing[100,101].

Differences between the behaviour and impacts of different greenhouse gases and aerosols are not discussed in detail here, but are also very important. For example: tropospheric ozone, methane and black carbon all have relative short atmospheric lifetimes, and therefore may be amenable to emission control with relatively rapid benefits, not only to climate but also human health (black carbon)[102] and agricultural productivity (tropospheric ozone)[103]. Black carbon particles have significant heating effect on the lower troposphere and potential effect on the hydrological cycle through changes in cloud microphysics, and snow and ice surface albedo[104].

## 3.2 Observed and projected impacts of climate change, including ocean acidification, on biodiversity

### *3.2.1 Overview of climate change impacts on biodiversity*

Temperature, rainfall and other components of climate strongly influence the distribution and abundance of species; they also affect the functioning of ecosystems, through species interactions. Whilst vegetation shifts, population movements and genetic adaptation have lessened the impacts of previous, naturally-occurring climate change (e.g., during geologically-recent ice age cycles)[105], the scope for such responses is now reduced by other anthropogenic pressures on biodiversity, including over-exploitation; habitat loss, fragmentation and degradation[106]; the introduction of non-native species; and pollution, and the rapid pace of projected climate change. Thus, anthropogenic climate change carries a higher extinction risk[107], since the abundance (and genetic diversity) of many species is already depleted. Human security may also be compromised by climate change[108,109], with indirect (but potentially serious) biodiversity consequences in many regions.

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[102] Shindell D. & 23 others. (2012). Simultaneously mitigating near-term climate change and improving human health and security. *Science* 335, 183-189; doi: 10.1126/science.1210026

[103] UNEP-WMO. (2011).*Integrated Assessment of Black Carbon and Tropospheric Ozone. Summary for Decision Makers.* www.wmo.int/pages/prog/arep/gaw/other_pub.html

[104] Ramanathan V & Carmichael G. (2008). Global and regional climate changes due to black carbon. *Nature Geoscience* 1, 221-227; doi: 10.1038/ngeo156

[105] Jackson S.T. & Overpeck J.T. (2000). Responses of plant populations and communities to environmental changes of the late Quaternary. *Paleobiology* 26, 194-220

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[108] Barnett J. & Adger W.N. (2007). Climate change, human security and violent conflict. *Political Geography* 26, 639-655.

[109] Hsiang S.M., Meng K.C., & Cane M.A. (2011). Civil conflicts are associated with the global climate. *Nature*, 476, 438-

Whilst some species may benefit from climate change, many more will not. Observed impacts and adaptation responses arising from anthropogenic climate changes that have occurred to date include the following[110]:

- Shift in geographical distributions towards higher latitudes and (for terrestrial species) to higher elevations[111]. This response is compromised by habitat loss and anthropogenic barriers to range change;
- Phenological changes relating to seasonal timing of life-cycle events;
- Disruption of biotic interactions, due to differential changes in seasonal timing; e.g., mismatch between peak of resource demand by reproducing animals and the peak of resource availability;
- Changes in photosynthetic rates and primary production in response to $CO_2$ fertilization and increased nutrient availability (nitrogen deposition and coastal eutrophication). Overall, gross primary production is expected to increase, although fast growing species are likely to be favoured over slower growing ones, and different climate forcing agents (e.g., $CO_2$, tropospheric ozone, aerosols and methane) may have very different effects[112].

As noted above, the IPCC AR4 report estimated future global warming to be between 1.1°C to 6.4°C by 2100, with the upper part of that range becoming increasingly likely if current trajectories continue. Five reasons for concern for a similar temperature range had been previously identified in the IPCC's Third Assessment Report[113], relating to risks to unique and threatened (eco)systems; risks of extreme weather events; disparities of (human) impacts and vulnerabilities; aggregate damages to net global markets; and risks of large-scale discontinuities. These reasons for concern were re-assessed eight years later using the same methodology[114], with the conclusion that smaller future increases in global mean temperature – of around 1°C – lead to high risks to many unique and threatened systems, such as "coral reefs, tropical glaciers, endangered species, unique ecosystems, biodiversity hotspots, small island states and indigenous communities" (Figure 3.4).

**Figure 3.4: Projected impacts of global warming, as "Reasons for Concern"[115].**

441; doi: 10.1038/nature10311.

110 CBD Secretariat. (2009). *Connecting Biodiversity and Climate Change Mitigation and Adaptation.* Report of the Second Ad Hoc Technical Expert Group on Biodiversity and Climate Change. Montreal, Technical Series No. 41, 126 pages.

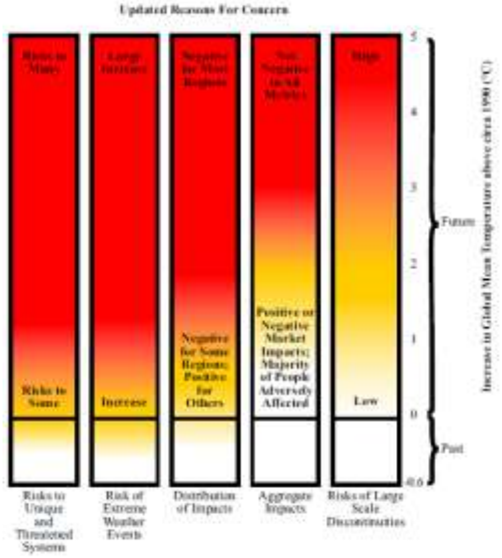
111 Cheng I.-C., Hill J.K., Ohlemüller R., Roy D.B. & Thomas C.D. (2011). Rapid range shift of species associated with high levels of climate warming. *Science* 333, 1024-1026; doi: 10.1126/science.1206432

112 Huntingford C., Cox P.M., Mercado L.M., Sitch S., Bellouin N, Boucher O. & Gedney N.. (2011). Highly contrasting effects of different climate forcing agents on terrestrial ecosystem services. *Phil. Trans. Roy. Soc. A*, 369, 2026-2037; doi: 10.1098/rsta.2010.0314

113 Smith J.B., Schellnhuber H.-J. & Mirza M.M.Q. (2001). Vulnerability to climate change and reasons for concern: a synthesis. Chapter 19 in *IPCC Third Assessment Report, Working Group II*, p 913-967. Cambridge University Press, Cambridge, UK.

114 Smith J. B. & 14 others. (2009). Assessing dangerous climate change through an update of the Intergovernmental Panel on Climate Change (IPCC) ''reasons for concern''. *Proc. Natl. Acad. Sci. USA*, 106, 4133–4137; doi: 10.1073/pnas.0812355106

115 Smith J. B. & 14 others. (2009). Assessing dangerous climate change through an update of the Intergovernmental Panel on Climate Change (IPCC) ''reasons for concern''. *Proc. Natl. Acad. Sci. USA*, 106, 4133–4137; doi: 10.1073/pnas.0812355106




*Updated "reasons for concern" plotted against increase in global mean temperature. Note that: i) this figure relates risk and vulnerability to temperature increase without reference to a future date; ii) the figure authors state that the colour scheme is not intended to equate to 'dangerous climatic interference' (since that is a value judgement); and iii) there was a marked worsening of the authors' prognosis in comparison to an assessment published 8 years earlier[116], using the same methodologies.*

The relatively specific and quantifiable risk of rate of extinction was assessed by the CBD's Second Ad hoc Technical Expert Group on Biodiversity and Climate Change, with the estimate that ~10% of species will be at risk of extinction for every 1°C rise in global mean temperature[117]. A recent meta-analysis[118] provides a similar, although lower, estimate, indicating that extinction is likely for 10-14% of all species by 2100. Even if such losses only occur locally or regionally rather than globally (i.e. extirpations, with species possibly 'saved from extinction' in zoos, seed-banks or culture collections), biodiversity reductions at those scales must inevitably lead to severe disruptions of many ecosystems and their services[119], with serious social, cultural and economic consequences. Due to the complex nature of the climate-biodiversity link, there will inevitably be uncertainty about the extent and speed at which climate change will impact biodiversity, species interactions[120], ecosystem services, the thresholds of climate change above which ecosystems no longer function in their current form[121], and the effectiveness of potential conservation measures[122,123].

### *3.2.2 Projected impacts of climate change on terrestrial ecosystems*

The geographical locations where greatest terrestrial biodiversity change might be expected has been assessed using multi-model ensembles and IPCC SRES A2 and B1 emission scenarios to predict the

[116] Smith J.B., Schellnhuber H.-J. & Mirza M.M.Q. (2001). Vulnerability to climate change and reasons for concern: a synthesis. Chapter 19 in *IPCC Third Assessment Report, Working Group II*, p 913-967.

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

[118] Maclean I.M.D. & Wilson R.J. (2011). Recent ecological responses to climate change support predictions of high extinction risk. *Proc. Nat. Acad,Sci. U.S.A.*, 108, 12337-12342; doi 10.1073/pnas.1017352108.

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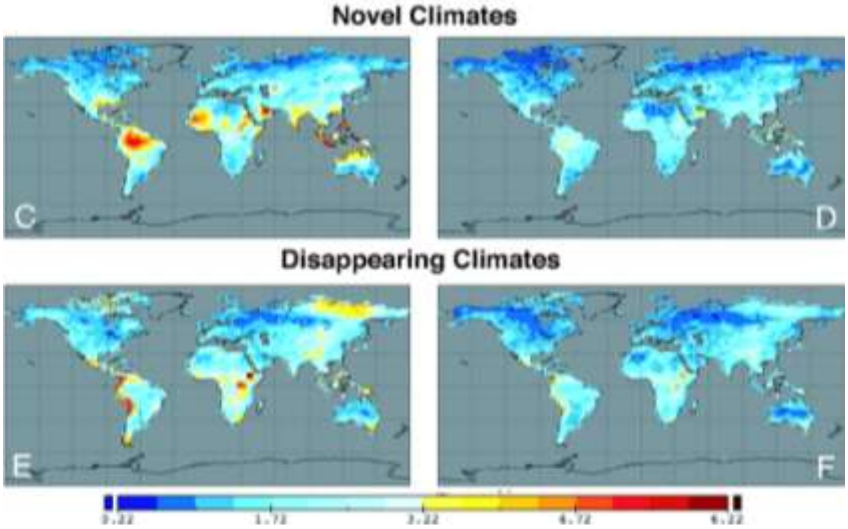
[123] Dawson T.P., Jackson S.T., House J.I., Prentice I.C. & Mace G.M. (2011). Beyond predictions: biodiversity conservation in a changing climate. *Science*, 332, 53-58; doi: 10.1126/science.1200303

appearance or disappearance of new and existing climatic conditions[124] (Figure 3.5). The A2 scenario indicates that, by 2100, 12-39% of the Earth's land surface will experience 'novel' climatic conditions (where the $21^{st}$ century climate does not overlap with $20^{th}$ century climate); in addition, 10-48% will experience disappearing climatic conditions (where the $20^{th}$ century climate does not overlap with the $21^{st}$ century climate).

**Figure 3.5: Novel and disappearing terrestrial climatic conditions by 2100**




*Model projections of novel (upper) and disappearing (lower) terrestrial climatic conditions by 2100. Left-hand maps: based on A2 emission scenario; right-hand maps: based on B1 emission scenario. Novel climatic conditions are projected to develop primarily in the tropics and subtropics. Disappearing climatic conditions are concentrated in tropical montane regions and the poleward parts of continents. Scale shows relative change, with greatest impact at the yellow/red end of the spectrum.*

Montane habitats (e.g., cloud forests, alpine ecosystems) and endemic species (e.g. on actual islands or 'stranded' species) have also been identified[125] as being particularly vulnerable because of their narrow geographic and climatic ranges, and hence limited – or non-existent – dispersal opportunities. Other terrestrial and coastal habitats considered to be at high risk include tundra ecosystems, tropical forests and mangroves. For coastal habitats, rising sea level will be an additional environmental stress.

A more physiological approach to assessing climatic vulnerability and resilience found that temperate terrestrial ectotherms (cold-blooded animals, mostly invertebrates) might benefit from higher temperatures, whilst tropical species, already close to their upper temperature tolerances, would be disadvantaged even though the amount of change to which they will be exposed is smaller (Figure 3.6)[126]. More limited data for vertebrate ectotherms (frogs, lizards and turtles[127]) demonstrated a similar pattern indicating a higher risk to tropical species from climate change. In temperate regions, insect crop pests and disease vectors would be amongst those likely to benefit from higher temperatures (with negative implications for ecosystem services, food security and human health), particularly if their natural predators are disadvantaged by climate change.

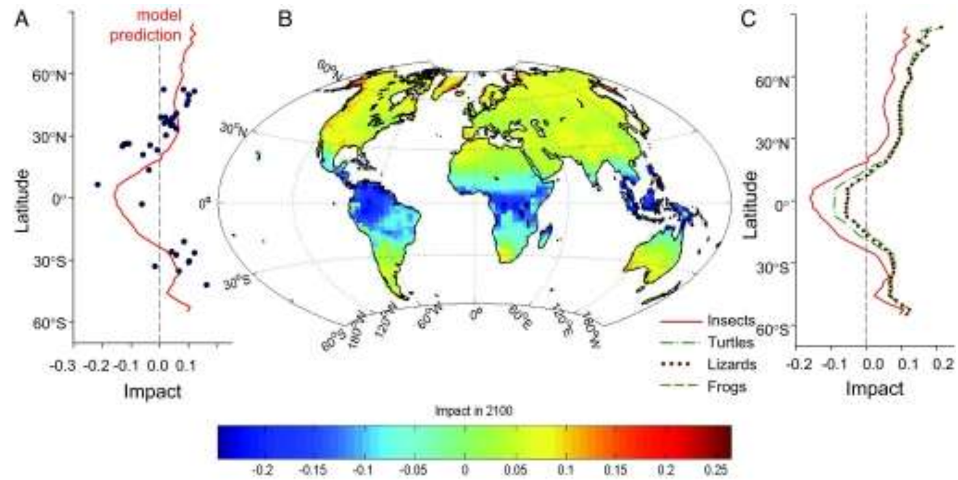
[124] Williams J.W., Jackson S.T. & Kutzbach J.E. (2007). Projected distributions of novel and disappearing climates by 2100 AD. *Proc. Natl. Acad. Sci. USA*, 104, 5738-5742; doi: 10.1073/pnas.0606292104

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

[126] Deutsch C.A., Tewksbury J.J., Huey R.B., Sheldon K.S., Ghalambor C.K., Haak D.C. & Martin P.R.(2008). Impacts of climate warming on terrestrial ectotherms across latitude. *Proc. Natl. Acad. Sci. USA.*, 105, 6668-6672; doi: 10.1073/pnas.0709472105

[127] Additional issues arise for turtles since their sex ratio can depend on the temperature during egg incubation. Several populations of marine turtles are already female biased, and ultra-bias (jeopardising population survival) could be caused by a further 1°C of warming. [Hawkes L.A., Broderick A.C., Godfrey M.H. & Godley B.J. (2007). Investigating the potential impacts of climate change on a marine turtle population. *Global Change Biology* 13, 923-932; doi: 10.1111/j.1365-2486.2007.01320.x]

**Figure 3.6: Projected impact of projected future warming (for 2100) on the fitness of terrestrial ectotherms[128]**




*Latitudinal impacts of climate change, based on thermal tolerance. A) and B), insect data; map shows negative impacts in blue, positive impacts in yellow/red. C), comparison of latitudinal change in thermal tolerance for insects with more limited data for turtles, lizards and frog.*

In general, vulnerability to climate change across species will be a function of the extent of climate change to which they are exposed relative to the species' natural adaptive capacity. This capability varies substantially according to species biology and ecology, as well as interactions with other affected species. Species and ecosystems most susceptible to decline will be those that not only experience high rates of climate change (including increased frequency of extreme events), but also have low tolerance of change and poor adaptive capacities[129].

Given their importance in the carbon cycle, the response of forest ecosystems to projected climate change is a critical issue for natural ecosystems, biogeochemical feedbacks and human society[130]. Key unresolved issues include the relative importance of water availability, seasonal temperature ranges and variability, the frequency of fire and pest abundance, and constraints on migration rates. Whilst tropical forests may be at risk, recent high resolution modelling has given some cause for optimism[131], in that losses in one region may be offset by expansion elsewhere.

### *3.2.3 Projected impacts of climate change and ocean acidification on marine ecosystems*

The marine environment is also vulnerable to climate change, with the additional stress of ocean acidification. Although, future surface temperature changes (with the exception of the Arctic) may not be as high as on land (Figure 3.2), major poleward distributional changes have already been observed; for example, involving population movements of hundreds and thousands of kilometres by

[128] Deutsch C.A., Tewksbury J.J., Huey R.B., Sheldon K.S., Ghalambor C.K., Haak D.C. & Martin P.R. (2008). Impacts of climate warming on terrestrial ectotherms across latitude. *Proc. Natl. Acad. Sci. USA.*, 105, 6668-6672; doi: 10.1073/pnas.0709472105

[129] Dawson T.P., Jackson S.T., House J.I., Prentice I.C. & Mace G.M. (2011). Beyond predictions: biodiversity conservation in a changing climate. *Science*, 332, 53-58; doi: 10.1126/science.1200303.

[130] Bonan G. (2008). Forests and climate change: forcings, feedbacks, and the climate benefit of forests. *Science*, 320, 1444-1449; doi: 10.1126/science.1155121

[131] Zelazowski P, Malhi Y, Huntingford C, Sitch S. & Fisher J.B. (2011). Changes in the potential distribution of humid tropical forests on a warmer planet. *Phil. Trans. Roy. Soc. A*, 369,, 137-160; doi: 10.1098/rsta.2010.0238

fish[132] and plankton[133],[134] respectively in the North East Atlantic. Increases in marine pathogenic bacteria have also been ascribed to climate change[135].

For temperate waters, increases in planktonic biodiversity (in terms of species numbers) have recently occurred in response to ocean warming[136]. Such changes do not, however, necessarily result in increased productivity nor benefits to ecosystem services, e.g., fisheries. In the Arctic, the projected loss of year-round sea ice this century[137] is likely to enhance pelagic biodiversity and productivity, but will negatively impact charismatic mammalian predators (polar bears and seals). The loss of ice will also increase the biological connectivity between the Pacific and Atlantic Oceans, with potential for major introductions (and novel interactions) for a wide variety of taxa via trans-Arctic exchange[138].

Marine species and ecosystems are also increasingly subject to an additional and yet closely linked threat: ocean acidification. Such a process is an inevitable consequence of the increase in atmospheric $CO_2$: this gas dissolves in sea water, to form carbonic acid; subsequently, concentrations of hydrogen ions and bicarbonate ions increase, whilst levels of carbonate ions decrease.

By 2100, a pH decrease of 0.5 units in global surface seawater is projected under SRES scenario A1FI[139], corresponding to a 300% increase in the concentration of hydrogen ions. This may benefit small-celled phytoplankton (microscopic algae and cyanobacteria), but could have potentially serious implications for many other marine organisms, including commercially-important species that are also likely to be subject to thermal stress[140]. Fish sensory perception, and hence behaviour, may also be affected[141]. However, responses by a wide range of taxa can be highly variable, with some species showing positive or neutral responses to lowered pH. For marine invertebrates, differences in sensitivity can occur between populations and within life cycles[142], and seem closely linked to metabolic activity[143] and food availability. Overall, effects are likely to be negative: a meta-analysis[144] of 73 studies showed that laboratory survival, calcification and growth were all significantly reduced when a wide range of organisms was exposed to conditions likely to occur in 2100 under conditions of unmitigated climate change (Figure 3.7).

**Figure 3.7: Meta-analysis of experimental studies on effect of pH change projected for 2100.**

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[132] Perry A.L., Low P.J., Ellis J.R. & Reynolds J.D. (2005). Climate change and distribution shifts in marine fishes. *Science* 308,1912-1915; doi: 10.1126/science.1111322

[133] Beaugrand G., Reid P.C., Ibanez F., Lindley J.A. & Edwards M. (2002). Reorganization of North Atlantic marine copepod biodiversity and climate. *Science*, **296:**1692-1694.

[134] Perry A.L., Low P.J., Ellis J.R. & Reynolds J.D. (2005). Climate change and distribution shifts in marine fishes. *Science* 308,1912-1915; doi: 10.1126/science.1111322

[135] Vezzuli L., Brettar I., Pezzati E., Reid P.C., Colwell R.R., Höfle M.G. & Pruzzo C. (2012). Long-term effects of ocean warming on the prokaryotic community: evidence from the vibrios. *The ISME Journal, 6, 21-30*; doi: 10.1038/ismej.2011.89

[136] Beaugrand G., Edwards M. & Legendre L (2010). Marine biodiversity, ecosystem functioning, and carbon cycles. *Proc. Nat. Acad. Sci. USA*, 107, 10120-10124; doi: 10.1073/pnas.0913855107

[137] Boé J., Hall A. & Qu X. (2009). September sea-ice cover in the Arctic Ocean projected to vanish by 2100. *Nature Geosciences*, 2, 341-343; doi: 10.1038/ngeo467

[138] Greene C.H., Pershing A.J., Cronin T.M. & Ceci N. (2008). Arctic climate change and its impacts on the ecology of the North Atlantic. *Ecology*, 89 (Supplement),S24–S38

[139] Caldeira K. & Wickett M.E. (2005). Ocean model predictions of chemistry changes from carbon dioxide emissions to the atmosphere and ocean. *J. Geophys. Res.- Oceans*, 110, C09S04

[140] CBD Secretariat. (2009). *Scientific Synthesis of the Impacts of Ocean Acidification on Marine Biodiversity*. CBD Montreal, Technical Series No. 46, 61 pp

[141] Munday, P.L., Dixson, D.L., Donelson, J.M., Jones, G.P., Pratchett, M.S., Devitsina, G.V. & Døving, K.B. (2009). Ocean acidification impairs olfactory discrimination and homing ability of a marine fish. *Proc. Natl. Acad. Sci. USA* 106, 1848-1852; doi: 10.1073/pnas.0809996106

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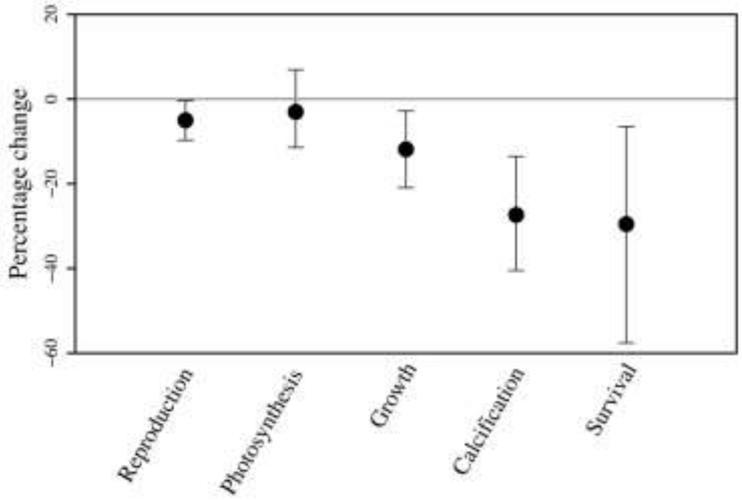
[143] Melzner, F., Gutowska, M.A., Langenbuch, M., Dupont, S., Lucassen, M., Thorndyke, M.C., Bleich, M. & Pörtner, H.-O. (2009). Physiological basis for high $CO_2$ tolerance in marine ectothermic animals: pre-adaptation through lifestyle and ontogeny? *Biogeosciences* 6**,** 2313-2331.

[144] Kroeker K.J., Kordas R.L., Crim R.N. & Singh G.G. (2010). Meta-analysis reveals negative yet variable effects of ocean acidification on marine organisms. *Ecol. Lett.* 13, 1419-1434; doi: 10.1111/j.1461-0248.2010.01518.x




*Effect of pH decrease of 0.4 units on reproduction, photosynthesis, growth, calcification and survival under laboratory conditions for a wide taxonomic range of marine organisms. Mean effects and 95% confidence limits calculated from log-transformed response ratios, here re-converted to a linear scale. Redrawn[145] with original lead author's permission[146].*

For a recent overview of ocean acidification and its physiological and ecological impacts, see Gattuso & Hansson[147]. Actions to address ocean acidification have recently been reviewed by the CBD[148],

The threshold for 'dangerous' ocean acidification has yet to be defined at the intergovernmental level, in part because its ecological impacts and economic consequences are currently not well quantified[149,150]. An atmospheric $CO_2$ stabilisation target of 450 ppm could still risk large-scale and ecologically-significant impacts. Thus, at that level: 11% of the surface ocean would experience a pH fall of >0.2 relative to pre-industrial levels; only 8% of present-day coral reefs would experience conditions considered optimal for calcification, compared with 98% at pre-industrial atmospheric $CO_2$ levels[151]; and around 10% of the surface Arctic Ocean would be aragonite-undersaturated for part of the year[152] (increasing metabolic costs for a wide range of calcifying organisms). Potentially severe local impacts could occur elsewhere in upwelling regions and coastal regions[153], with wider feedbacks[154].

Both cold water and tropical corals seem likely to be seriously impacted by ocean acidification; however, the latter are especially vulnerable since they are also subject to temperature stress (coral

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[145] Williamson P. & Turley C. (2012). Ocean acidification in a geoengineering context. *Phil. Trans. Roy. Soc. A* (in press)

[146] Kroeker K.J., Kordas R.L., Crim R.N. & Singh G.G. (2010). Meta-analysis reveals negative yet variable effects of ocean acidification on marine organisms. *Ecology Letters* 13, 1419-1434; doi: 10.1111/j.1461-0248.2010.01518.x

[147] Gattuso J.-P. & Hansson L. (eds) (2011). *Ocean Acidification*. Oxford University Press, 326 pp.

[148] CBD Secretariat. (2012). *Practical responses to address ocean acidification*. Report on expert meeting; UNEP/CBD/SBSTTA/16/INF/14.

[149] Turley C., Eby M., Ridgwell A.J., Schmidt D.N., Findlay H.S., Brownlee C., Riebesell U., Gattuso J.-P., Fabry V.J. & Feely R.A. (2010). The societal challenge of ocean acidification. *Mar. Poll. Bull.* 60, 787–792.

[150] Cooley S. R. & Doney S.C. (2009). Anticipating ocean acidification's economic consequences for commercial fisheries. *Environ. Res. Lett.* 4, 024007, doi: 10.1088/1748-9326/4/2/024007

[151] Cao L. & Caldeira K. (2008) .Atmospheric $CO_2$ stabilization and ocean acidification. *Geophy. Res. Lett.* 35, L19609; doi: 10.1029/2008GL035072

[152] Steinacher M., Joos F., Frölicher T.L., Plattner G.-K. & Doney S.C. (2009). Imminent ocean acidification in the Arctic projected with the NCAR global coupled carbon cycle-climate model. *Biogeosciences* 6, 515-533; doi: 10.5194/bg-6-515-2009

[153] Feely R.A., Alin S.R., Newton J., Sabine C.L., Warner M., Devol A., Krembs C. & Maloy C. (2010). The combined effects of ocean acidification, mixing, and respiration on pH and carbonate saturation in an urbanized estuary. *Est. Coastal & Shelf Sci*. 88, 442-449; doi: 10.1016/j.ecss.2010.05.004

[154] Gehlen M., Gruber N., Gangstø R., Bopp L. & Oschlies A. (2011). Biogechemical consequences of ocean acidification and feedbacks toi the Earth system. In*: Ocean Acidification* (Ed: J.-P. Gattusso & L. Hansson), Oxford University Press, p 230- 248.

bleaching), coastal pollution (eutrophication and increased sediment load) and sea-level rise. Population recovery time from bleaching would be prolonged if growth is slowed due to acidification (together with other stresses), although responses are variable and dependent on local factors[155]. The biodiversity value of corals is extremely high, since they provide a habitat structure for very many other organisms; they protect tropical coastlines from erosion; they have significant biotechnological potential; and they are highly-regarded aesthetically. More than half a billion people are estimated to depend directly or indirectly on coral reefs for their livelihoods[156].

### 3.3 The role of biodiversity in the Earth system and in delivering ecosystem services

The biosphere plays a key role in the Earth system, especially as part of the global cycles of carbon, nutrients and water, thereby providing ecosystem services of immense human value. Interactions between species, ecosystems and a very wide range of other natural and human-driven processes must therefore also be considered when assessing the impacts of climate change (and geoengineering) on biodiversity. The conservation and restoration of natural terrestrial, freshwater and marine biodiversity are essential for the overall goals of both the CBD and UNFCCC, not only on account of ecosystems' active role in global cycles but also in supporting adaptation to climate change.

Carbon is naturally captured and stored by terrestrial and marine ecosystems, through biologically-driven processes. The amount of carbon in the atmosphere, ~750Gt, is much less than the ~2,500 Gt C stored in terrestrial ecosystems[157]; a further 1,000 Gt C occurs in the upper layer of the ocean, and an additional ~37,000 Gt C is stored in the deep ocean, exchanging with the atmospheric over relatively long time scales. On average ~160 Gt C exchange annually between the biosphere (both ocean and terrestrial ecosystems) and atmosphere. Proportionately small changes in ocean and terrestrial carbon stores, caused by changes in the balance of exchange processes, might therefore have large implications for atmospheric $CO_2$ levels. Such a change has already been observed: in the past 50 years, the fraction of $CO_2$ emissions that remains in the atmosphere each year has slowly increased, from about 40% to 45%, and models suggest that this trend was caused by a decrease in the uptake of $CO_2$ by natural carbon sinks, in response to climate change and variability[158].

It is therefore important to improve our representation of biogeochemical feedbacks (mostly driven by plants and microbes, on land and in the ocean) in Earth system models – not just climate models – in order to understand how biodiversity may influence, and be influenced by, human activities. The range of non-climatic factors important in this context, as direct and indirect drivers of biodiversity change, and the range of ecosystem goods and services that are involved are summarised in Figure 1.1.

### 3.4 Projected socio-economic and cultural impacts of climate change, in biodiversity context

The scientific literature on the societal implications of projected climate change is vast, and a detailed assessment is inappropriate here. Nevertheless, a very brief overview of the socio-economic consequences of current trajectories (in the context of biological diversity and ecosystem processes) is necessary, to complete the conceptual picture of linkages between climate, biodiversity, non-marketed goods and services, and human well-being. Such considerations provide important context for the discussion of how geoengineering (with its own impacts) might be used to counteract climate change. Chapter 6 gives additional attention to CBD-relevant socio-economic and cultural aspects of geoengineering.

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[155] Pandolfi J.M., Connolly S.R., Marshall D.J. & Cohen A.L. (2011). Projecting coral reef futures under global warming and ocean acidification. *Science*, 333, 418-422; doi: 10.1126/science.1204794.

[156] TEEB. (2009). *The Economics of Ecosystems and Biodiversity: Climate Issues Update, September 2009*. www.unep.ch/etb/ebulletin/pdf/TEEB-ClimateIssuesUpdate-Sep2009.pdf

[157] Ravindranath N.H. & Ostwald M. (2008). *Carbon Inventory Methods Handbook for Greenhouse Gas Inventory, Carbon Mitigation and Roundwood Production Projects*. Springer Verlag, Advances in Global Change Research, pp 304, ISBN 978-1-4020-6546-0.

[158] Le Queré C. & 30 others (2009). Trends in the sources and sinks of carbon dioxide. *Nature Geoscience*, 2, 831-836; doi: 10.1038/ngeo689.

The Stern Review[159] estimated that, without action, the overall costs of climate change would be equivalent to a future annual loss of 5-20% of gross domestic product. Although that analysis was much discussed[160] and criticised by some economists, projected economic impacts of climate change of similar range and scale were identified in the IPCC Fourth Assessment Report (AR4, Working Group II). Table 3.1 summarises those findings on a regional basis, with emphasis on environmental impacts. The IPCC Fifth Assessment Report, AR5 now nearing completion, will provide additional, updated information, using improved projections (e.g., for sea level rise) and a wider range of impacts (e.g., including ocean acidification).

**Table 3.1. Examples of some projected environmental impacts of climate change and their socio-economic implications for different regions (all with very high or high confidence). Information from IPCC AR4 Synthesis Report[161].**

| | |
|---|---|
| **Africa** | • By 2020, agricultural yields reduced by up to 50% in some countries, affecting food security and exacerbating malnutrition. 75-250 million people exposed to increased water stress.<br>• By 2080, arid and semi-arid land likely to increase by 5-8%.<br>• By 2100, sea level rise will affect low-lying coastal areas with large populations; adaptation costs could be at least 5-10% of Gross Domestic Product |
| **Asia** | • By 2050, decreased freshwater availability in Central, South,East and South-East Asia<br>• Coastal areas, especially heavily populated regions in South, East and South-East Asia, at increased flooding risk from the sea (and, in some megadeltas, river flooding)<br>• Associated increased risk of endemic morbidity and mortality due to diarrhoeal disease |
| **Australasia** | • By 2020, significant biodiversity loss in the Great Barrier Reef, Queensland wet tropics and other ecologically rich sites<br>• By 2030, reduced agricultural and forest production over much of southern and eastern Australia, and parts of New Zealand, due to increased drought and fire.<br>• By 2050, ongoing coastal development and population growth exacerbate risks from sea level rise and increases in the severity and frequency of storms and coastal flooding. |
| **Europe** | • Negative impacts include increased risk of inland flash floods and more frequent coastal flooding and increased erosion (due to storminess and sea level rise).<br>• Mountainous areas will experience glacier retreat, reduced snow cover and species losses of up to 60% by 2080 (under high emissions scenarios).<br>• In southern Europe, reduced water availability, hydropower potential, summer tourism and crop productivity, together with increased health risks due to heat waves and wildfires. |
| **Latin America** | • By 2050, gradual replacement of tropical forest by savanna in eastern Amazonia; elsewhere semi-arid vegetation will tend to be replaced by arid-land vegetation. Associated risk of significant biodiversity loss through species extinction<br>• Decreased productivity of many crops and livestock, with adversely affecting food security.<br>• Hydrological changes are expected to significantly affect water availability for human consumption, agriculture and energy generation. |
| **North America** | • Moderate climate change is projected to increase yields of rain-fed agriculture by 5-20%, but with important variability among regions. Major challenges expected for crops near the warm end of their suitable range or which depend on highly utilised water resources.<br>• Increased number, intensity and duration of heat waves during the course of the century, with potential for adverse health impacts.<br>• Coastal communities and habitats will be increasingly stressed by climate change impacts interacting with development and pollution. |
| **Polar regions** | • Reductions in thickness and extent of glaciers, ice sheets and sea ice; changes in natural ecosystems include adverse effects on migratory birds, mammals and higher predators.<br>• For human communities in the Arctic, impacts are projected to be mixed; detrimental impacts include those on infrastructure and traditional indigenous ways of life.<br>• In both polar regions, specific ecosystems and habitats are projected to be vulnerable, as |

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[159] Stern N. (2006). *The Economics of Climate Change. The Stern Review*. 712 pp, Cambridge University Press, Cambridge, UK

[160] Barker et al. (2008). *Special Topic: The Stern Review Debate* (6 editorials and 8 related papers). *Climatic Change*, 89, 173-446.

[161] IPCC. (2008). *Climate Change 2007 – Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Pachauri R.K. & Resinger A. (Eds). IPCC, Geneva, Switzerland, 104 pp.

| | |
|---|---|
| | climatic barriers to species invasions are lowered. |
| **Islands** | • Sea level rise is expected to exacerbate inundation, storm surge, erosion and other coastal hazards, threatening vital infrastructure that supports the livelihood of island communities.<br>• Reduced water resources in many small islands, e.g., in the Caribbean and Pacific, may become insufficient to meet demand during low-rainfall periods.<br>• Higher temperatures will increase frequency of coral bleaching and, for mid- and high-latitude islands, the risk of invasion by non-native species. |

# CHAPTER 4: POTENTIAL IMPACTS ON BIODIVERSITY OF CLIMATE GEOENGINEERING ACHIEVED BY SUNLIGHT REFLECTION METHODS

As summarized in Chapter 3, if anthropogenic greenhouse-gas emissions continue on current trajectories, the resultant projected climate change will pose an increasingly severe threat to biodiversity and ecosystem services, adding to the many factors already influencing biodiversity loss. Effective actions intended to reduce the magnitude of future climate change would therefore be expected to reduce its impacts on biodiversity. However, such measures may not fully achieve their intended benefits, and are also likely to have additional unintended consequences (Figure 2.1), that may offset (or augment) their intended effects. Thus if a proposed geoengineering approach can be shown to be potentially feasible and effective in reducing the risks, costs and uncertainties of climate change, its projected positive impacts need to be considered alongside any projected further impacts of the geoengineering measure (mostly technique-specific), with their own risks, costs and uncertainties.

This chapter explores whether and how sunlight reflection methods (SRM) might be able to reduce climate-imposed threats to biodiversity and ecosystem services, including consideration of the uncertainties of those intended, beneficial impacts. It also examines the potential for unintended side effects of SRM. The projected positive and negative impacts that are common to all techniques involving reduction in incoming solar irradiance (as would result from space- or atmospheric-based SRM) are reviewed in section 4.1; technique-specific impacts for a wider range of approaches are reviewed in section 4.2. Carbon dioxide removal (CDR) techniques are examined in Chapter 5.

Most comparisons given here are in relation to a future world where the climate has changed and is impacting biodiversity due to inadequate efforts to reduce greenhouse-gas emissions. Limiting the future temperature increase to 2°C will be extremely challenging, and an increase of 3-5°C seems much more likely if current emission trajectories continue.

## 4.1 Potential impacts on biodiversity of generic SRM that causes uniform dimming

### *4.1.1 Potential reduction in temperature and other climatic effects from uniform dimming*

Studies of the potential impacts of SRM have been primarily based on computer modelling, as discussed below. Observations of the natural world (e.g., volcanic eruptions, recent[162][163] and historical[164,165,166]) are also relevant, since these provide precedents for temporary changes in solar irradiance reaching the Earth's surface, of similar order of magnitude to proposed SRM interventions.

Several models have assumed that SRM is able to cause uniform dimming to counter the climate change projected from doubled[167],[168] or quadrupled[169],[170] $CO_2$, or for specific IPCC SRES scenarios[171].

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[162] Dutton E.G. & Christy J.R. (1992). Solar radiative forcing at selected locations and evidence for global lower tropospheric cooling following the eruptions of El Chichón and Pinatubo. *Geophys. Res. Lett*. 19, 2313-2316; doi:10.1029/92GL02495

[163] Trenberth K.E. & Dai A. (2007). Effects of Mount Pinatubo volcanic eruption on the hydrological cycle as an analog of geopengineering. *Geophys. Res. Lett*., 34, L15702; doi: 10.1029/2007GL030524

[164] Miller G.H., Geirsdóttir Á., Zhong Y., Larsen D.J., Otto-Bliesner B.L., Bailey D.A.,Refsnider K.A.,Lehman S.J.,Southon J.R.,Anderson C.,Björnsson H., & Thordarson T (2012). Abrupt onset of the Little Ice Age triggered by volcanism and sustained by sea-ice/ocean feedbacks. *Geophys. Res. Letters*, 39, L02708, doi: 10.1029/2011GL050168

[165] Oman L., Robock A., Stenchikov G.L. & Thordarson T. (2006). High latitude eruptions cast shadow over the African monsoon and flow of the Nile. *Geophys. Res. Lett*., 33, L18711; doi: 10.1029/2006GL027665

[166] Oman, L., Robock A., Stenchikov G., Schmidt G.A. & Ruedy R. (2005), Climatic response to high-latitude volcanic eruptions. *J. Geophys. Res.*,110, D13103, doi:10.1029/2004JD005487.

[167] Caldeira K. & Wood L. (2008). Global and Arctic climate engineering: numerical model studies. *Phil. Trans. Roy. Soc. A,* 366, 4039-4056; doi:10.1098/rsta.2008.0132

[168] Jones A., Haywood J.M. & Boucher O. (2011). A comparison of the climate impacts of geoengineering by stratospheric $SO_2$ injection and by brightening of marine stratocumulus cloud, *Atmos. Sci. Lett.*, 12, 176-183; doi: 10.1002/asl.291

[169] Irvine P.J., Ridgwell A., & Lunt D.J. (2010). Assessing the regional disparities in geoengineering impacts. *Geophys. Res. Lett.* 37, L18702, doi: 10.1029/2010GL044447

[170] Schmidt H., Alterskær K., Karam D.B., Boucher O., Jones A., Kristansson J.E., Niemeier U., Schulz M., Aaheim A.,

This is a useful starting point; however, the assumption of uniform dimming is only valid (and might still be unachievable) for space-based or stratospheric-based techniques where particular effort is made to achieve that goal. Reviews[172,173] of results from those idealised models have concluded that: i) it is theoretically possible to fully counteract, at the *global* scale, the radiative forcing due to increased anthropogenic greenhouse gases under such scenarios; and ii) the projected temperature changes due to greenhouse gas forcing can be greatly reduced for all areas of the planet. However, uniform dimming simulations are unable to fully restore surface temperatures to either current or pre-industrial conditions at the *regional* level, since the temperature gradients between the equator and both poles are reduced. As a result, the modelled SRM interventions leave either excess cooling in the tropics, or excess warming in high latitudes, or both, compared to existing conditions.

Water availability is at least as crucial as temperature for biodiversity, ecosystems and human well-being. Thus it is an important finding that the modelled cooling caused by uniform dimming is also apparently able to counteract most of the precipitation changes caused by increased atmospheric levels of greenhouse gases (previously presented in Figure 3.2). But not all of those precipitation changes are offset: models of the 'SRM world' that fully counter anthropogenic radiative forcing consistently show a slowing of the hydrological cycle, with up to a 2% decrease in global mean precipitation compared to the current climate. This may be most pronounced over land and/or in equatorial regions, among the most biodiverse regions.

Thus the overall conclusion of several groups, working with different models, is that uniform dimming, if achievable, could reduce the worst negative impacts of unmitigated climate change, yet is also likely to lead to significant geographical redistribution of such climatic effects[174,175,176,177,178,179,180].

The speed with which SRM would be expected to reduce temperatures, once deployed at the global scale, is a unique attribute of these techniques. While SRM would start reducing temperature immediately after global deployment, in a similar way to volcanically-induced cooling[181], it would take decades (or longer) for emissions cuts or CDR deployment to lower global temperatures. This means that space- or stratospheric-based SRM is the only approach developed to date[182] that might allow a rapid reduction in temperatures, should that be considered necessary.

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Benduhn F., Lawrence M. & Timmreck C. (2012). Can a reduction in solar irradiance counteract $CO_2$-induced climate change? – Results from four Earth system models. *Earth Syst. Dynam. Discuss*., 3, 31-72

[171] Jones A., Haywood J., Boucher O., Kravitz B. & Robock A. (2010). Geoengineering by stratospheric $SO_2$ injection: results from the MetOffice HadGEM2 climate model and comparison with the Goddard Institute for Space Studies ModelE. *Atmos. Chem. Phys*. 10, 5999-6006; doi: 10.5194/acp-10-5999-2010

[172] Rasch P.J., Times S., Turco, R.P., Robock A., Oman L., Chen C.-C., Stenchikov G.L. & Garcia R.R. (2008). An overview of geoengineering of climate using stratospheric sulphate aerosols. *Phil. Trans. Roy. Soc. A*, 366, 4007-4037; doi: 10.1098/rsta.2008.0131; also

[173] Vaughan N.E.& Lenton T.M. (2011). A review of climate geoengineering proposals. *Climatic Change,* 109, 745-790; doi: 10.1007/s10584-011-0027-7.

[174] Matthews H.D. & Caldeira K. (2007),Transient climate-carbon simulations of planetary geoengineering. *Proc. Natl. Acad. Sci. USA*, 104, 9949-9954; doi: 10.1073/pnas.07009419104

[175] Robock A., Oman L. & Stenchikov G. (2008). Regional climate responses to geoengineering with tropical and Arctic $SO_2$ injections. *J. Geophys. Res*., 113, D16101, doi: 10.1029/2008JD010050 .

[176] Caldeira K. & Wood L. (2008). Global and Arctic climate engineering: numerical model studies. *Phil. Trans. Roy. Soc. A,* 366, 4039-4056. doi:10.1098/rsta.2008.0132.

[177] Ricke K.L., Morgan M.G. & Allen M.R. (2010). Regional climate response to solar radiation management. *Nature Geosciences*, 3: 537-541; doi: 1038/ngeo915

[178] Lunt D.J., Ridgwell A, Valdes P.J. & Seale A. (2008) "Sunshade world": a fully coupled GCM evaluation of the climatic impacts of geoengineering. *Geophys. Res. Lett*., 35, L12710; doi: 10.1029/2008GL033674

[179] Schmidt H., Alterskær K., Bou Karam D., Boucher O., Jones A., Kristansson J.E., Niemeier U., Schulz M., Aaheim A., Benduhn F., Lawrence M. & Timmreck C. (2012). Can a reduction in solar irradiance counteract $CO_2$-induced climate change? – Results from four Earth system models. *Earth Syst. Dynam. Discuss*., 3, 31-72

[180] Pongratz J., Lobell D.B., Cao L. & Caldeira K. (2012). Crop yields in a geoengineered climate. *Nature Climate Change,* 101-105; doi: 10.1038/nclimate1373

[181] Dutton E.G. & Christy J.R. (1992). Solar radiative forcing at selected locations and evidence for global lower tropospheric cooling following the eruptions of El Chichón and Pinatubo. *Geophys. Res. Lett*. 19, 2313-2316; doi:10.1029/92GL02495

[182] Relatively rapid cooling might also be possible from cirrus cloud manipulation; however, the practicalities of that

As indicated above, if the cooling from SRM were realised as simulated by (idealised) models, many of the projected impacts of unmitigated climate change on biodiversity would be much reduced. However, there is scope for further modelling work, since many uncertainties remain. Thus existing model outcomes cannot yet be used to confidently predict the totality of effects, comprising not only which areas are projected to benefit (fully, partially or maybe not at all, compared with unmitigated control) from reduced changes in temperature and precipitation under SRM deployment, but also the magnitude and relative importance – or unimportance – of other, unintended effects on biodiversity, ecosystems and their services.

The uncertainties associated with comparisons of regional climate changes in a high $CO_2$ world with and without SRM is inherent in the complexity of the climate system itself, affecting the ability of models to fully represent all the interacting physical and biogeochemical processes at the scale needed for regional climate projections. It is therefore unsurprising that different regional results are provided by different global climate models: as inter-comparison exercises for climate models (without SRM) have demonstrated[183], relatively small differences in model structure, parameterisations and start-up conditions can generate a diversity of regional climate projections for the same emission scenarios. In some regions, the results of several models converge, increasing confidence that regional projections are correct – although that may be because they may all share the same deficiency (e.g. omitting a feedback factor, due to inadequate knowledge of the processes involved). However, in other regions, there is either less or no agreement.

Inter-comparisons between models that include SRM simulations are currently underway[184,185], and preliminary results from one four-model experiment (based on quadrupling $CO_2$ and uniform dimming) have recently been published[186], broadly confirming the main conclusions discussed above. Recognising that full climate restoration is unlikely to be achievable (even with sophisticated application of non-uniform dimming, targeting specific regions[187]), recent papers have proposed SRM approaches that might nevertheless minimise the overall effects of adverse impacts[188], based on different social objectives – egalitarian, utilitarian or ecocentric[189], albeit at a relative crude level.

However applied, SRM would introduce a new dynamic between the heating effects of greenhouse gases and the cooling effects of sunlight reduction. There are no known palaeo-precedents for the radiative impacts of high greenhouse gases to be balanced by reduced light quantity; thus the stability of that combination is uncertain, and it is not clear what specific environmental challenges an "SRM world" would present to particular species and ecosystems, either on a short-term or long-term basis, as discussed below in greater detail.

#### *4.1.2 Projected impacts of uniform dimming on hydrological and nutrient cycles*

As noted above, modelling to date has mostly focussed on the global and regional temperature and precipitation changes likely to result from idealised SRM deployment compared to a high $CO_2$ world.

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techniques have yet to be investigated. The most rapid temperature reduction realistically achievable through mitigation is estimated to be ~1°C in 50 years, based on combined actions on $CO_2$, methane and black carbon. [Shindell D & 23 others (2012). Simultaneously mitigating near-term climate change and improving health and food security. *Science* 335, 183-189; 10.1126/science.1210026].

183 IPCC. (2007) *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Eds: Solomon S., Qin D., Manning M, Chen Z, Marquis M, Avery K.B., Tignor M. & Miller H.L. IPCC, Cambridge, UK and New York, NY, USA.

184 Kravitz B., Robock A., Boucher O., Schmidt H., Taylor K.,Stenchikov G. & Schulz M, (2011). The Geoengineering Model Intercomparison Project (GeoMIP). *Atmos. Sci. Lett*.,, 12, 162-167, doi:10.1002/asl.316.

185 Robock A., Kravitz B. & Boucher O. (2011). Standardizing experiments in geoengineering: GeoMIP Stratospheric Aerosol Geoengineering Workshop, New Jersey, 10-12 February 2011; *Eos*, 92, 197; doi: 10.1029/2011ES003424

186 Schmidt H., Alterskær K., Bou Karam D., Boucher O., Jones A., Kristansson J.E., Niemeier U., Schulz M., Aaheim A., Benduhn F., Lawrence M. & Timmreck C. (2012). Can a reduction in solar irradiance counteract $CO_2$-induced climate change? – Results from four Earth system models. *Earth Syst. Dynam. Discuss*., 3, 31-72.

187 Even if such sophistication were possible, we would never know exactly how the naturally-dynamic climate system would have evolved in the absence of SRM; e.g. as a consequence of natural decadal variability in climatic processes, that may partly be due to highly uncertain changes in the 'solar constant'.

188 Ban-Weiss G.A. &.Caldeira K. (2010). Geoengineering as an optimization problem, *Environ. Res. Lett.,* 5, 1-9.

189 Moreno-Cruz J.B., Ricke K.L. & Keith D.W. (2012). A simple model to account for regional inequalities in the effectiveness of solar radiation management. *Climatic Change* 110, 649-668: doi: 10.1007/s10584-011-0103-z

However, for biodiversity, ecosystems and their services, relative precipitation changes and temporal patterns in precipitation delivery are much more important than absolute amounts. Thus, for an arid region, a change in quantity or timing of around 5-10 cm $yr^{-1}$ could be critical, yet such a change would be insignificant for areas annually receiving several metres of precipitation. Furthermore, precipitation minus evaporation (P-E) is a much more useful metric of biologically-available water than is precipitation alone[190], with soil moisture the key hydrological variable for healthy terrestrial ecosystems. Additional relevant processes affecting soil and plant water loss (evapotranspiration) include total insolation, the response of plants to increased $CO_2$ (affecting stomatal opening), and the different projected changes in the distribution of different ecosystems in response to different emission scenarios.

The combined response of these processes to SRM-induced solar dimming is currently highly uncertain, and there is likely to be considerable regional variability. Whilst it has been calculated that SRM might be able to reduce the overall P-E change due to global warming by ~75%[191] (compared to doubled $CO_2$), soil moisture in the tropics under SRM is still likely to be significantly less than at present[192,193]. Changes in P-E and soil moisture have major implications for terrestrial ecosystems since this is a key parameter determining net primary production (NPP)[194], with consequences for the carbon cycle[195] and a wide range of biogeochemical feedbacks. P-E is also a crucial factor for agriculture, the frequency of forest fires[196]; and freshwater quantity and quality[197].

SRM that aims to achieve uniform dimming could have both predictable and unknown side effects on the atmospheric cycling of nutrients, their deposition[198] and recycling processes, in soil and in the ocean. Relative to unmitigated climate change, the recycling of soil nutrients could be expected to be slowed, since this process is highly temperature dependent. However, it is not yet known to what degree SRM might be able to counteract the overall changes to nutrient cycles that might occur in a high $CO_2$ world.

### *4.1.3 Projected impacts of uniform dimming on species and ecosystems*

Reducing temperature through deployment of idealised SRM would, if achievable, benefit those species and ecosystems identified in Chapter 3 as being particularly vulnerable to the negative impacts of increased temperature due to unmitigated climate change; e.g., endemic, isolated populations ('stranded' species or on islands), and polar and mountain ecosystems. Long-lived species which are poor at adapting to climate change (e.g. non-mobile species, such as many trees, and others that reproduce slowly), are also likely to benefit from SRM in comparison to unmitigated climate change, as are species with temperature-regulated sex determination. However, species that are particularly poor at adapting to climate change are also those most at risk from sudden SRM termination (Section 4.1.5).

There are many uncertainties relating to the ability of existing species and ecosystems to adapt to living in novel environments resulting from rapid global climate change. This is true both for a world of unmitigated climate change (high temperatures, altered precipitation patterns, increased $CO_2$

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concentrations) and for a world where radiative forcing due to high levels of greenhouse gases is masked by SRM (more diffuse light, altered precipitation patterns, high $CO_2$ concentrations).

Overall, *if* i) the world behaves the way that it does in most global climate models developed to date; ii) uniform or near-uniform global dimming is achievable, and iii) there are no serious additional adverse side effects, *then* SRM-induced (uniform) dimming would greatly reduce the impacts of climate change on biodiversity relative to a high greenhouse gas world. Nevertheless, climate model predictions have their limitations (being unable to exactly match changes in the real world, particularly at fine spatial and temporal scales, i.e. regionally and annually); and there is inevitably some risk of unexpected, as well as unintended, side effects.

Global-scale SRM necessarily involves 'unknown unknowns', since it is unlikely that all potential risks can be identified through smaller-scale deployments[199]. Furthermore, the comparison with 'unmitigated climate change' necessarily covers a range of potential scenarios, although (as pointed out in Chapter 3) current trajectories indicate that global warming of at least 3-5°C by 2100 is now very likely.

#### *4.1.4 Impacts of high $CO_2$ under SRM*

SRM does not seek to reduce the atmospheric concentrations of anthropogenic $CO_2$, and the process of ocean acidification will therefore continue. As a result, marine biodiversity will be increasingly exposed to the adverse impacts of decreasing pH (Section 3.2.3). Nevertheless, there may be significant second order effects[200]. One unintended, additional negative impact would be more $CO_2$ dissolving in the ocean if its surface temperature has been reduced by SRM, in comparison to unmitigated climate change. However, that is likely to be countered by the avoidance of additional biogenic $CO_2$ in the atmosphere (as much as 100 ppm by 2100, under an A2 SRES scenario) as a feedback response to global warming, due to temperature-driven changes in the productivity and decomposition of terrestrial biomass[201], particularly affecting Arctic regions[202].

SRM will not address the effects of high $CO_2$ concentrations on terrestrial ecosystems, such as favouring some plant groups over others[203]. However, high $CO_2$ can have beneficial effects on plant productivity, reducing water stress[204], and such positive impacts could be expected to continue under SRM.

#### *4.1.5 Rate of environmental change and the termination effect*

It is not just the magnitude, nature and distribution of environmental changes (from climate change or from solar geoengineering) that will affect biodiversity and ecosystem services, but also the rate at which the changes take place. In general, the faster an environment changes, the greater the risk to species[205]. SRM, if effective, could slow, halt or even reverse the pace of global warming much more quickly than mitigation measures (within months, versus decades or longer), notwithstanding potential side effects. Therefore, it could either be deployed as an 'emergency response'[206,207] in order to counter imminent threats, or more gradually to shave the peaks off more extreme warming, in order to

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[207] Rapid cooling due to full-scale SRM deployment could also itself have negative impacts for biodiversity, as well as potentially triggering climatic instabilities

allow more time both for adaptive measures and natural adaptation[208], and for effective mitigation measures to be implemented.

However, there is an additional issue to consider when evaluating the general effects of SRM on biodiversity and ecosystem services: the so-called ‘termination effect’.

Atmospheric-based SRM techniques would only offset global warming as long as they are actively maintained. Whilst abrupt discontinuation would be unplanned, there is inevitably risk of such an eventuality, due to political instabilities or policy changes at either the national or international level; for example, in response to the occurrence of regionally-severe extreme events. Such events would undoubtedly be perceived as due to the SRM action (with consequences for public acceptability and international legal compensation), even if direct attribution could not be scientifically proven. Such cessation of SRM that had been deployed for some time would, in the absence of effective stabilisation or reduction of atmospheric greenhouse gas concentrations, result in increased rates of climatic change: all the warming that would have otherwise taken place (either over just a few years or several decades) is projected to take place over a much shorter period[209].

Under such circumstances, the rapid warming due to SRM termination would almost certainly have large negative impacts on biodiversity and ecosystem services, with potentially severe socio-economic implications[210]and these effects would be more severe than those resulting from gradual climate change. Most plants, animals and their interactions are likely to be affected, since current rates of anthropogenic climate change are already altering, or are projected to alter, community structure[211], biogeochemical cycles[212], and fire risk[213].

For the above reason (and because of ocean acidification effects), it is important that SRM should not be regarded as an alternative to strong emission reductions, in order to stabilise, and preferably reduce, the levels of greenhouse gases in the atmosphere. SRM might, however, be considered as a supplementary action.

### 4.2 Potential impacts of SRM on biodiversity at the technique-specific level

Thus far, this chapter has addressed the general effects of space- or atmospheric-based SRM on biodiversity, based on uniform dimming; as noted, such a change in the Earth’s radiative energy budget may not be achievable in practice. Below, the potential benefits and drawbacks associated with three specific techniques – stratospheric aerosol injection, cloud brightening and surface albedo enhancement – are considered, on the basis that these are the options most frequently proposed, and are each theoretically capable of counteracting either all or most of the radiative forcing from greenhouse gases[214]. Important technique-specific considerations include the height above the Earth’s surface where the sunlight reflection occurs, and whether there may be additional physico-chemical interactions. The potential positive and negative impacts of space-based reflectors[215],[216],[217] are

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expected to be similar to those theoretically indicated by models for uniform-dimming SRM described above.

### *4.2.1 Potential impacts on biodiversity of stratospheric aerosol injection*

In addition to the positive and negative impacts of idealised SRM already described, the climatic effects of geoengineered stratospheric sulphate aerosol will depend on where (injection altitude and locality) and how (injection technique and timing) this technique is deployed, with significant effects of both factors on aerosol microphysics and behaviour, including the radius, radiative impact and longevity of the aerosols[218]. Furthermore, this proposed technique could affect precipitation acidity, stratospheric ozone depletion, and the overall quantity and quality of light reaching the biosphere, with subsequent effects on biodiversity and ecosystem services. Some, but not all, of these unintended negative impacts might be avoided if aerosols other than sulphates were to be used for this approach. Other particles that have been suggested include electrostatic or magnetic nano-particles[219], potentially with relatively long atmospheric lifetimes; there is also the possibility of designing a particle with specific attributes[220]. However, they might bring with them their own particular risks – together with additional public acceptability issues.

#### *4.2.1.1 Increased precipitation acidity*

Use of sulphate aerosols for SRM would, to some degree, increase the acidity of precipitation ('acid rain'), with consequent impacts on ecosystems. However, the size of this effect is considered to be small, since the quantities of sulphur estimated to be needed for this form of SRM are ≤10% of the current global deposition, and possibly as little as 1%[221]. Furthermore, sulphur deposition would be more widely distributed than is currently the case from anthropogenic sulphur emissions, and buffering processes mean than ocean acidification is unlikely to be significantly worsened[222].

#### *4.2.1.2 Ozone depletion and increased UV radiation*

If stratospheric sulphate injection were to be used for SRM, there is evidence that this could result in increased ozone depletion, primarily in polar regions in spring. This effect was observed[223] after the 1991 Mt Pinatubo eruption. However, the consequences of decreased ozone (in terms of allowing additional ultra violet (UV) radiation to reach the Earth's surface) could be at least partly offset by UV scattering and attenuation by the sulphate aerosol itself. If surface UV were to significantly increase, some species would be affected more than others. Certain plants possess a protective layer on the upper surface of their leaves, making them less susceptible to UV damage. The ecological effects of any increased UV radiation will also depend on which spectral form (UVA, UVB and UVC) is most affected.

An additional uncertainty is the appropriate comparison to be made with regard to future conditions, since projections of stratospheric ozone in 50-100 years time are subject to assumptions regarding societal behaviour (the future effectiveness of the Montreal Protocol, or other measures that might be introduced), as well as climate-induced changes in atmospheric chemistry[224].

#### *4.2.1.3 Changes in the nature and amount of light reaching ecosystems*

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Stratospheric aerosols would decrease the amount of photosynthetically active radiation (PAR) reaching the Earth; they would also increase the amount of diffuse (as opposed to direct) short-wave solar irradiation. For terrestrial ecosystems, these processes would have opposing ecological effects, with the net impact likely to differ between species and between ecosystems. The net impact may also depend on the percentage reduction in PAR, and the absolute levels under current conditions; these vary latitudinally and are also subject to spatial variability in cloud cover.

Thus, the net efficiency of carbon fixation by a forest canopy is increased when light is distributed more uniformly throughout the canopy, as occurs with diffuse light. Diffuse light penetrates the canopy more effectively than direct radiation because direct light saturates upper sunlit leaves but does not reach shaded, lower leaves. The negative effects of a (small) reduction in total PAR might be less than the positive effects of the increase in diffuse radiation giving a net improvement in photosynthetic efficiency, hence an overall increase in terrestrial primary production. Crop species may also benefit[225] although inter-species differences are likely, as a function of canopy structure. There may also be additional hydrological effects driven by the effects of the diffuse/direct ratio on evapotranspiration[226]. There is evidence for such responses following the Mt. Pinatubo eruption[227], and during the ‘global dimming’ period (1950-1980)[228,229].

However, the magnitude and nature of such effects on biodiversity are currently not well understood, and their wider ecological significance is uncertain. Even if gross primary production (GPP) were to increase, GPP is not necessarily a good proxy for biodiversity: increases in GPP could be due to a few plant species thriving in more diffuse light. Furthermore, for ecosystems where total light availability is the major growth-limiting factor, the negative impacts of total radiation decrease could be greater than any benefits provided by the increase in diffuse radiation.

A further complication is that while diffuse light is better at penetrating a multi-layered canopy, sunflecks (bursts of strong light which penetrate the canopy and reach ground level) would be less intense with diffuse light as opposed to direct light[230].

Analyses of effects of large-scale, aerosol-based SRM on marine photosynthesis have not been carried out; however, primary production in the upper ocean is closely linked to the depth of light penetration, that is greatest for direct sunlight[231]. Thus, ocean productivity could be expected to decrease under SRM in comparison to present-day values. However, the comparison to unmitigated climate change is not straightforward, since many other factors would also then be involved.

The potential effects on animals of the (relatively small) changes in total solar irradiance and its direct/diffuse ratio that would result from SRM using stratospheric aerosols have yet to be investigated. Bees and other insects that use polarized light for navigation may be particularly sensitive; whilst they are still able to detect celestial polarization patterns under cloudy skies[232], year-to-year variability in early summer sunshine can have a significant effect on honey production[233].

#### *4.2.2 Potential impacts on biodiversity of cloud brightening*

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Cloud brightening involves increasing the concentration of cloud-condensation nuclei (CCN) in the troposphere (lower atmosphere), to increase the reflection back to space of short-wave solar radiation[234]. The technique is effectively limited to ocean areas[235,236], particularly the southern hemisphere, where CCN abundance is naturally low. Whilst deployment locations could (in theory) be chosen to spatially maximise beneficial effects[237], the large-scale application of this technique seems likely to cause strong regional or local atmospheric and oceanic perturbations[238] with potentially significant impacts on terrestrial and marine biodiversity and ecosystems.

Cloud brightening, if effective, could be expected to reduce local radiative forcing by up to 40 W $m^{-2}$ in tropical areas. Persistent local/regional cooling on that scale could affect regional weather systems of high ecological and societal importance, such as the West African Monsoon and the El Niño Southern Oscillation. These complex systems, and their year-to-year variability, are not well-represented in current global climate models; comparisons with future, unmitigated climate change scenarios are therefore highly uncertain.

A reduction in solar radiation at the ocean surface would be expected to reduce global evaporation and hence precipitation elsewhere[239]. Increased numbers of cloud droplets could also suppress precipitation[240]. An idealised model that assumed that cloud droplet size could be reduced uniformly over all the global ocean has indicated that such an 'intervention' could counteract most of the temperature and precipitation changes caused by doubling $CO_2$, although with an (unexpected) slight residual increase in precipitation over land, compared to the pre-industrial climate, for double $CO_2$ plus CCN increase[241]. This model is, however, unrealistic in many of its assumptions.

In addition to these uncertain local, regional and global effects of cloud brightening (with potential for both positive or negative effects on terrestrial biodiversity), the relatively dramatic changes in light intensity and temperature near to the sites of deployment are also likely to affect ocean productivity. Increases in primary production are, however, more likely than decreases, since the ocean areas most suitable for cloud brightening deployment are mostly strongly stratified, with photosynthesis constrained by nutrient availability rather than lack of light. Strong local cooling could be expected to increase upper ocean mixing and nutrient re-supply, with subsequent effects on biodiversity and ecosystems.

The possibility that CCN abundance could also be enhanced biologically, particularly in the Southern Ocean, has been suggested[242], but this approach is not generally considered to be either realistic or effective[243]

### *4.2.3 Potential impacts on biodiversity of surface albedo enhancement*

#### *4.2.3.1 Land surface*

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The reflectivity (albedo) of the land surface could be increased by whitening the built environment (e.g. roofs and roads)[244]; developing crops, grasses or shrubs with more reflective foliage[245,246]; or covering 'unused' land surface (e.g. deserts) with reflective material[247]. These techniques are likely to have varying degrees of climatic effectiveness, cost-effectiveness and achievability.

In general, surface albedo changes are less effective than those above or within the atmosphere, since the reflected irradiance has to travel twice through the Earth's atmosphere before it is returned to space, with energy (heat) losses on both inward and outward journeys[248]. Thus such changes would have to be deployed over very large areas to have a significant effect on the global climate. Assuming that the albedo of *all* the Earth's land surface could be changed, significant inter-hemispheric climate effects occur in model simulations[249] due to the asymmetric inter-hemispheric distribution of land and ocean. Although unrealistic, such results indicate that (as for cloud brightening) the climatic effects of the technique are location-sensitive. While a high degree of localised cooling could potentially benefit ecosystems that are experiencing the adverse consequences of climate change, the 'patchy' nature of the cooling might change local systems as much, or possibly more, than the global warming that the schemes are seeking to address.

Whitening the built environment could potentially reduce energy use for air conditioning and provide other local benefits[250]. It cannot, however, be considered as a viable geoengineering technique, since the maximum possible change in radiative forcing (with all urban surfaces becoming white) has been estimated to counteract <5% of the forcing from anthropogenic greenhouse gases[251]. A realistically achievable areal coverage would be at least an order of magnitude less.

For croplands, grasslands and savannah regions the maximum global-scale effect of albedo change may be potentially much higher than for urban areas, but little serious attention has been given to how this might be achieved. The albedo of crops is likely to be manageable[252], to some degree, yet selection for significant changes in leaf colour or micro-structures to increase albedo by 25-40% is likely to have other physiological consequences, with implications for crop productivity, harvested food quality, and the biodiversity of agricultural areas. Such issues have yet to be addressed. Whilst GM (genetic modification) technologies could be used accelerate the development of high-albedo strains, additional issues would then be raised. Even if developed, the large-scale deployment of high albedo crops would not be straightforward, with additional ecological and socio-economic risks arising from increased dependence on monocultures. The feasibility of replacing at the scale required (several million $km^2$) the current vegetation of semi-natural grasslands, shrublands and savannah with species or varities of higher albedo is even more questionable. If it could be done, the potential implications for biodiversity, ecosystems and their services are likely to be very high.

Non-biological means have been proposed to increase the reflectivity of (stable) desert regions, by covering them with a polyethylene/aluminium membrane[253]. The proponent of that scheme

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considered such areas to be expendable, on the basis that they are largely uninhabitated and sparsely vegetated. Nevertheless, deserts are not devoid of natural life, nor people: both would be highly impacted if such an approach were to be implemented at a climatically-significant scale, with significant negative ecological effects[254]. Desert dust also makes an important contribution to marine productivity, providing the main source of iron to most of the global ocean[255].

*4.2.3.2 Water surface*

It has been proposed that the albedo of the surface ocean – and potentially other large water bodies, such an inland seas – might be enhanced through the introduction of microbubbles ('bright water') on the basis that microbubbles can be effective at enhancing reflectivity at parts per million levels[256].

The feasibility of this scheme at the scale required is highly questionable[257]. If it were possible, there would be major biodiversity and biogeochemical implications. Not only would there be impacts of decreased light penetration and temperature changes on phytoplankton, but the microbial composition of the sea surface microlayer[258] would change, and air-sea exchange rates of $CO_2$ and other gases (highly sensitive to sea surface properties, including bubbles[259]) would also be affected.

Maintaining year round sea-ice cover in the Arctic would be the most effective and ecologically benign form of ocean albedo management. Unfortunately that option seems increasingly unlikely under current climate change trajectories[260].

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Level-of-ForcingOffsets/Desert-Area-Coverage/ag28.htm

[254] The Royal Society (2009) *Geoengineering the Climate: Science, Governance and Uncertainty*. RS Policy document 10/09. The Royal Society, London, 82 pp

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[258] Cunliffe M., Upstill-Goddard R.,C. & Murrell J.C. (2011). Microbiology of aquatic surface microlayers. *FEMS Microbiol. Rev*. 35, 233-246; doi: 10.1111/j.1574-6976.2010.00246.x

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[260] Meier W.N., Stroeve J. & Fetterer F. (2007). Whither Arctic sea ice? A clear signal of decline regionally, seasonally and extending beyond the satellite record. *Ann. Glaciol*. 46, 428-434; doi: 10.3189/172756407782871170

# CHAPTER 5: POTENTIAL IMPACTS ON BIODIVERSITY OF CARBON DIOXIDE REMOVAL GEOENGINEERING TECHNIQUES

## 5.1 General features of CDR approaches

### *5.1.1 Reducing the impacts of climate change*

By removing carbon dioxide ($CO_2$) from the atmosphere, CDR techniques are intended to reduce the concentration of the main causal agent of anthropogenic climate change. In addition, they are expected to ameliorate ocean acidification (Figure 2.1).

Any reductions in the negative impacts of climate change and ocean acidification on biodiversity (as summarised in Chapter 3) that might be achieved by effective and feasible CDR techniques would therefore be expected to have positive impacts on biodiversity, in a way that is far more certain than for SRM. However, as noted in Chapter 2: i) these beneficial effects are generally slow acting; ii) the climatic conditions resulting from a specific atmospheric $CO_2$ value may be different if $CO_2$ is falling (as a result of a CDR measure) from the conditions previously experienced at the same $CO_2$ value when it was rising[261]; and iii) several CDR techniques are of only modest or doubtful effectiveness[262,263], with few (if any) considered realistically capable of fully offsetting current anthropogenic carbon emissions.

In addition, any positive effects from reduced impacts of climate change and/or ocean acidification due to reduced atmospheric $CO_2$ concentrations may be offset (or, in a few cases, augmented) by additional, unintended impacts on biodiversity of the particular CDR technique employed. Such additional impacts are summarised in Table 5.1, and are reviewed on a technique-specific basis in section 5.2 below.

### *5.1.2 Carbon sequestration (removal and storage)*

The term ‘carbon sequestration’ was (provisionally) defined by the 10$^{th}$ Conference of the Parties to the CBD[264] as “the process of increasing the carbon content of a reservoir/pool other than the atmosphere”. However, in a geoengineering context this usage is ambiguous, since no temporal constraints are included. It is therefore preferable to clearly recognise that carbon sequestration (through CDR geoengineering) necessarily involves two steps:

i) removal of $CO_2$ from the atmosphere; and

ii) long-term storage of the captured carbon, taking it out of circulation for a climatically-significant period (e.g. at least 10 years, and preferably > 100 years).

These processes occur naturally, but the former does not necessarily lead to the latter. Thus most of the products of either terrestrial or marine photosynthesis are re-cycled annually or on shorter timescales by plant, animal or microbial respiration. Effective sequestration requires that both steps can be demonstrated. Nevertheless, the term is sometimes used as the descriptor for only the latter, storage component[265], contrasting to the CBD’s definition above that seems to focus only on the initial removal.

In some biologically- and chemically-driven CDR processes these two steps are very closely linked; for example, in ocean fertilization techniques, and for afforestation, reforestation and soil carbon enhancement. In such cases, the impacts of the CDR technique on biodiversity are

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[262] Vaughan N.E. & Lenton T.M. (2011). A review of climate geoengineering proposals. *Climatic Change*, 109, 745-790; doi: 10.1007/s10584-011-0027-7

[263] McLaren D. (2011). *First stop digging. An assessment of the potential for negative emission techniques to contribute safely and fairly to meeting carbon budgets in the 21$^{st}$ century*. McLaren Environmental Research & Consultancy Working Paper 1/11; https//sites.google.com/site/mclarenerc

[264] Footnote to CBD Decision X/33, paragraph 8(w)

[265] In legal and/or financial usage, sequestration involves secure holding and access restrictions, e.g. of assets.

**Table 5.1**: **Classification of CDR techniques and summary of additional impacts** relevant to biodiversity (other than climatic benefits via reduced radiative forcing). See text for discussion of available information on effectiveness and feasibility.

| **Technique** | | **Location of side effects** | | **Ameliorates ocean acidification[+]?** | **Nature of potential additional impacts** |
|---|---|---|---|---|---|
| | | Capture | Storage | | *Some of these are very uncertain; all are highly scale-dependent* |
| 1. **Ocean fertilization** | direct external fertilization | – Ocean – | | Relocates OA effects from ocean surface to ocean interior | Changes to phytoplankton productivity and diversity, food-webs and biogeochemical cycling; increased anoxia and acidification in deep sea |
| | up/downwelling modification | – Ocean – | | | |
| 2. **Enhanced weathering** | Ocean alkalinity | – Ocean[++] – | | Yes, but risk of local excess alkalinity | Habitat destruction from mining and transport on land; high energy use; local impacts of excess alkalinity at sea |
| | Spreading of base minerals | – Land[+++] – | | Yes | Habitat destruction from mining and transport; high energy use; effects on soil structure and fertility; increased soil albedo |
| 3. **Terrestrial ecosystem management** | Afforestation | – Land – | | Yes | Negative and positive impacts of land use change |
| | Reforestation | – Land – | | Yes | Generally positive impacts on forest ecosystems |
| | Soil carbon enhancement | – Land – | | Yes | Mostly positive impacts of soil carbon enhancements |
| 4. **Biomass** | Biomass production | Land | *Na* | Yes | Land-use/habitat change; potential for nutrient depletion |
| | Biofuels with CCS | *na* | Sub-surface | OA amelioration achieved via $CO_2$ removal (covered above) | *Above,* plus estimated small risk of leakage from CCS storage |
| | Charcoal storage | | Land | | *Above* , plus mostly benign but uncertain impacts on soil water retention and fertility; effects on $N_2O$ emissions; decreased albedo |
| | Ocean biomass storage | | Ocean | Local leakage risk | *Above*, plus damage to benthic environments |
| 5. **Direct air capture** | | Either | *Na* | Yes | Minor land cover changes; water and energy use; pollution risks |
| 6. **Carbon storage** | Ocean $CO_2$ storage | *na* | Ocean | Severe local OA impacts | Damage to deep sea ecosystems, via severe local ocean acidification |
| | Geological carbon reservoirs | | Sub-surface | Low leakage risk | Estimated small risk of leakage |

[+] "Yes" in this column indicates that amelioration of ocean acidification is expected to be directly proportional to absolute or relative reduction achieved in atmospheric $CO_2$.

[++] As indicated in right-hand column, ocean alkalinity will also have unintended, indirect impacts on land

[+++] Spreading of alkaline minerals will eventually have impacts (expected to be mostly positive) on shelf seas and ocean through river run-off .

almost entirely limited to either the environmental system (marine or terrestrial) where the technique is carried out. In other cases, the steps are discrete, and various combinations of carbon removal and storage options are possible. Thus CDR processes that initially involve land biomass production could subsequently involve carbon storage in the ocean as crop residues; or carbon burial in soil as charcoal (potentially with some energy extraction); or use of the carbon directly as biofuel with the resultant $CO_2$ removed at source and stored either in sub-surface reservoirs or the deep ocean. In all these cases, each step will have different and additive potential impacts on biodiversity, and both marine and terrestrial environments may be affected.

In the case of enhanced weathering, there will be the indirect impacts of large-scale mining and processing of minerals, and their transport, in terrestrial environments (with associated energy and water implications) as well as the direct impacts of the measure in the ocean and/or on the land.

#### *5.1.3 Impact on ocean acidification*

While removal of $CO_2$ from the atmosphere should reduce ocean acidification (based on a near-linear relationship between atmospheric $CO_2$ and surface ocean hydrogen ion concentration, at constant temperature)[266], this positive impact may be compromised[267]. For example, if the $CO_2$ leaks into the ocean from geological storage sites or as a result of decomposition of ocean stored biomass, or if the net effect of the CDR measure is to transfer $CO_2$ from the atmosphere to the ocean interior. Technique-specific effects on ocean acidification are discussed in greater detail under section 5.2 below, as far as they are known.

#### *5.1.4 Potentially vulnerable biodiversity*

##### *5.1.4.1 Ocean-based approaches and potentially vulnerable marine biodiversity*

The unintended impacts of ocean-based CDR will vary greatly according to techniques. Whilst one approach – ocean iron fertilization – has been relatively well investigated through small-scale experiments and models (with several reviews[268,269]), most other interventions remain theoretical and their effectiveness is unproven.

The behaviour of marine ecosystems when subject to large-scale, long term perturbations is inherently difficult to model and predict due to the complex interactions between marine physical, chemical and biological processes. Even under strong mitigation scenarios, unintended CDR impacts will be superimposed on climatically-driven physical changes (temperature, circulation and mixing; also changes in ice cover and river inputs), operating over a wide range of spatial and temporal scales. Furthermore, several CDR techniques use the deep sea, seafloor or sub-seafloor for long term carbon sequestration[270], potentially affecting species and ecosystems that seem likely to be particularly vulnerable, yet are not well known[271]. For example, many deep sea multicellular organisms are long-lived, relatively immobile and produce few offspring[272]. If such populations were to be severely impacted at the local/regional level, recolonization and community recovery in the deep ocean may take decades to centuries, compared to months to years in shallow waters[273].

The deep sea and its sub-seafloor sediments also contain high abundances and diversity of prokaryotes (bacteria and archaea)[274,275], responsible for longterm element re-cycling. Several of

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[267267] Williamson P. & Turley C. M. (2012). Ocean acidification in a geoengineering context. *Phil. Trans. Roy. Soc. A*; in press.

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[274] Fry J.C., Parkes R.J., Cragg B.A., Weightman A. & Webster G. (2008). Prokaryotic biodiversity and activity in the deep

these groups have high biotechnological potential[276]. However, marine microbes in deep sea sediments are not well studied: the overwhelming majority of such taxa are undescribed, and their role in delivering ecosystem services is currently poorly understood.

Other than at vent sites, the abundance of non-microbial benthic organisms generally decreases with depth, probably associated with the diminishing flux of food. However, species diversity can be high between 2000 and 3000 m depth, with each species having a low population size[277]. The fauna living in the water column is generally less diverse than that on the sea floor, due to physical mixing (slow, but operating on a global scale) and the relative uniformity of vast volumes of water in the deep ocean.

Most experimental studies on $CO_2$ (and pH) sensitivity of benthic and sediment-dwelling organisms have been carried on shallow-water species[278]. Cold-water corals currently living close to carbonate saturation horizons (2000m in the North Atlantic; 50-600m in the North Pacific) are likely to be especially vulnerable to CDR-enhanced deepwater pH changes[279]. Those species living at greater water depths already experience relatively low pH (< 7.4, cf ~8.1 in the upper ocean)[280], that will vary according to episodic inputs of organic material from the upper ocean[281]. Within sediments, pH can vary by more than 1.7 units within the top few millimetres or centimetres[282], with deeper values being relatively insensitive to changes in the overlying seawater.

*5.1.4.2 Land-based approaches and potentially vulnerable terrestrial biodiversity*

Land-based CDR potentially covers a range of proposals, although (as noted in Chapter 2) there is not yet consensus regarding the inclusion within geoengineering of several approaches, such as bio-energy carbon capture and storage, and changes in forest cover and land use. In many cases, such methods replicate natural processes or reverse past anthropogenic changes to land cover and land use. Here, techniques are considered as CDR geoengineering if carried out for the purpose of carbon removal and storage, and deployed (collectively) at sufficient scale to achieve a significant climatic effect.

The level of information concerning many of the land-based CDR approaches, as broadly defined above and in section 2.1, is relatively well-developed. For example, reforestation and restoration activities reverse previous human-induced land-use changes, and the implications of these activities on biodiversity, ecosystem services, surface albedo, and local/regional hydrological cycles are reasonably well known. There have been several field-based assessments to measure the impacts of biochar on crop yield, nutrient cycles, water availability and other factors (see discussion below, under 5.2.4.2.1),; nevertheless, many uncertainties remain.

Studies to date on land-based CDR approaches can only provide limited information on effectiveness, feasibility and safety for geoengineering deployments. That is because the scale of intervention to significantly affect climate would be several orders of magnitude greater than what has been investigated thus far.

Because of the range of land-based CDR techniques considered here, it is difficult to identify which terrestrial ecosystems and species will be most vulnerable to potential negative impacts. However, in

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subseafloor biosphere. *FEMS Microbiol. Ecol*. 66, 181-196; doi: 10.1111/j..1574-6941.2008.00566.x

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discussions on biofuel production, Parties to the CBD identified the following four vulnerable components of terrestrial biodiversity that warranted particular consideration: primary forests with native species; rare, endangered, threatened and endemic species; high biodiversity grasslands; and peatlands and other wetlands[283].

## 5.2 Projected impacts on biodiversity of individual CDR approaches

### *5.2.1 Ocean fertilization and associated techniques*

Ocean fertilization involves enhancing the supply of nutrients to the marine environment with the aim of increasing the uptake of $CO_2$ in the oceans through biological processes and the subsequent long-term storage of a portion of the additional organic carbon in the deep sea. Fertilization may be achieved through the addition of nutrients from external sources, or by modifying ocean upwelling/downwelling, to increase natural nutrient re-cycling. Enhanced downwelling, without necessarily increasing marine primary production, has also been proposed; all such approaches are discussed below.

#### *5.2.1.1 Direct external ocean fertilization*

Most attention has been given to iron, an element lacking in some ocean areas (primarily the Southern Ocean and equatorial Pacific), yet only required in small quantities as a micro-nutrient by phytoplankton and other marine organisms. Other proposed approaches include the addition of macro-nutrients such as nitrogen and phosphorus, in very much greater amounts.

There have been 13 field experiments on iron-based ocean fertilization over the last 20 years, at the scale of 50-500 $km^2$, and two on macro-nutrient additions. Although not designed for geoengineering purposes, these studies have addressed several of the uncertainties concerning the impacts of ocean fertilization on biodiversity[284,285]. They have also shown (together with associated modelling) that this is a technique of limited effectiveness for long term carbon sequestration, since most of the enhanced carbon uptake is returned to the atmosphere relatively rapidly, rather than being transported and stored in the deep ocean or in sea-floor sediments. Several issues relating to technical feasibility have yet to be resolved, and the costs of monitoring and verification of long-term sequestration (with assessment of whether negative impacts might be occurring locally or elsewhere) seem likely to be high.

*Changes in marine biodiversity, ecosystem services and marine bio-resources*

For ocean fertilization to work, biological primary production (photosynthesis by algae and bacteria) needs to increase; this will inevitably involve changes in phytoplankton community structure and diversity[286,287], with implications for the wider food-web. Such effects can be considered either positive or negative from a biodiversity perspective. Whilst the duration of those changes will depend on the fertilization method and treatment frequency, the desired outcome would be to closely mimic or enhance natural phytoplankton blooms, typically lasting a few weeks.

More significant and longer-term changes are, however, likely if ocean fertilization is sustained, and carried out on a climatically-significant scale. Such changes may include an increased risk of harmful algal blooms, involving toxic diatoms[288,289]. In addition, if the supply of organic matter to deep sea

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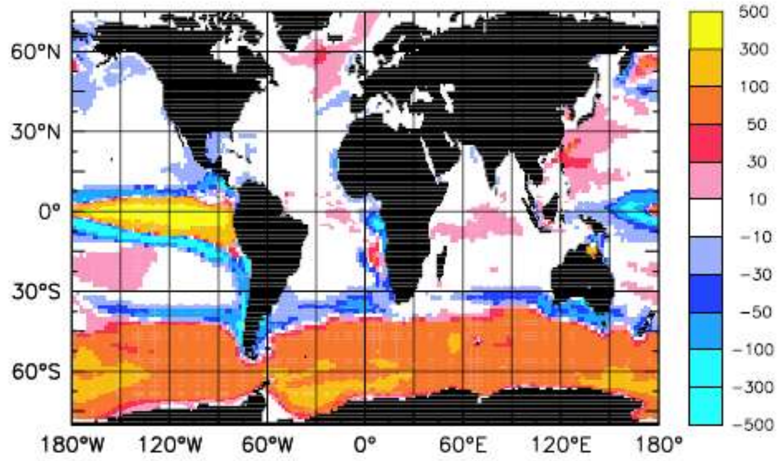
sediments were significantly enhanced, that could be expected to result in greater densities and biomass of benthos[290].

Iron-induced increases in marine productivity and carbon uptake will only occur in those ocean regions where iron is currently lacking yet macro-nutrients are abundant, primarily the Southern Ocean and equatorial Pacific. However, increases in net primary productivity in these regions will be offset (to some degree) by decreases in other areas (Figure 5.1) due to use of upper ocean macro-nutrients as part of the fertilization process[291].

**Figure 5.1. Changes in primary production after 100 years of global iron fertilization[292]**




*Projected increases (red, orange and yellow) and decreases (blue) in vertically integrated primary productivity (gC/m²/yr) after 100 years of global iron fertilization.*

Increases in marine productivity (and associated $CO_2$ removal from the atmosphere) on a much wider spatial scale could, in theory, be achieved if biologically-available nitrogen (N) or phosphorus (P) were added to the ocean instead of iron (Fe); such an approach has been proposed[293].

Whilst no large-scale N addition experiments have been carried out, the two experiments with P additions in P-deficient waters did not result in the expected productivity enhancements[294], presumably because other nutrients were also limiting. Thus (as on land) the addition of a range of macro- and micro-nutrients would almost certainly be necessary to stimulate substantive increases in marine production in most of the global ocean, currently nutrient limited – with the implication that, for geoenengineering purposes, many thousands of millions of tonnes of fertilizer are likely to be needed every year to achieve discernible climatic effects. Such considerations greatly reduce the cost-effectiveness and sustainability of ocean fertilization based on external macro-nutrients.

Fish stocks might, however, benefit from any increase in phytoplankton (and zooplankton) that could be achieved from ocean fertilization, whether by Fe, N, P or other nutrients. Field Fe-based studies to date have been too small and too short to test such ideas; nevertheless, caution would be needed, since fish production could also decrease in far field areas where primary production is reduced (Figure 5.1), and in response to altered water quality (increased anoxic zones and lower pH) in mid and deep water.

[290] Wolff G.A., Billett D.S.M., Bett B.J., Holtvoeth J., FitzGeorge-Balfour T.,Fisher E.H., Cross I., Shannon R., Salter I., Boorman B., King N.J., Jamieson A. & Chaillan F. (2011). The effects of natural iron fertilisation on deep-se ecology: The Crozet Plateau, Southern Indian Ocean. *PLoS ONE* 6, e20697; doi: 10.1371/journal.pone.0020697

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*Effects on ocean acidification and other biogeochemical changes*

Although ocean fertilization may slow near-surface ocean acidification, it would increase acidification of the deep ocean. The benefits of the former effects seem unlikely to be great: a maximum pH offset of 0.06 units has been calculated for fully-global iron fertilization[295] (i.e. less than the pH change that has occurred in the upper ocean in the past century), with the maximum global reduction in atmospheric $CO_2$ estimated to be ~33 ppm after 100 years of global deployment[296].

Nevertheless, if successful, ocean fertilization would increase biogeochemical cycling in surface layers. One expected consequence would be enhanced production and remineralisation of sinking particles, with associated potential additional production of methane ($CH_4$) and nitrous oxide ($N_2O$)[297]. If released in any quantity to the atmosphere, these greenhouse gases could significantly reduce the (modest) effectiveness of ocean fertilization as a geoengineering technique. Whilst enhanced dimethyl sulfide (DMS) emissions from plankton might be considered a 'beneficial', unintended outcome of ocean fertilization, due to albedo effects[298], the scale (and even sign) of this response is uncertain, and the overall linkage between DMS and climate is now considered relatively weak[299].

### *5.2.1.2 Modification of upwelling and downwelling*

Artificial upwelling is an ocean fertilization technique that has been proposed to bring deep water (from 200 - 1000 m) naturally rich in a range of nutrients to the surface, through some type of pipe, to fertilize the phytoplankton[300]. Limited field experiments have been carried out in the Pacific[301,302].

The intended effects are essentially the same as for externally-adding nutrients, as above. and will therefore not be repeated here. However, there is a major problem with the concept, as the nutrient-rich water brought up to the surface also contains high concentrations of dissolved $CO_2$ derived from the decomposition of organic material. The release of this $CO_2$ to the atmosphere[303, 304] would counteract most (if not all) of the potential climatic benefits from the fertilization of the plankton.

Upwelling in one area necessarily also involves downwelling elsewhere. Modifying downwelling currents to carry increased carbon into the deep ocean by either increasing the carbon content of existing downwelling or by increasing the volume of downwelling water has also been proposed as a possible geoengineering approach, without necessarily involving enhanced biological production.

While the view of some authors[305] is that "modifying downwelling currents is highly unlikely to ever be a cost-effective method of sequestering carbon in the deep ocean", lower-cost structural approaches have recently been proposed, with the claim that the downwelling would stimulate adjacent upwelling, increasing primary production and carbon drawdown, and benefitting fisheries[306].

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[306] Salter S.H. (2009) A 20GW thermal 300-metre$^3$/sec wave-energised, surge-mode nutrient-pump for removing atmospheric carbon dioxide, increasing fish stocks and suppressing hurricanes. Proc. 8$^{th}$ European Wave & Tidal Energy Conference, Uppsala, Sweden, 2009; p 1- 6.

In order to estimate the number of such structures necessary to achieve global climate impact, the hydrodynamics and biogeochemistry of such systems would need further attention. However, such an approach is likely to require coverage of a significant proportion of the ocean surface, since – as for other CDR techniques – the geoengineering requirement is for long-term sequestration of anthropogenic carbon, not stimulating carbon cycling per se. In particular: i) if the increased phytoplankton growth is stimulated by nutrients from deeper water, such water will also contain higher $CO_2$, thus net drawdown of atmospheric $CO_2$ is unlikely to be achieved; ii) there is considerable variability in the timescale of carbon re-cycling in the ocean interior, determining the rate of return of additional, biologically-fixed $CO_2$ to the atmosphere and iii) enhancement of biological production at the scale required for climatic benefits is likely to significantly deplete mid-water oxygen, resulting in increased $CH_4$ and $N_2O$ release.

Because of these complications, the overall effectiveness of any upwelling/downwelling modification is questionable. Furthermore, high costs are likely to be involved in achieving reliable data on any long term carbon removal (needed for international recognition of the effectiveness of the intervention), and in quantifying potentially counter-active negative impacts, over large areas (ocean basin scale) and long time periods (10-100 years).

### *5.2.2 Geochemical sequestration of $CO_2$*

$CO_2$ is naturally removed from the atmosphere by the weathering (dissolution) of carbonate and silicate rocks, forming bicarbonates and other compounds. However, the process of natural weathering is very slow: $CO_2$ is consumed at less than one hundredth of the rate at which it is currently being emitted[307]. It has therefore been proposed that, in order to combat climate change, the natural process of weathering could be artificially accelerated. There is a range of proposed techniques that include releasing calcium carbonate or dissolution products of alkaline minerals into the ocean, or spreading abundant silicate minerals such as olivine[308] over agricultural soils – as discussed below.

#### *5.2.2.1 Enhanced ocean alkalinity*

This proposed approach is based on adding alkaline minerals (e.g., carbonate or silicate[309] rock) or their dissolution products to the ocean in order to chemically enhance ocean storage of $CO_2$; it also expected to buffer the ocean to decreasing pH, and thereby help to counter ocean acidification[310].

It has been proposed that dissolution products of alkaline minerals could be released into the ocean through a range of techniques that include: i) $CO_2$-rich gases dissolved in sea water to produce a carbonic acid solution that is then reacted with a carbonate mineral to form calcium and bicarbonate ions[311,312,313]; ii) addition to the ocean of bicarbonate ions produced from the electrochemical splitting of calcium carbonate (limestone)[314]; and iii) addition of magnesium and calcium chloride salts from

[307] Uchikawa, J. & Zeebe R.E. (2008). Influence of terrestrial weathering on ocean acidification and the next glacial inception. *Geophys. Res.Letters*, 35, L23608, doi:10.1029/2008GL035963, 2008

[308] Schuiling R.D. & Krijgsman P. (2006). Enhanced weathering; an effective and cheap tool to sequester $CO_2$. *Climate Change*, 74, 349-354

[309] The weathering of calcium carbonate ($CaCO_3$) by $CO_2$ mostly produces bicarbonate ions and calcium ions; the weathering of magnesium silicate (olivine; $Mg_2SiO_4$) mostly produces bicarbonate ions, magnesium ions, and silicic acid ($H_4SiO_4$). In theory, the latter is more efficient, absorbing four molecules of $CO_2$ for each molecule of magnesium silicate, with potential sequestration of 0.34 tonnes of carbon for each tonne of olivine .

[310] Kheshgi H. (1995). Sequestering atmospheric carbon dioxide by increasing ocean alkalinity. *Energy* 20, 915-922.

[311] Rau G.H. & Caldeira K. (1999) Enhanced carbonate dissolution: a means of sequestering waste $CO_2$ as ocean bicarbonate. *Energy Conversion & Management* 40, 1803-1813.

[312] Caldeira K. & Rau G.H. (2000) Accelerating carbonate dissolution to sequester carbon dioxide in the ocean: Geochemical implications. *Geophys. Res. Letters* 27, 225-228.

[313] Rau G.H. (2011) $CO_2$ mitigation via capture and chemical conversion in seawater. *Environ. Sci. & Technol*. 45, 1088-1092.

[314] Rau G.H. (2008) Electrochemical splitting of calcium carbonate to increase solution alkalinity: Implications for carbon dioxide and ocean acidity. *Environ. Sci. & Technol*.42, 8935-8940.

hydrogen and chlorine ions produced from the electrolysis of sea water to form hydrochloric acid which is then reacted with silicate rocks[315].

For deployment for geoengineering purposes, all of these techniques would require very large volumes of feedstock minerals, abundant (non-carbon) energy, water, and extensive associated operational infrastructure. Most proposals envisage the addition of material through a pipeline into the sea or indirectly through discharge into a river: hence constraining their application to coastal zones, and limiting the potential for rapid dilution (thereby increasing the risk of local negative impacts on ecosystems).

Other proposals involve the direct addition of limestone powder[316] or calcium hydroxide[317] to the ocean from ships, thereby increasing flexibility with the sites of application and also potentially achieving much higher dilution rates (therby minimising short-term pH spikes). Note that the manufacture of calcium hydroxide requires energy and releases $CO_2$ (that would need to be captured and safely stored), although the overall process is theoretically capable of net uptake.

Such processes undoubtedly could have high long term effectiveness, i.e. on geological timescales. However, for geoengineering purposes, the maximum potential effectiveness of generic enhanced alkalinity techniques (in terms of their radiative forcing) has been estimated[318] as very low, at $\leq 0.03$ W $m^{-2}$. This value is less than 1% of the forcing required to counteract anthropogenic climate change. In part this likelihood of very low effectiveness is due to the very large volume of the ocean (1.3 billion $km^3$): substantive changes to the carbonate chemistry of a significant proportion of that volume need to be made to have any drawdown effect on atmospheric $CO_2$.

*Impacts of local excess alkalinity on marine biodiversity*

While the theoretical chemistry of the processes of enhancing ocean alkalinity is relatively straightforward, the impacts on those processes on biodiversity (if the technique were to be deployed) are much more uncertain. In particular, the biological effects of temporarily enhanced $Ca_2^+$ ions and dissolved inorganic carbon are not adequately known.

It could be expected that the initial local spatial and temporal pH spike might be harmful to biodiversity (and hence, potentially, ecosystems and their services). However, this impact is transient and could be minimised through rapid dilution and dispersion and, in the case of particulate material, by controlling the dissolution rate of the substance through its particle size.

There are large unknowns associated with enhanced ocean alkalinity, due to limited knowledge of effects on atmospheric $CO_2$ and potential biological impacts. In particular, no field experiments have been carried out, and there are a limited number of theoretical papers available. Furthermore, as already noted, it is questionable whether any of the approaches above can be scaled-up sufficiently to make a difference to the global carbon budget in a cost-effective way. Nevertheless, local use of enhanced alkalinity techniques may provide a means of counteracting the worst effects of ocean acidification for specific high-value marine ecosystems, e.g. coral reefs.

*5.2.2.2 Land-based enhanced weathering*

Closely similar to the techniques discussed above, it has been proposed that the natural process of land-based weathering could be artificially accelerated; for example, by reacting silicate rocks with $CO_2$ to form carbonates, bicarbonates and other products. One proposed method is to spread finely-ground silicate minerals such as olivine over agricultural soils and river catchments[319]. It has been estimated that this approach could globally sequester up to 1 Gt C $yr^{-1}$, using at least 3-4 Gt $yr^{-1}$ of olivine (for comparison, current coal production is ~6 Gt $yr^{-1}$).

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[315] House K.Z., House C.H., Schrag D.P. & Aziz MJ (2007) Electrochemical acceleration of chemical weathering as an energetically feasible approach to mitigating anthropogenic climate change. Environ. Sci & Technol. 41, 8464-8470.

[316] Harvey L.D.D. (2008) Mitigating the atmospheric $CO_2$ increase and ocean acidification by adding limestone powder to upwelling regions. *J.Geophys. Res*. 113, C04028, doi: 10.1029/2007JC004373

[317] Cquestrate (http://www.cquestrate.com/)

[318] Vaughan N.E. & Lenton T.M. (2011). A review of climate geoengineering proposals. *Climatic Change*, 109, 745-790; doi: 10.1007/s10584-011-0027-7

[319] Schuiling R.D. & Krijgsman P. (2006) Enhanced weathering: an effective and cheap tool to sequester $CO_2$. *Climate Change*, 74: 349-354.

The method would be most effective in the humid tropics. If the Amazon and Congo basins could both be fully treated with olivine at an application rate of ~300 g $m^2$ $yr^{-1,}$ their combined carbon sequestration potential has been calculated[320] as 0.6 Gt C yr-1. However, river pH would estimated to rise to 8.2 (currently 5.7 – 7.8) and the additional delivery of biologically-available silicon could increase the regional-scale abundance of diatoms in the ocean. The latter effect could potentially increase atmospheric $CO_2$ drawdown through ocean fertilization effects[321].

No field studies have been published to date to quantify $CO_2$ uptake rates by land-based enhanced weathering, although direct measurements of chemical changes, with associated carbon uptake, have been made for magnesium carbonate minerals in mine waste[322].

*Impacts on biodiversity*

The addition of alkaline rock dust, e.g. olivine, to low pH, nutrient-deficient soils may (under certain conditions) increase the productivity of those soils, thereby reducing the incentive to convert previously non-agricultural land into agricultural land. However, positive impacts cannot be assumed for all soil types, and, in order to have a significant effect on the Earth's climate, large-scale mining, processing and transport activities would necessarily be involved. Such additional impacts would potentially exacerbate habitat degradation and loss, for climatic benefits that are currently relatively uncertain (at the timescale required).

Whilst there is the possibility of modest positive impact on planetary albedo, a relatively high proportion of the Earth's land surface would need to be significantly lightened to achieve additional climatic benefits by that means (section 4.2.3).

As raised in the previous section, effects of land-based enhanced weathering would not be limited to the terrestrial environment, with rivers, coastal seas and the open ocean also potentially impacted if the techniques were to be applied at a climatically-significant scale[323].. The likely impacts of increased river pH (enhanced alkalinity) on freshwater biodiversity have yet to be investigated in a geoengineering context. The liming of acidified lakes and rivers provides some relevant data, and in Norway such treatment has generally been considered as ecologically-beneficial[324]. However, that treatment has been carried out to restore the pH of rivers to their historic baselines, rather than changing them to a novel state.

### *5.2.3 Restoration, afforestation, reforestation, and the enhancement of soil carbon*

Although not always viewed as geoengineering per se, familiar methods such as afforestation, reforestation, and the enhancement of soil carbon can play a small but significant role in moderating climate change[325] through increasing carbon storage in natural and managed ecosystems (forests, plantations and agricultural lands).

Afforestation involves the direct and intentional conversion of land that has not been forested (for at least 50 years, for the purposes of the first commitment period of the Kyoto Protocol) into forested land, through planting, seeding and/or the promotion of natural seed sources by humans. Reforestation involves similar techniques, but is carried out on land that was previously forested but converted to non-forested land at a certain point in time (before 31 December 1989, for the purposes of the first commitment period of the Kyoto Protocol). Since both afforestation and reforestation result in increased forest cover, their potential impacts on biodiversity and ecosystem services are discussed collectively below. Restoration of some other ecosystems (marine as well as terrestrial), while making

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[320] Köhler P, Hartmann J & Wolf-Gladrow D.A. (2010). Geoengineering potential of artificfially enhanced silicate weathering of olivine. *Proc. Natl. Acad. Sci. USA*, 107, 20228-20233; doi 10.1073/pnas.1000545107

[321] Oral presentation by Peter Köhler at Planet under Pressure conference, London, 27 March 2012.

[322] Wilson S.A., Dipple G.M., Power I.M., Thom J.M., Anderson R.G., Raudsepp M., Gabitres J.E. & Southam G. (2009). Carbon dioxide fixation within mine wastes of ultramafic-hosted ore deposits: examples from the Clinton Creek and Cassiar chrysotile deposits, Canada. *Economic Geology*, 104,95-112; doi; 10.2113/gsecongeo.104.1.95

[323] Köhler P, Hartmann J & Wolf-Gladrow D.A. (2010). Geoengineering potential of artificfially enhanced silicate weathering of olivine. *Proc. Natl. Acad. Sci. USA*, 107, 20228-20233; doi 10.1073/pnas.1000545107

[324] Fiellheim A. & Raddum G. (2001). Acidification and liming of River Vikedal, western Norway. A 20 year study of responses in the benthic invertebrate fauna. *Water, Air, Soil Pollution*, 130, 1379-1384; doi: 10.1023/A:1013971821823

[325] The Royal Society (2009). *Geoengineering the Climate: Science, Governance and Uncertainty*. RS Policy document 10/09. The Royal Society, London, 82 pp

significant contributions to biodiversity, may also make additional though smaller contributions to reducing atmospheric $CO_2$.

A related means of ecosystem carbon storage is the enhancement of soil carbon. This is achieved by improving land management practices; for instance, preventing captured $CO_2$ from reaching the atmosphere, and altering livestock grazing patterns so as to increase root mass in the soil.

*5.2.3.1 Impacts on biodiversity*

The impacts on biodiversity of ecosystem carbon storage depend on the method and scale of implementation. If managed well, this approach has the potential to increase or maintain biodiversity. However, if managed badly, it may result in the reduction of the distribution of certain biomes; the introduction of invasive alien species; inappropriate land use conversion (e.g., from natural, mixed grassland to monoculture forest); and subsequent loss of species. Since afforestation, reforestation and land use change are already being promoted as climate change mitigation options, much guidance has already been developed. For example, the CBD has developed guidance to maximize the benefits of these approaches to biodiversity, such as the use of assemblages of native species, and to minimize the disadvantages and risks[326,327,328] such as the use of monocultures and potentially invasive species . The CBD is also developing advice for the application of REDD+ biodiversity safeguards (reducing emissions from deforestation and forest degradation and the role of conservation, sustainable management of forests and enhancement of forest carbon stocks in developing countries).

In order to maximize biodiversity benefits, ecosystem storage of carbon should be based on an environmental impact assessment including impacts related to biodiversity and native species. Interventions should also incorporate resilience to anticipated climate change, and should prioritize climatically-appropriate native assemblages of species. Where such recommendations have not been followed (e.g., in reforestation projects using non-native species), the result has often been monoculture plantations which are unable to support viable population of endemic species[329].

*5.2.3.2 Impacts on ecosystem services*

Increased soil carbon can increase the amount of water retained in the soil, thereby increasing the resilience of ecosystems and potentially mitigating the water-depleting effects of climate change in arid areas. In addition, increased soil carbon has the potential to enhance crop productivity. This may reduce the incentive to convert previously non-agricultural land into agricultural land, and could therefore help to safeguard biodiversity. As demonstrated by a watershed-scale study in Oregon, USA, increasing carbon storage through the introduction of land-use policies can benefit a wide range of ecosystem services[330]. Moreover, several regional studies have demonstrated that benefits to ecosystem services such as water regulation, biodiversity conservation, and agriculture, can result from integrated land-use planning that delivers enhanced $CO_2$ sequestration[331].

However, while increased soil water retention (as a result of increased soil carbon) may generally have positive effects, in some areas, increased water retention could lead to more anoxic conditions, increasing $CH_4$ and $N_2O$ emissions. Moreover, enhanced plant productivity does not necessarily produce positive ecosystem impacts, if fast growing species are favoured. This could lead to shifts in ecosystem composition, interactions between species, and changes within food webs.

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[326] Secretariat of the Convention on Biological Diversity. (2009). *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.

[327] Secretariat of the Convention on Biological Diversity (2003). *Interlinkages between biological diversity and climate change. Advice on the integration of biodiversity considerations into the implementation of the United Nations Framework Convention on Climate Change and its Kyoto protocol*. CBD Montreal, Technical Series No.10, 154 pp.

[328] CBD COP decision VI/22 Annex and X/33 paragraph 8(p)

[329] Ramanamanjato J. & J.U. Ganzhorn J.U. (2001) Effects of forest fragmentation, introduced *Rattus rattus* and the role of exotic tree plantations and secondary vegetation for the conservation of an endemic rodent and a small lemur in littoral forests of southeastern Madagascar. *Animal Conservation*, 4(2): 175-183.

[330] Nelson E., Mendoza G., Regetz J., Polasky S., Tallis H., Cameron D.R., Chan K.M.A., Daily G.C./, Goldstein J., Kareiva P.M.,Lonsdorf E., Naidoo R., Ricketts T.H. & Shaw M.R. (2009) Modelling multiple ecosystem services, biodiversity conservation, commodity production, and trade-offs at landscape scales. *Frontiers Ecol.Environ.* 7, 4-11.

[331] Royal Society (2001). *The role of land carbon sinks in mitigating global climate change*. Policy document 10/01. The Royal Society, London.

#### *5.2.3.3 Risks and uncertainties*

Large-scale increases in forest cover can have an impact on both planetary albedo and the hydrological cycle, and can create a protecting buffer for neighboring ecosystems against floods and other environmental perturbations. Newly created forests are also likely to emit volatile organic compounds (VOCs), which increase the concentration of cloud condensation nuclei and therefore affect cloud formation. However, the combined effects of increased forest cover on the hydrological cycle[332], planetary albedo and cloud cover, and subsequent impacts on biodiversity and ecosystem services, are currently not well understood[333]. This is an area where the need for further research and assessment has been identified[334].

Other key uncertainties relate to which soil types are most suitable for carbon enhancement, to avoid adverse side effects (e.g. anoxic conditions and methane release). It is also currently unclear how a soil carbon change might affect the community of species dependent on a particular soil type, and whether biodiversity benefits would ultimately increase or decrease.

### ***5.2.4 Biological carbon capture and storage in land biomass***

As already noted, land-based biomass approaches to $CO_2$ removal involve two steps: biomass production and biomass storage or disposal.

#### *5.2.4.1 General issues on biomass production*

Biomass-based approaches are based on the assumption that biomass production is either carbon neutral or results in very low greenhouse-gas emissions. However, recent work[335,336] shows that this assumption can be seriously flawed and that biomass production, if not well-managed, may incur a carbon debt for several decades or centuries.

*Habitat loss*

Production of biomass for carbon sequestration on a scale large enough to be climatically significant would likely entail large changes in land use leading to the significant loss of biodiversity and habitats directly, or indirectly as biomass production displaces food crops, which subsequently leads to encroachment into natural areas. These effects are similar to those resulting from expansion of biofuels[337,338,339]. For example, a recent assessment of global biochar potential (see section 5.2.4.2.2***)*** indicates that the capture of 12% of annual anthropogenic $CO_2$ emissions would require 556 million hectares of dedicated biomass plantations, much of it through the conversion of tropical grasslands[340]. In addition to the impacts on biodiversity, these land use changes would entail net greenhouse-gas

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[332] Arora V.K. & Montenegro A. (2010). Small temperature benefits provided by realistic afforestation efforts. *Nature Geoscience,* 4, 514-518; doi: 10.1038/ngeo1182

[333] Anderson R.G., Canadell J.G., Randerson J.T.,Jackson R.B., Hungate B.A., Baldocchi D.B., Ban-Weiss G.A., Bonan G.B., Caldeira K., Cao L., Diffenbaugh N.S., Gurney K.R., Kueppers L.M., Law B.E., Luyssaert S. & O'Halloran T.L. (2011). Biophysical considerations in forestry for climate protection. *Frontiers Ecol. Environ.* **9,** 174–182. doi: 10.1890/090179

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[335] IAASTD: http://www.agassessment.org/docs/SR_Exec_Sum_280508_English.htm

[336] Searchinger T.D., Hamburg S.P., Melillo J., Chameides W., Havlik P., Kammen D.M., Likens G.E., Lubowski R.N., Obersteiner M., Oppenheimer M., Robertson G.P., Schlesinger W.H. & Tilman G.D. (2009) Fixing a critical climate accounting error. *Science*, 326, 527-528 ; doi : 10.1126/science.1178797

[337] Righelato R. & Spracklen D.V. (2007) Carbon mitigation by biofuels or by saving and restoring forests? *Science* 317 , 902; doi: 10.1126/science.1141361.

[338] Searchinger T, Heimlich R,. Houghton R. A., Dong F. Elobeid A., Fabiosa J., Tokgoz T., Hayes D. & Yu, T. (2008) Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land use change. *Science* 319, 1238-1240; doi: 10.1126/science.1151861.

[339] Fargione J., Hill J., Tilman D., Polasky S. & Hawthorne P. (2008). Land clearing and the biofuel carbon debt. *Science*, 319, 1235 – 1238; doi: 10.1126/science.1152747 .

[340] Woolf D., Amonett J.E., Streeet-Perrott F.A., Lehmann J & Joseph S. (2010) Sustainable biochar to mitigate global climate change. *Nature Communications* 1, Article 56; doi; 10.1038/ncomms1053

emissions due to land use change[341,342]. Biomass production on previously degraded areas, if well-managed, may deliver biodiversity benefits; however, even here, greater benefits in terms of both biodiversity and net greenhouse gas reductions may be achieved through restoration of natural habitats on these lands [343].

The environmental consequences of an ambitious global cellulosic biofuels programme up to 2050 have been modelled[344]. The study looked at two scenarios: one in which there were no restrictions on deforestation and in which any land would be available for biofuel production as long as it was economically viable (deforestation scenario), and the other in which the conversion of natural forests and other "unmanaged land" was limited to recent regional land conversion rates (intensification scenario). The study concluded that the more optimistic intensification scenario would see the loss of 3.4 million $km^2$ of grasslands currently used for grazing, 38% of the natural forest cover and 38% of wooded savannah in sub-Saharan Africa based on 2000 figures. In Latin America, the same scenario would be associated with the loss *Other impacts on biodiversity*

Proposals for carbon sequestration of carbon as crop residues in the ocean (see section 5.2.4.2.3) envisage the removal of some 30% of crop residues from agricultural systems[345]. This is likely to have negative impacts on productivity, biodiversity, and soil quality.

There are clear trade-offs between optimizing land for bioenergy crop yield and for biodiversity benefits; where monocultures of non-native species are employed in the production of biofuels the projected impacts on biodiversity are negative. If, however, native assemblages of species are planted on degraded land and managed in a sustainable manner, benefits may be positive.

*Bioenergy Carbon Capture and Storage (BECCS)*

Bioenergy carbon capture and storage (BECCS) combines existing or planned technology for bioenergy/biofuels and for carbon capture and storage (CCS)[346],[347]. It involves harvesting biomass, using it as a fuel, and sequestering the resulting $CO_2$.

Issues related to bioenergy production are covered above. Issues related to carbon capture and storage are addressed in section 5.2.5

*5.2.4.2 Storage of carbon in terrestrial biomass*

*Charcoal production and storage (biochar)*

CDR based on biochar involves the production of black carbon (charcoal) from land plant biomass, usually through pyrolysis (decomposition in a low- or zero-oxygen environment), and its longterm storage in soils or elsewhere, potentially for thousands of years[348].

Land-use issues related to the production of biomass for charcoal production are covered above (section 5.2.4.1), while issues related to biochar storage in soils are addressed here.

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[341] Searchinger T, Heimlich R,. Houghton R. A., Dong F. Elobeid A., Fabiosa J., Tokgoz T., Hayes D. & Yu, T. (2008) Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land use change. *Science* 319, 1238-1240; doi: 10.1126/science.1151861..

[342] Fargione J., Hill J., Tilman D., Polasky S. & Hawthorne P. (2008). Land clearing and the biofuel carbon debt. *Science*, 319, 1235 – 1238; doi: 10.1126/science.1152747.

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[345] Strand S.E. & Benford G. (2009) Ocean sequestration of crop residue carbon: Recycling fossil fuel carbon back to deep sediments. *Environ. Sci. & Technol.* 43, 1000-1007.

[346] 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

[347] Lenton T.M. (2010). The potential for land-based biological $CO_2$ removal to lower future atmospheric $CO_2$ concentration. *Carbon Management*, 1, 145-160

[348] Spokas K. (2010) Review of the stability of biochar in soils: predictability of O:C molar ratios. *Carbon Management*, 1, 289–330.

Charcoal production and storage can potentially help slow the increase in atmospheric $CO_2$ since it prevents the natural process of biomass decomposition by micro-organisms, which returns carbon to the atmosphere. Biochar is very much more stable and resistant to such decomposition[349], due to the bonds between its carbon atoms being much stronger than those in plant matter. However, assumptions regarding the longevity and benefits of black carbon are challenged by the variable results from field trials, indicating that impacts on soil carbon and soil carbon sequestration may be unpredictable and not always positive, even over a short time-span[350,351,352,353].

*Impacts of charcoal storage in soils on biodiversity and ecosystems*

There is a wide variety of raw materials (feedstocks) for creating charcoal – such as wood, leaves, food waste and manure – and various conditions under which pyrolysis can take place. These variations, combined with the diversity of soil types to which biochar can be added, provide the main explanation why the impacts of biochar on soils, crop yields, soil microbial communities and detritivores can be highly variable[354,355,356]. In addition, the impacts of biochar on mycorrhizal fungi are not yet fully understood[357].

As with increased soil (organic) carbon, discussed above, biochar can increase soil water retention, thereby enhancing the resilience of ecosystems and potentially mitigating the water-depleting effects of climate change in arid areas. However, while this property may have positive effects in some areas, in other areas increased water retention could lead to more anoxic conditions. Moreover, the large-scale deposition of biochar in suitable terrestrial locations is likely to require considerable transport, burying and processing, which could compromise the growth, nutrient cycling and viability of the ecosystems involved[358].

There is a great deal of uncertainty surrounding the impacts of biochar on biodiversity and ecosystem services due to a lack of published research on biochar. Compounding this limitation is the fact that many field trials have relied on charcoal produced by wildfires rather than by the modern method of pyrolysis proposed for biochar geoengineering[359].

Two other unintended impacts warrant mention. First, biochar application may decrease soil $N_2O$ emissions, thereby potentially providing additional benefits[360]. Second, if used on light-coloured soils, biochar can decrease albedo, at least on a seasonal basis[361]. Whilst unlikely to have a

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[353] Steiner C, Teixeira W.G., Lehmann J., Nehls T., de Macêdo J.L.V., Blum W.E.H. & Zech W. (2007). ,Long term effects of manure, charcoal and mineral fertilization on crop production and fertility on a highly weathered Central Amazonian upland soil, *Plant Soil* 291, 275-290; doi: 10.1007/s11104-007-9193-9

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[361] Genesio L., Miglietta F., Lugato E., Baronti S., Pieri M. & Vaccari F.P. (2012) Surface albedo following biochar

climatically significant effect, the potential for that additional, negative, impact should nevertheless also be taken into account if very large-scale use of biochar is proposed for geoengineering purposes.

*Ocean storage of terrestrial biomass*

Ocean biomass storage (for example, the CROPS proposal: Crop Residue Oceanic Permanent Sequestration), involves the deep ocean sequestration of terrestrial crop residues on or in the seabed[362, 363]. These proposals suggest that up to 0.6 Gt C (30% of global annual crop residues of 2 Gt C) could be available sustainably, deposited in an annual layer 4m deep in an area of seabed of ~1,000 $km^2$. However, an annual sequestration rate < 1 Gt C/yr would only make a modest contribution to slowing climate change[364].Potentially, charcoal (biochar), timber or other organic remains could also be deposited on the seabed, if suitably ballasted. Nevertheless, it seems unlikely that deposition on the seabed would be the most effective use of such materials; e.g., it would seem more effective to obtain at least some energy from them, via a BECCS approach.

It should be noted that this technique would seem to be covered by the existing category of wastes ‘Organic material of natural origin’ in Annex I of the London Protocol and ‘Uncontaminated organic material of natural origin’ in Annex I of the London Convention.[365]. That does not mean such disposal is prohibited; however, an appropriate regulatory framework would seem to be in place.

*Impacts on biodiversity*

Where crop residues are deposited as ballasted bales, it is likely that there will be significant physical impact (although of a relatively local nature) on the seabed due to the sheer mass of the material. In addition, there may be wider chemical and biological impacts through reductions in oxygen and potential increases in $H_2S$, $CH_4$, $N_2O$ and nutrients arising from the degradation of the organic matter.

The degradation of crop residue bales is likely to be slow due to the ambient conditions of low temperature and limited oxygen availability; the apparent lack of a marine mechanism for the breakdown of ligno-cellulose material; and the anaerobic conditions within the bales[366]. While it can be argued that potential impacts could be reduced if deposition occurred in areas of naturally high sedimentation, such as off the mouths of major rivers (e.g., Mississippi)[367], many such areas are already susceptible to eutrophication and anoxia from existing anthropogenic, land-derived nutrient inputs. These effects are likely to be worsened if increased use of inorganic fertilizer is needed to replace the nutrients removed in the crop residues.

The type of packaging would also be significant when assessing potential impacts as its permeability to water and gases has the potential to influence the flux of substances into near-seabed water. If the bales are buried within the sediment, then such impacts are likely to be significantly reduced. Additional manipulations would, however, almost certainly have cost implications.

The addition of significant amounts of organic matter to the deep sea floor could lead to greater densitiy and biomass of benthic organisms over a long period in the locations where the crop residues are deposited: a perturbation from the natural state.

The limited knowledge of ecosystem services from the deep sea combined with limited understanding of the impacts of ocean biomass storage lead to a lack of understanding about its impacts on ecosystem services. However, if done in the shallower end of the water depths suggested (1000 –

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application in durum wheat. *Environ. Res. Lett*. 7, 014025; doi: 10.1088/1748-9326/7/1/014025change

[362] Metzger R.A. & Benford G. (2001) Sequestering of atmospheric carbon through permanent disposal of crop residue. *Climatic Change* 49, 11–19.

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[366] Strand S.E. & Benford G. (2009) Ocean sequestration of crop residue carbon: Recycling fossil fuel carbon back to deep sediments. *Environ.Sci. & Technol.* 43, 1000-1007.

[367] Strand S.E.& Benford G. (2009) Ocean sequestration of crop residue carbon: Recycling fossil fuel carbon back to deep sediments. *Environ. Sci. & Technol.* 43, 1000-1007.

1500 m), its impacts on ecosystem services could be more significant since this is now within the range of deep sea fisheries. Whilst the area directly affected could be relatively restricted (on a global scale), larger-scale and longer-term indirect effects of oxygen depletion and deep-water acidification could be regionally significant if there is cumulative deposition of many gigatonnes of organic carbon to the seafloor, and most of this is eventually decomposed.

There are large unknowns due to limited knowledge as indicated above. No field experiments have been carried out and only a few peer-reviewed papers on the proposed technique have been published. Furthermore, while there is a lot of knowledge about the impact of organic enrichment on continental shelf environments, it is unclear whether this is easily translated into the very different deep sea environment.

### *5.2.5 Chemically-based carbon dioxide capture and storage*

#### *5.2.5.1 $CO_2$ capture from ambient air*

Direct $CO_2$ capture is an industrial process that removes the gas from exhaust streams or ambient air, producing a pure $CO_2$ stream for use or disposal[368,369]. Three main technologies are being explored for achieving this: i) adsorption of $CO_2$ onto solids; ii) absorption into highly alkaline solutions; and iii) absorption into moderately alkaline solutions with a catalyst.. The technical feasibility of air capture technologies is in little doubt and has already been demonstrated ; for example, in the commercial removal of $CO_2$ from air for use in subsequent industrial processes. However, no large-scale geoengineering prototypes have yet been tested.

Capturing $CO_2$ from the ambient air (where its concentration is 0.04%) is more difficult and energy intensive than capturing $CO_2$ from exhaust streams of power stations where the $CO_2$ concentration is about 300 times higher. The main problem is the high energy cost[370]. Thus the process would need to be powered by a non-carbon fuel source (e.g. solar or nuclear energy) otherwise as much (or more) $CO_2$ would be produced than was captured.

A recent study[371] re-assessed the energetic and financial costs of capturing $CO_2$ from the air, considering that these issues placed the viability of this approach in doubt. There is also some risk of pollution from the manufacture of the sorbents involved (e.g. NaOH, produced by the chloralkali process) when manufactured at the very large scale that would be necessary for effective geoengineering. Such approaches are discussed in Chapter 6 of the IPCC Special Report on Carbon Dioxide Capture and Storage[372].

Subsequent storage of the captured $CO_2$ is necessary, as considered below (section 5.2.6).

*Land and water requirements*

Negative impacts on biodiversity through habitat loss due to land-use conversion would be relatively small for air capture systems, since they are expected to have a land-use footprint that is hundreds (or thousands) of times smaller per unit of carbon removed than that of biomass-based approaches[373].

However, some proposed methods of air capture have a relatively high requirement for fresh water, which is already a scarce resource in most of the world. Furthermore, the disposal of captured $CO_2$, and the potential for leakage, might also impact terrestrial and marine ecosystems, as discussed below..

#### *5.2.5.2 $CO_2$ storage techniques*

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$CO_2$ that has been extracted from the atmosphere by direct air capture (or from other geoengioneering processes, e.g. the CCS part of BECCS) must be stored on a long term basis, with the quantities involved limiting such storage to either the ocean interior or sub-surface geological reservoirs. Such approaches are discussed comprehensively in Chapter 6 of the IPCC Special Report on Carbon Capture and Storage[374].

*Ocean $CO_2$ storage*

The main variants of ocean $CO_2$ storage involve either adding $CO_2$ to middle/deep ocean waters or putting $CO_2$ in depressions in the seabed to form lakes/pools[375, 376]. It has also been suggested to deposit solid $CO_2$ blocks in the sea[377]; inject liquid $CO_2$ a few hundred metres into deep-sea sediments at greater than 3,000 m depth[378], displace the methane by $CO_2$ in methane hydrates on continental margins and in permafrost regions[379]; or discharge liquid $CO_2$ mixed with pulverized limestone at an intermediate depth of greater than 500 m in the ocean[380]. However, the economic viability of these methods has not been assessed, and none would permanently sequester the $CO_2$ since it will eventually return to the atmosphere over century-to-millennial time scales depending on where it was introduced[381]. So whilst they could help in buying time, it would be at the expense of future generations.

Disposal of $CO_2$ into the water column, on or in the seabed (other than in sub-seabed geological formations), is not permitted under the global instruments of the London Protocol 1996 and is explicitly ruled out under the regional OSPAR Convention covering the north East Atlantic region. The situation under the London Convention 1972 is currently unclear.

*Impacts on biodiversity and ecosystem services*

Ocean $CO_2$ storage will necessarily alter the local chemical environment, with a high likelihood of biological effects. Knowledge available for surface oceans indicates that effects on mid-water and deep benthic fauna/ecosystems is likely on exposure to pH changes of 0.1 to 0.3 units, primarily in marine invertebrates and possibly in unicellular organisms[382]. Calcifying organisms are the most sensitive to pH changes; they are however naturally less abundant in deep water, particularly if calcium carbonate saturation is already <1.0 (i.e. $CaCO_3$ dissolves, unless protected).

Total destruction of deep seabed biota that cannot flee can be expected if lakes of liquid $CO_2$ are created. The scale of such impacts would depend on the seabed topography, with deeper lakes of $CO_2$ affecting less seafloor area for a given amount of $CO_2$. However, pH reductions would still occur in large volumes of water near to such lakes[383], and mobile scavengers are likely to be attracted (and themselves deleteriously affected) by the scent of recently-killed organisms[384].

Ecosystem services from the deep seabed are generally of an indirect nature, relating to nutrient cycling and long term climate control. However, all deep water does eventually return to the surface and/or mix with the rest of the ocean. The use of the deep sea for large-scale $CO_2$ storage will therefore eventually reduce ocean pH as a whole, with potential effects greatest in upwelling regions (currently highly productive and supporting major fisheries).

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The chronic effects of direct $CO_2$ injection into the ocean on ecosystems over large ocean areas and long time scales have not yet been studied, and the capacity of ecosystems to compensate or adjust to such $CO_2$ induced shifts is unknown. Several short-term and very small field experiments (litres) have, however, been carried out, e.g., on meiofauna[385], and peer-reviewed literature on potential $CO_2$ leakages from geological sub-sea storage[386] is also relevant.

*$CO_2$ storage in sub-surface geological reservoirs*

$CO_2$ storage in sub-surface geological reservoirs is already being implemented at pilot-scale levels, and has been used industrially as part of enhanced oil recovery. Based in part on this experience, the risks are generally regarded as low. However, leakage from such reservoirs could have locally significant biodiversity implications[387]. It is expected that, where $CO_2$ storage in sub-seabed geological formations is authorized (by permit) under the London Protocol, information on the leakage and potential impacts will be reported and amassed over time.

There is potentially reduced risk of leakage from sub-surface reservoirs if the $CO_2$ is injected into basalt[388],[389] or other minerals rich in calcium and/or magnesium[390] with which it would react – in a similar way to the enhanced weathering reactions described in section 5.2.2. With pure $CO_2$, the reactions are expected to be relatively rapid, limited by the porosity of the rock. This process is currently being tested at commercial scale[391]

### 5.3. Sequestration of other greenhouse gases

CDR techniques necessarily focus on the removal of $CO_2$ from the atmosphere. Nevertheless, there could be significant climatic benefits if other greenhouse gases, particularly methane ($CH_4$) and nitrous oxide ($N_2O$) could also be removed[392]. Techniques are understood to be under development, but have not yet been reported in peer reviewed literature.

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[385] Barry J.P., Buck K.R., Lovera C.F., Kuhnz L., Whaling P.J., Peltzer E.T., Walz P. & Brewer P.G. (2004). Effects fo direct ocean $CO_2$ injection on deep-sea meiofauna. *J Oceanography*, 60, 759-766

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[392] Boucher O. & Folberth G.A. (2010). New directions: atmospheric methane removal as a way to mitigate climate change? *Atmospheric Environment* 44, 3343-3345,: doi: 10.1016/j.atmosenv.2010.04.032

# CHAPTER 6. SOCIAL, ECONOMIC, CULTURAL AND ETHICAL CONSIDERATIONS OF CLIMATE-RELATED GEOENGINEERING

## 6.1 Introduction

Climate change is likely to have serious impacts on biodiversity, ecosystems and associated ecosystem services. The social, economic and cultural implications of unmitigated climate change and continued degradation of ecosystems should not be underestimated (Chapter 3). Furthermore, the social, economic and cultural considerations regarding geoengineering have significant inter- and intra-generational equity issues.

Geoengineering proposals have proved to be highly controversial, with a wide divergence of opinions about potential risks and benefits. All new technologies or techniques are embedded in a wider social context and have social, economic and cultural impacts that might become apparent only once they have been employed. However, geoengineering raises issues beyond technical scientific assessments due to its intentionality, and the inter- and intra-generational equity issues associated with its potential impacts. The controversies surrounding nuclear power, genetically modified organisms (GMOs) and nano-technologies have shown the importance of connecting scientific research to its wider social context.

The CBD Conference of the Parties, through its decision X/33 requested the Executive Secretary to identify social, economic and cultural considerations associated with the possible impacts of geoengineering on biodiversity. In this chapter, we discuss those issues, together with the role of indigenous groups and local communities in the context of geoengineering and biodiversity. Initial sections deal with social, economic and cultural issues that are relevant for geoengineering in general[393], in order to put geoengineering technologies in a wider social context, and to highlight social, political, economic and cultural issues that ought to be of interest for the Parties of the CBD. The second part of the chapter has an explicit focus on potential social concerns associated with different geoengineering proposals and technologies and their impacts on biodiversity.

## 6.2 Available information

Assessing the social, economic and cultural impacts of geoengineering technologies as they relate to biodiversity is an important, yet difficult, task considering the current state of knowledge and the lack of peer-reviewed literature on the topic. It has also been questioned whether peer-reviewed literature can adequately reflect indigenous knowledge; knowledge which is often as much a process of knowing as it is a thing that is known, and so does not lend itself to the practice of documentation[394,395]. This is a major concern considering the role indigenous and local communities play in actively managing ecosystems, sometimes through an active application of local ecological knowledge that has evolved over long periods through co-management processes and social learning[396].

Some work on this matter has been conducted within the framework of CBD activities on biodiversity and climate change, including a workshop on opportunities and challenges of responses to climate change for indigenous and local communities, their traditional knowledge and biological diversity (March 2008, Helsinki)[397], as well as through the consideration of the role of traditional knowledge innovations and practices during the second Ad hoc Technical Expert Group on Biodiversity and Climate Change[398]; however, further work remains to be done. In addition, there is a growing

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[393] These initial sections could be considered as beyond the explicit mandate of the group, but are included to put the technologies in a wider social context, as well as responding to comments on a draft of this report.

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literature on social dimensions of geoengineering[399],[400],[401] including examples of social perceptions from historic efforts to engineer the climate and other large-scale planetary processes[402]. Issues related to geoengineering ethics, governance and socio-political dimensions have also been discussed within the geoengineering research community, as exemplified by the “Oxford Principles”[403] and the subsequent “Asilomar Principles”[404].

It should also be noted that there is very little information available about the perspectives from indigenous peoples and local communities, especially among developing countries within geoengineering discussions[405]. The CBD Secretariat has initiated a process to bring in the views of indigenous communities, and the results are presented in a separate report[406].

### 6.3 General social, economic and cultural considerations

There are a number of social, economic and cultural considerations from geoengineering technologies that may emerge, regardless of the specific geoengineering approach considered. These considerations are not necessarily unique for geoengineering, but have clear parallels to on-going discussions on social dimensions of climate change, emerging technologies, and complex global risks. It should be re-stated that this is not intended to be a complete all-encompassing analysis of costs and benefits, but should rather be seen as social, economical and cultural issues of potential concern. In addition, social perceptions of risks in general, are highly differentiated across social groups, are highly dynamic[407], and pose particular socio-political challenges in settings defined by complex bio-geophysical interactions[408,409]. This complicates any projection of how the general public, non-governmental organizations and governments would perceive any experimentation and deployment of geoengineering technologies.

#### *6.3.1 Ethical considerations*

Humanity is now the major changing force on the planet, reflected in the proposal to define the Anthropocene[410] as a new geological epoch driven by human activities This shift has important repercussions, not only because it forces us to consider multiple and interacting global environmental changes[411],[412], but also because it opens up difficult discussions on whether it is desirable to move from unintentional modifications of the Earth system, to an approach where we intentionally try to modify the climate and associated bio-geophysical systems to avoid the worst outcomes of climate

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[400] Victor D.G., Morgan M.G., Apt J., Steinbruner J. & Ricke K. (2009). The geoengineering option. A last resort against global warming? *Foreign Affairs* 88, 64-76

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[404] Asilomar Scientific Organizing Committee (ASOC), (2010). *The Asilomar Conference Recommendations on Principles for Research into Climate Engineering Techniques,* Climate Institute, Washington DC.

[405] However, public engagement initiatives have been piloted in the developed world, as a means of gauging public opinions on geoengineering, e.g. Ipsos MORI (2010). *Experiment Earth? Report on a Public Dialogue on Geoengineering.* Online at www.nerc.ac.uk/about/consult/geoengineering-dialogue-final-report.pdf

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change. Hence, the very fact that the international community is presented with geoengineering as a potential option to be further explored is a major social and cultural issue.

Geoengineering poses numerous ethical challenges[413],[414],[415],[416],[417],[418]. The successful governance of geoengineering also requires the international community to resolve the conflicting objectives of avoiding the adverse effects of global climate change whilst also avoiding the risks and uncertainties of geoengineering.

Public engagement is an important part of this process, providing guidance on the research and input to policy-making. Although the need for such dialogue is widely recognised[419,420,421], and some upstream public engagement on geoengineering has been trialled[422,423] current discussions on geoengineering are often based on technical approaches whose implications are not readily understood nor easily assessed[424]. There is a growing discussion and literature on ethical considerations related to geoengineering, including issues of "moral hazard"[425] (whereby attention to geoengineering reduces the effort given to mitigation); the potential for the opposite effect[426]; intergenerational issues of submitting future generations to the need to maintain the operation of the technology or suffer accelerated change[427]; the possibility that development and uses of geoengineering techniques are perceived to be threatening by governments [428]; as well as the question of whether it is ethically permissible to remediate one pollutant by introducing another[429].

### *6.3.2 Unintended consequences and technological lock-in*

Technological innovation has in very many ways helped to transform societies and improve the quality of life, but not always in a sustainable way[430]. Failures to respond to early warnings of

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unintended consequences of particular technologies have been documented[431]. The possibilities of unintended side effects in the large-scale application of geoengineering techniques is a frequent concern in the literature and wider debate, especially for SRM methods (Chapter 4). The concept of 'technologies of hubris' has been introduced, calling for a better balance between the idea that technology can solve problems and the concern that technological approaches may not be the best option for addressing social and ethical issues[432].

An additional concern is the possibility of technological, political and social 'lock in' – the possibility that the development of geoengineering technologies also result in the emergence of vested interests and increasing social momentum. It has been argued that this path dependency could make deployment more likely, and/or limit the reversibility of geoengineering techniques[433,434,435].

It is important that research on geoengineering does not itself contribute to that 'lock in'. To minimize that risk, it is essential that any such research is fully transparent, open-minded and objective (i.e., without prejudice to the desirability or otherwise of geoengineering implementation), and preferably carried out on an international basis.

### *6.3.3 Governance and legal considerations*

Issues related to geoengineering governance and regulation have gained increased prominence in the literature[436,437438]. It should be noted that the challenges for regulation and governance of geoengineering include the variety of evolving technologies as well as their different stages of development – ranging from theory to modelling, to sub-scale field testing, and large scale deployment[439]. Governance structures also need to provide different functions ranging from ensuring transparency, participation, containing risks, the coordination of science, bridging the science-policy divide, and create structures to secure funding[440].

These issues, along with precautionary principle/approach and human rights approaches, are discussed in more detail in a parallel study in response to CBD Decision X/33 entitled "Regulatory Framework of Climate-related Geoengineering Relevant to the Convention on Biological Diversity", and are therefore not explored in detail here.

### *6.3.4 Societal distribution considerations*

The large-scale application of geoengineering would raise a number of questions regarding the distribution of resources and impacts within and amongst societies and across time. First, access to natural resources is needed for several geoengineering techniques. Competition for limited resources can be expected to increase if geoengineering technologies emerge as a competing activity for land or water use. For example, possible competition for land as a result of land based albedo changes, or land based CDR will reduce land available for other uses such as the production of food crops, medicinal plants or the exploitation of non-timber forest products. These competing demands for land

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use can increase social tensions unless addressed by national and local institutions[441]. In addition, changes in land use may impact local communities and indigenous people's cultural and spiritual values of natural areas, sacred groves and water shades[442].

These issues could also be relevant in the marine environment where experimentation or deployment of geoengineering proposals such as ocean fertilization could impact traditional marine resource use[443,444]. The use of the deep water as reservoirs for storage of $CO_2$ or biomass, as well as for ocean fertilization, would also use ocean space. To the extent that most of these activities would happen on the high seas, they are unlikely to raise significant distributional issues as a social consideration.

Enhanced weathering on land however will have clear local impacts as it requires large mining areas and associated transport infrastructure. In addition, the mineral resources required will only be available in certain locations, therefore reducing the opportunity for choosing between alternative sites. Based on historical experience, large mining activities could have serious social impacts. In addition, land space is needed for weathering to happen.

Second, the distribution of *impacts* of geoengineering are not likely to be even or uniform as are the impacts of climate change itself. Regarding impacts on climate, this appears to be mainly an issue arising from SRM. Regarding other impacts, CDR could have local and possibly also regional *impacts* that could raise distributional issues. Such impacts are explored below in this chapter. Where distributional effects arise, this raises questions about how the uneven impacts can be addressed for instance through proper governance mechanisms.

Third, as with climate change, geoengineering could also entail intergenerational issues. As a result of possible technological "lock in", future generations might be faced with the need to maintain geoengineering measures in general in order to avoid impacts of climate change. This mainly has been identified as an issue for SRM. However, it is also conceivable that CDR-techniques entail similar "lock in" effects depending on emission trajectories. Conversely, it could be argued that *not* pursuing further research on geoengineering could limit future generations' options for reducing climate risk.

### *6.3.5 Political considerations*

There are also a number of social and political considerations to bear in mind especially when considering SRM. Establishing agreement on the desirability and governance for international action will be extremely difficult, and countries and societies will also have to deal with the possibility of unilateral deployment of geoengineering. In cases in which geoengineering experimentation or interventions have (or are suspected to have) transboundary effects or impacts on areas beyond national jurisdiction, geopolitical tensions could arise regardless of causation of actual negative impacts, especially in the absence of international agreement[445,446,447].

Furthermore, some civil society organizations have expressed opposition to geoengineering experiments and deployment[448,449,450]. Tensions could also increase in cases where geoengineering

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[450] Poumadère M., Bertoldo R. & Samadi J. (2011) Public perceptions and governance of controversial technologies to tackle climate change: nuclear power, carbon capture and storage, wind, and geoengineering, *WIREs Climate Change*, 2, 712-717;

technologies are combined with other emerging and controversial technologies, such as biotechnology (e.g. albedo-enhanced crops) and nanotechnology (e.g. 'designer aerosols' for SRM), and where those involved are perceived to have ulterior motives. Polarization of the debate could prove detrimental to political decision-making[451].

### 6.4 Specific social, economical and cultural considerations of geoengineering technologies as they relate to biodiversity

As discussed in Chapter 3, climate change is expected to result in altered ecosystems consisting of new assemblages of species[452], and therefore affect biodiversity in ways that are relevant for all sort of local uses of land-based and marine ecosystems, and their associated ecosystem services. Reducing the impacts of climate change through geoengineering interventions may *in theory* address the loss of ecosystems upon which traditional knowledge is based. On the other hand, deployment of geoengineering interventions may itself alter ecosystems (see examples below), resulting in this impact being offset or eclipsed[453]. This however, is highly dependent on the geoengineering technology of interest, how it is deployed, and the institutions (local and national) in place.

In addition to the social considerations that generally arise from geoengineering, in this section we briefly elaborate social, economical and cultural considerations that result specifically from geoengineering's impacts on biodiversity.

#### *6.4.1 Geoengineering, and indigenous and local communities and stakeholders*

CBD Decision X/33 calls for the integration of the views and experiences of indigenous and local communities and stakeholders into the consideration of the possible impacts of geoengineering on biodiversity and related social, economic and cultural considerations. Integrating such views is important as indigenous peoples and local communities, especially in developing countries, tend to be among the populations whose livelihoods are most reliant upon biodiversity resources. In addition, disadvantaged users of ecosystems and their associated ecosystem services, are at constant risk of losing out in conflicts related to local resources, have less of a voice in decision-making at all levels, and may have fewer opportunities to engage in regulatory and other policy forums to support their interests[454,455].

The issue here is as much about physical resources, as about cultural uses and worldviews associated with ecosystems and their management. Forest taboo systems in Madagascar[456] and the unique cultural features of Balinese water temples[457] are just two examples.

All forms of environmental change – resulting from geoengineering or not – have local implications for livelihoods and ecosystem services. In fact, the Second Ad hoc Technical Expert Group on Biodiversity and Climate Change concluded that indigenous people will be disproportionately impacted by climate change because their livelihoods and cultural ways of life are being undermined by changes to local ecosystems[458]. As such, if geoengineering can reduce the negative impacts of climate change, without effecting more environmental change than that which is avoided,

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doi: 10.1002/wcc.134.

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geoengineering could contribute to the preservation of traditional knowledge, innovations and practices.

However, there is considerable uncertainty regarding the impacts of any environmental change on indigenous peoples and local communities since these changes are difficult to predict with current modelling capabilities[459]. Furthermore, there is the risk that SRM geoengineering, could effect change more rapidly than unmitigated climate change itself[460].

In order to ensure that the impacts of geoengineering on indigenous peoples and local communities are adequately considered and addressed, there is a role for such stakeholders in various phases of geoengineering research, ranging from theory and modelling, technology development, subscale field-testing; and potential deployment. The participation of indigenous peoples and local communities could hence be included in all parts of research development, especially in cases where technological interventions are projected to have impacts for biodiversity and ecosystem services.

Guidelines for the consideration of the views and knowledge of indigenous peoples and local communities have already been proposed by the Second Ad hoc Technical Expert Group on Biodiversity and Climate Change with regards to climate change[461]. These guidelines (see box 1) may be useful to consider by scientists and national governments alike when assessing the social, economic and cultural impacts of geoengineering.

As noted above, the CBD Secretariat has initiated a separate process to bring in the views of indigenous communities, and the results are presented in a separate report[462].

**Box 1: Activities to promote the consideration of the views of indigenous peoples and local communities consistent with Article 8(j) of the Convention:**

- Promote the documentation and validation of traditional knowledge, innovations and practices. Most knowledge is not documented and has not been comprehensively studied and assessed. Therefore there is need to enhance links between traditional knowledge and scientific practices.
- Revitalize traditional knowledge, innovations and practices on climate change impacts on traditional biodiversity based resources and ecosystem services through education and awareness-raising, including in nomadic schools.
- Explore uses of and opportunities for community-based monitoring linked to decision-making, recognizing that indigenous people and local communities are able to provide data and monitoring on a whole system rather than single sectors based on the full and effective participation of indigenous and local communities.

### *6.4.2 Social, economic and cultural considerations of sunlight reflection methods (SRM)*

As discussed in Chapter 4, SRM is only expected to partly, not fully, prevent undesirable climate change, with implications for ecosystem productivity and associated livelihoods. Any shifts of temperature and changes to the hydrological cycle might affect local and indigenous communities, especially those dependent on provisioning ecosystem services such as food, energy. Cultural services such as ceremonies that follow planting and harvesting seasons in most rain fed agricultural regions (e.g., Nigeria and Ghana[463]) could also be affected by any changes in hydrological regimes. Whilst such impacts are expected to be less than for unmitigated climate change, there is an ethical difference in that they are the consequence of deliberate action.

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[459] Robock,A. Bunzl M., Kravitz B., Georgiy L. & Stenchikov (2010). A test for geoengineering? *Science* 29. 327, 530 - 531

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[463] IITA (2010). *Research to Nourish Africa*. R4D Review. http://r4dreview.org/2010/04/yam-festival.

In theory, SRM might be able to counteract the adverse impacts of climate change to a greater extent in some regions[464] (e.g., the Arctic[465,466]) than others; thus such approaches *might* be tailored to preserve threatened traditional livelihoods. However, there are many uncertainties regarding the impact of SRM on the climate system, and hence on food security, ecosystem productivity and associated issues. For example, as discussed in Chapter 4, whether there might be increases in plant productivity due to the increase in diffuse insolation; whether the the albedo of crop leaves[467] can be increased without affecting crop yields; and what changes SRM would cause to regional precipitation patterns and extreme events, with the likelihood of substantive impacts on rainfed agriculture and traditional pastoral livelihoods.

Stratospheric aerosols could also: i) adversely affect ground-level astronomical observation; ii) interfere with satellite-based remote sensing of Earth, and iii) make skies whiter (less blue). However, such effects have not been investigated in detail, and their magnitude may be slight[468].

### *6.4.3 Social, economic and cultural considerations of land-based CDR techniques*

The non-climatic consequences of land based CDR are highly technique specific, as discussed in Chapter 5, with corresponding variability in socio-economic impacts via ecosystem productivity and associated livelihoods. Some approaches could, in theory, increase ecosystem productivity[469] and food production; e.g. through increased carbon and nutrient content in soils[470]. It is, however, less certain whether such unintended benefits could be sustained, and whether the intended benefits could be of sufficient magnitude to significantly counteract anthropogenic climate change[471].

The large-scale implementation of direct air capture of $CO_2$ ("artificial trees", although unlikely to be tree-like structures) could compromise locally significant features or degrade culturally significant landscapes, with possible parallels to the debate over wind farms. Such methods might also be associated with operational noise, depending on the deployment arrangements. Concerns have also been raised about the energy and (fresh)water requirements of this approach, with the possibility that the latter might adversely affect water security, whilst negatively impacting local freshwater biodiversity.

Large-scale afforestation involves landscape changes that are likely to have both positive and negative impacts on biodiversity, ecosystems services and their uses. In addition to implications for competing land uses, altered landscapes affect hydrological regimes (evapo-transpiration and water run-off) and may also habitat fragmentation and/or loss. Some of these concerns could also apply to reforestation.

It has been suggested that some land based CDR techniques could make use of genetic modification of organisms or monoculture hybrid crop breeding[472]. The potential benefits obtained by such approaches would need to be carefully assessed in the context of any potential negative impacts on traditional crop varieties and non-target species, including those of cultural or medicinal importance. Where such approaches are considered in a geoengineering context, the safe handling of such

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[464] Ban-Weiss G.A. & Caldeira K. (2010). Geoengineering as an optimization problem. *Environ. Res. Letters*, 5, 1-9.

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materials would be expected to follow the provisions set out in the Cartagena Protocol on Biosafety[473].

### 6.4.4 Social, economic and cultural considerations of ocean based CDR techniques

The non-climatic impacts of ocean-based CDR are similarly technique specific, and also may involve regional disparities – and considerable uncertainties. The consequences of enhanced ocean alkalinity for marine species of economic and cultural importance are highly uncertain, since this technique has not been tested in field experiments. Whilst it could assist in counteracting ocean acidification, it would be a high-risk strategy to carry out field trials adjacent to coral reefs.

The consequences of ocean fertilization for marine communities in the upper ocean are somewhat better known[474,475]; however, impacts on fisheries due to changes in marine food chains are uncertain, and could be positive in some areas and negative in others. If carried out on a very large scale, ocean fertilization would have far-field effects that are inherently difficult to predict, so distant ecological and human communities could be affected and the overall effectiveness of the technique would be very difficult to assess. Whilst there is also a suggested risk of toxic blooms, land-based nutrient inputs are likely to continue to be the main cause for concern in that regard, at least for shelf seas and coastal waters.

[473] Cartagena Protocol on Biosafety. http://bch.cbd.int/protocol/

[474] Wallace D.W.R, Law C.S., Boyd P.W., Collos Y., Croot P., Denman K., Lam P.J., Riebesell U., Takeda S. & Williamson P. (2010) *Ocean fertilization: A scientific summary for policy makers*. IOC/UNESCO, Paris (IOC/BRO/2010/2)

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

## CHAPTER 7. SYNTHESIS

This study has: introduced the range of proposed geoengineering techniques (Chapter 2); reviewed the projected impacts of likely climate change on biodiversity (Chapter 3); considered the impacts of specific geoengineering techniques on biodiversity (Chapters 4 and 5); and discussed associated socio-economic and cultural issues (Chapter 6). Based on that information, this chapter provides a short summary of the drivers of biodiversity loss under the scenarios of i) continuation of current trends of increasing energy use; ii) rapid and substantive reduction in greenhouse-gas emissions; and iii) the deployment of geoengineering techniques to address climate change, against a baseline scenario of (i), i.e. taking little or insufficient action to reduce anthropogenic climate change. Intermediate and alternative scenarios are also possible.

The chapter also includes remarks on the importance of scale, and highlights key areas where further knowledge and understanding is required.

### 7.1 Changes in the drivers of biodiversity loss

As noted in Chapter 1, the main direct drivers of biodiversity loss are habitat conversion, over-exploitation, the introduction of invasive species, pollution and climate change.

For terrestrial ecosystems, the largest driver of biodiversity loss at the global scale has been, and continues to be, land use change. In the ocean, over-exploitation has been the major cause of ecosystem degradation, with loss of top predators (fish and marine mammals). For both environments, climate change is rapidly increasing in importance as a driver of biodiversity loss. However, the relative importance of different drivers of loss vary between ecosystems, and from region to region.

The baseline scenario (i) described in Chapter 3 considers the climatic consequences of continued anthropogenic greenhouse-gas emissions, without urgent action to achieve a low-carbon economy at the global scale. Under those conditions, global temperature increases of 3-5°C are projected by 2100, posing an increasingly severe range of threats to biodiversity and ecosystem services not only as a result of changes in temperature, but also in precipitation, water availability, sea level and the associated phenomenon of ocean acidification. The impacts are exacerbated by the other anthropogenic pressures on biodiversity (such as over-exploitation; habitat loss, fragmentation and degradation; the introduction of non-native species; and pollution) since these reduce the opportunity for gradual ecosystem shifts, population movements and genetic adaptation. In addition, climate change is likely to increase some of the other drivers; for example, by providing additional opportunities for invasive alien species (e.g. mixing of Pacific and Atlantic marine plants and animals).

Under this baseline scenario of taking insufficient action to address climate change, the climate change driver will increase substantially.

Under scenario (ii) of addressing climate change through a rapid and substantive reduction in greenhouse-gas emissions, there would be a transition to a low-carbon economy in both the way we produce and use energy, and in the way we manage our land. Measures to achieve that effect could include: increased end-use efficiency; the use of renewable energy technologies alongside nuclear and carbon capture and storage; and ecosystem restoration and improved land management. These measures would substantially reduce the adverse impacts of climate change on biodiversity, although significant further climate change is now considered unavoidable. Generally, most other impacts on biodiversity, mediated through other drivers, would be small (e.g., use of nuclear power to replace fossil fuels) or positive (e.g., avoided deforestation, ecosystem restoration). Although some of the climate change mitigation measures have potential negative side-effects on biodiversity (e.g., bird kill by wind farms; disruption of freshwater ecosystems by hydropower schemes) these can be minimized by careful design. Overall, strong climate change mitigation measures are expected to be beneficial for biodiversity, and for the provision of ecosystem services.

Under this scenario, the climate change driver would be very much reduced. Land use change would also likely be significantly reduced relative to the baseline scenario. Pollution and invasive species are expected to be somewhat reduced compared to the baseline, while there are few reasons to expect significant differences in over-exploitation.

A third scenario (iii) involves deploying geoengineering techniques to counteract climate change in the absence of substantive emission reductions. Under such a scenario, some of the negative impacts of climate change on biodiversity could be reduced, provided that the geoengineering techniques prove to be feasible and climatically-effective. At the same time, most geoengineering techniques would have additional impacts on biodiversity, that may be either negative or positive. The totality of effects on biodiversity will vary depending on the techniques employed, and many aspects are, and will remain, difficult to predict. All geoengineering techniques are associated with significant risks and uncertainties.

Under this scenario, the climate change driver would be expected to be significantly reduced (compared to the baseline scenario of taking minimal action) for some or all aspects of climate change and/or their impacts. For several techniques (e.g., surface albedo and afforestation) there would be increases in land use change compared to the baseline scenario, though this driver could be unaffected for some other techniques. For some techniques (e.g., afforestation) there might be an increased risk from invasive species compared to the baseline, although this risk could be minimised through good design. Some other techniques (e.g., stratospheric aerosols, ocean fertilization) may lead to a small increase in pollution compared to the baseline. There are no reasons to expect significant differences in over-exploitation compared to the baseline scenario.

### 7.2 The question of scale and its implications for feasibility and impacts of geoengineering techniques

The study describes a large range of potential impacts of geoengineering techniques on biodiversity and identifies the large uncertainties associated with many of these. To be effective in counter-acting anthropogenic climate change, geoengineering techniques need to be deployed on a large scale, either individually, or in combination. In most cases the risks associated with the techniques are highly dependent on the scale at which they are deployed. Several of the techniques (e.g., whitening of the built environment; afforestation; biomass production) are benign at a small scale, but scaling up is either difficult or impractical (e.g., spatial extent of the built environment is limited) or may be associated with greatly increased negative effects (afforestation – as opposed to reforestation – or biomass production on a very large scale is likely to have significant adverse effects on biodiversity via land-use change).

The scaling issue is particularly important for CDR techniques, since none on their own seem capable of counteracting more than a small proportion of current $CO_2$ emissions. The technique that is potentially the most climatically effective (direct air capture) would also seem to be the least cost-effective.

### 7.3 Gaps in knowledge and understanding

The report recognizes many areas where knowledge is very limited. These include: (1) the overall effectiveness of some of the techniques, based bon realistic estimates of their scalability; (2) how the proposed geoengineering techniques can be expected to affect weather and climate regionally and globally; (3) how biodiversity, ecosystems and their services are likely to respond to changes in climate, both with and without geoengineering; (4) the unintended, non-climatic effects of different proposed geoengineering techniques on biodiversity; and (5) the social and economic implications of climate change and potential geoengineering interventions, particularly with regard to geo-political acceptability, governance and the potential need for international compensation in the event of there being 'winners and losers'. Additional research in these areas would reduce uncertainties and improve evidence-based decision-making, without compromising the overall policy need to achieve rapid reductions in greenhouse-gas emissions.

In addition, there is very limited understanding among stakeholders of geoengineering concepts, techniques and their potential positive and negative impacts on biodiversity. Not only is there much less information available on geoengineering than for climate change, but there has been little consideration of the issues by local communities, indigenous peoples, marginalized groups and other stakeholders, especially in developing countries. Since these communities play a major role in actively managing ecosystems that deliver key climatic services, the lack of knowledge of their perspective is a major gap that requires further attention.

*Annex I*

## SUMMARY OF SELECTED DEFINITIONS OF CLIMATE-RELATED GEOENGINEERING

### 1. Convention on Biological Diversity – decision X/33

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).

*http://www.cbd.int/climate/doc/cop-10-dec-33-en.pdf*

### 2. Intergovernmental Panel on Climate Change – Fourth Assessment Report

Technological efforts to stabilize the climate system by direct intervention in the energy balance of the Earth for reducing global warming.

*http://www.ipcc.ch/pdf/glossary/ar4-wg3.pdf*

### 3. Intergovernmental Panel on Climate Change – Third Assessment Report

Efforts to stabilize the climate system by directly managing the energy balance of the Earth, thereby overcoming the enhanced greenhouse effect.

*http://www.ipcc.ch/pdf/glossary/tar-ipcc-terms-en.pdf*

### 4. The United Kingdom of Great Britain and Northern Ireland House of Commons Science and Technology Committee

Activities specifically and deliberately designed to effect a change in the global climate with the aim of minimising or reversing anthropogenic (that is, human made) climate change.

*http://www.publications.parliament.uk/pa/cm200910/cmselect/cmsctech/221/22102.htm*

### 5. The United States House of Representatives Committee on Science and Technology

The deliberate large-scale modification of the Earth's climate systems for the purposes of counteracting [and mitigating anthropogenic[476]] climate change.

*Hearing on 5 November 2009 - Geoengineering: Assessing the Implications of Large-Scale Climate Intervention*

### 6. The Royal Society (U.K.)

The deliberate large-scale manipulation of the planetary environment to counteract anthropogenic climate change.

*Geoengineering the Climate: Science, Governance and Uncertainty. September, 2009*

### 7. The National Academy of Science (U.S.A.)

Options that would involve large-scale engineering of our environment in order to combat or counteract the effects of changes in atmospheric chemistry.

[476] Added in the Report by the Chairman of the Committee on Science and Technology 'Engineering the Climate: Research Needs and Strategies for International Coordination – October, 2010'.

*http://books.nap.edu/openbook.php?record_id=1605&page=433*

### 8. The Australian Academy of Science

A branch of science which is focused on applying technology on a massive scale in order to change the Earth's environment.

*http://www.science.org.au/nova/123/123key.html*

### 9. The ETC Group (Non-Governmental Organization)

Geoengineering is the intentional, large-scale technological manipulation of the Earth's systems, including those related to climate.

*http://www.etcgroup.org/en/node/5217*

### 10. The Asilomar Conference Report: Recommendations on Principles for Research into Climate Engineering Techniques

Deliberate steps to alter the climate, with the intent of limiting or counterbalancing the unintended changes to the climate resulting from human activities.

*http://www.climateresponsefund.org/images/Conference/finalfinalreport.pdf*

*Annex II*

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