DOI: http://doi.org/10.1080/1943815X.2016.1159578

# Key impacts of climate engineering on biodiversity and ecosystems, with priorities for future research

Caitlin G. McCormack[1¶], Wanda Born[2†], Peter J. Irvine[2], Eric P. Achterberg[3,4], Tatsuya Amano[1], Jeff Ardron[5], Pru N. Foster[6], Jean-Pierre Gattuso[7,7a], Stephen J. Hawkins[3], Erica Hendy[6,8], W. Daniel Kissling[9&], Salvador E. Lluch-Cota[10], Eugene J. Murphy[11], Nick Ostle[12], Nicholas J.P. Owens[13], R. Ian Perry[14], Hans O. Pörtner[15], Robert J. Scholes[16], Frank M. Schurr[17], Oliver Schweiger[18], Josef Settele[18, 18a], Rebecca K. Smith[1], Sarah Smith[19], Jill Thompson[20], Derek P. Tittensor[19,21], Mark van Kleunen[22], Chris Vivian[23], Katrin Vohland[24], Rachel Warren[25], Andrew R. Watkinson[25], Steve Widdicombe[26], Phillip Williamson[27], Emma Woods[28], Jason J. Blackstock[29] and William J. Sutherland[1*].

[1] Conservation Science Group, Department of Zoology, University of Cambridge, Cambridge, UK; c.mccormack@zoo.cam.ac.uk; ta307@cam.ac.uk; rks25@hermes.cam.ac.uk; w.sutherland@zoo.cam.ac.uk

[2] Sustainable Interactions with the Atmosphere, Institute for Advanced Sustainability Studies e.V., Potsdam, Germany; wanda.born@iass-potsdam.de; peter.irvine@iass-potsdam.de

[3] Ocean and Earth Science, National Oceanography Centre Southampton, University of Southampton Waterfront Campus, Southampton, UK; eric@noc.soton.ac.uk; S.J.Hawkins@soton.ac.uk

[4] GEOMAR, Helmholtz Centre for Ocean Research, Germany; eric@noc.soton.ac.uk

[5] Global Contract for Sustainability, Institute for Advanced Sustainability Studies e.V., Potsdam, Germany; jeff.ardron@iass-potsdam.de

[6] School of Earth Sciences, University of Bristol, Wills Memorial Building, Bristol, UK; pru.foster@bristol.ac.uk; e.hendy@bristol.ac.uk

[7] Université Pierre et Marie Curie-Paris 6, Observatoire Océanologique de Villefranche, Villefranche-sur-Mer, France; [7a] CNRS, Laboratoire d'Océanographie, Villefranche-sur-mer France; gattuso@obs-vlfr.fr

[8] School of Biological Sciences, University of Bristol, Bristol, UK; e.hendy@bristol.ac.uk

[9] Institute for Biodiversity and Ecosystem Dynamics (IBED), University of Amsterdam, , The Netherlands; wdkissling@gmail.com

[10] Programa de Ecología Pesquera, Centro de Investigaciones Biológicas del Noroeste (CIBNOR), La Paz, Baja California Sur, México; slluch@cibnor.mx

[11] British Antarctic Survey, Cambridge, UK; ejmu@bas.ac.uk

[12] Lancaster Environment Centre, Lancaster University, Lancaster, UK; n.ostle@lancaster.ac.uk

[13] Sir Alister Hardy Foundation for Ocean Science, the Laboratory, Plymouth, UK; njpo@sahfos.ac.uk

[14] Department of Fisheries and Oceans, Pacific Biological Station, Nanaimo, British Columbia, Canada; Ian.Perry@dfo-mpo.gc.ca

[15] Alfred-Wegener-Institut für Polar- und Meeresforschung, Ökophysiologie, Germany; hans.poertner@awi.de

[16] Council for Scientific and Industrial Research, Pretoria, South Africa; BScholes@csir.co.za

[17] Institut des Sciences de l'Evolution de Montpellier, UMR-CNRS 5554, Université Montpellier II, France; frank.schurr@univ-montp2.fr

[18] UFZ Centre for Environmental Research, Department of Community Ecology, D-06120 Halle, Germany; oliver.schweiger@ufz.de, josef.settele@ufz.de; [18a] iDiv, German

Centre for Integrative Biodiversity Research (iDiv) Halle-Jena-Leipzig, 04103 Leipzig, Germany; josef.settele@ufz.de
[19] UNEP World Conservation Monitoring Centre, Cambridge, UK; sarah.smith@unep-wcmc.org
[20] Centre for Ecology and Hydrology, Penicuik, Midlothian, UK; jiom@ceh.ac.uk
[21] Department of Biology, Dalhousie University, Halifax, Canada; Derek.Tittensor@unep-wcmc.org
[22] Ecology, Department of Biology, University of Konstanz, Konstanz, Germany; mark.vankleunen@uni-konstanz.de
[23] Cefas, Lowestoft Laboratory, Lowestoft, UK; chris.vivian@cefas.co.uk
[24] Museum für Naturkunde, Leibniz-Institut für Evolutions-und Biodiversitätsforschung, Berlin, Germany; katrin.vohland@mfn-berlin.de
[25] School of Environmental Sciences, University of East Anglia, Norwich, UK; r.warren@uea.ac.uk; a.watkinson@uea.ac.uk
[26] Plymouth Marine Laboratory, Prospect Place, West Hoe, Plymouth, UK; swi@pml.ac.uk
[27] Natural Environment Research Council and School of Environmental Sciences, University of East Anglia, Norwich, UK; P.Williamson@uea.ac.uk
[28] The Royal Society, London, UK; emma.woods@royalsociety.org
[29] Science, Technology, Engineering and Public Policy, University College London, London, UK; jason.blackstock@ucl.ac.uk
[¶]Current address: caitlin.g.mccormack@gmail.com
[†]Current address: wanda_b@gmx.net

* Authors to whom correspondence should be addressed:
Professor Bill Sutherland
Conservation Science Group
Department of Zoology
University of Cambridge
Downing Street
Cambridge
CB2 3EJ
e-mail: w.sutherland@zoo.cam.ac.uk

**Short title:** Biodiversity impacts of climate engineering

**Type of article:** Review

**Word count:**

**Abstract:** 196

**Main text:** 8,404, of which 2,635 in tables (including references, titles and sub-titles)

**Text boxes:** n/a

**Number of references:** 103

**Number of figures:** Two (2)

**Number of tables:** Three (3)

**Number of Supporting Information appendices:** Four (4)

**Abstract**

Climate change has significant implications for biodiversity and ecosystems. With slow progress towards reducing greenhouse gas emissions, climate engineering (or 'geoengineering') is receiving increasing attention for its potential to limit anthropogenic climate change and its damaging effects. Proposed techniques, such as ocean fertilization for carbon dioxide removal or stratospheric sulfate injections to reduce incoming solar radiation, would significantly alter atmospheric, terrestrial and marine environments, yet potential side-effects of their implementation for ecosystems and biodiversity have received little attention. A literature review was carried out to identify details of the potential ecological effects of climate engineering techniques. A group of biodiversity and environmental change researchers then employed a modified Delphi expert consultation technique to evaluate this evidence and prioritize the effects based on the relative importance of, and scientific understanding about, their biodiversity and ecosystem consequences. The key issues and knowledge gaps are used to shape a discussion of the biodiversity and ecosystem implications of climate engineering, including novel climatic conditions, alterations to marine systems and substantial terrestrial habitat change. This review highlights several current research priorities in which the climate engineering context is crucial to consider, as well as identifying some novel topics for ecological investigation.

**Keywords**

biodiversity, carbon dioxide removal, climate engineering, ecosystems, geoengineering, solar radiation management

## 1. Introduction

Anthropogenic emissions of greenhouse gases including carbon dioxide are considered the main cause of an observed 0.8 °C increase in average global surface temperature since pre-industrial times (IPCC 2013). These changes in greenhouse gas concentrations have implications not only for temperature, but also for precipitation, ice-sheet dynamics, sea levels, ocean acidification and extreme weather events (IPCC 2013). Such changes are already starting to have substantive effects on biodiversity and ecosystems, including altered species' distributions, interspecific relationships and life history events, and are predicted to intensify into the future (Bellard et al. 2012; Chen et al. 2011; Warren et al. 2013). With continued slow progress towards reducing greenhouse gas emissions (International Energy Agency 2013; Peters et al. 2012), climate engineering ('geoengineering') has been receiving increasing attention for its potential to be used to counteract climate change and reduce its damaging effects (IPCC 2013).

Climate engineering refers to large-scale interventions in the Earth system intended to counteract climate change. There are two main types (see Figure 1, Table 1 and Supporting Information1 in Supporting Information): 1) carbon dioxide removal (CDR) techniques, designed to reduce atmospheric carbon dioxide concentrations, and 2) solar radiation management (SRM), designed to reflect solar radiation away from Earth (Caldeira et al. 2013; Secretariat of the Convention on Biological Diversity 2012; The Royal Society 2009). There are a range of other terms for these processes. If effective the primary impact of climate engineering would be to reduce the damaging effects of climate change; CDR by reducing $CO_2$ concentrations to abate the process of climate change itself and SRM by direct lowering of global temperatures. All techniques will also have secondary impacts associated with their implementation, ranging from local land-use changes to globally reduced stratospheric ozone levels, for example (Ricke et al. 2010; Secretariat of the Convention on Biological Diversity 2012; Tilmes et al. 2013). These secondary impacts have wide-reaching and potentially complex biodiversity implications (Winder 2004). However, the possible consequences and the research needed to determine them, have received little attention from the ecological research community and are largely absent from climate engineering discussions (Russell et al. 2012).

[*INSERT FIGURE 1 NEAR HERE]*

The current lack of consideration of climate engineering impacts on biodiversity and ecosystems is due in part to the number, complexity, novelty, and large spatial and temporal scale of the potential effects. It is difficult or impossible to empirically test the effects of most of the techniques (Keith 2000; MacMynowski et al. 2011; Keller et al. 2014) and deciding on the most pressing research topic can be difficult. The issue can seem an overwhelming challenge for ecological science, causing research to respond slowly, and to follow, rather than inform policy decisions (Sutherland & Woodroof 2009). Climate engineering has already entered policy discussions (International Maritime Organization 2013; IPCC 2013; Secretariat of the Convention on Biological Diversity 2012) and, to date, although implementation is regulated, there is no comprehensive international agreement covering all climate engineering techniques (Rickels et al. 2011). It is therefore critical that research to understand potential ecological effects of climate engineering begins as soon as possible so that it can inform the development of ecologically-sensitive techniques and evidence-based policy decisions.

For this study, a process of literature review and expert consultation was used to review the potential biodiversity and ecosystem effects of climate engineering. We focus on the potential side-effects of implementing the techniques rather than the anticipated climate change amelioration effect as the former have received relatively little attention and the latter is a large and complex body of ongoing research beyond the scope of the current project. We identify key areas where climate engineering presents important questions that should be considered within existing priority ecological research efforts, as well as identifying a number of novel knowledge gaps. We suggest a list of research questions which we hope will encourage timely investigation of the potential ecological effects of climate engineering.

## 2. Materials and methods

'Horizon-scanning' involves the systematic assessment of emerging threats and opportunities, in order to identify key upcoming issues (Martin et al. 2012; Sutherland 2006; Sutherland et al. 2012; Sutherland & Woodroof 2009). In the current study, an adapted process called 'impact scanning' was used; impacts of climate engineering were identified from the literature and reviewed to prioritize those which are likely to have the greatest effects on biodiversity and ecosystems. The degree of scientific understanding about the effects was also evaluated, to identify critical knowledge gaps. An expert consultation process combining elements of the Nominal Group and Delphi techniques (Hutchings & Raine 2006) was used

(Figure 2 gives a summary). Participants gave verbal consent to take part in this exercise. We did not obtain formal written consent as all data and comments are kept anonymous and it was agreed from the outset that participants were to be authors of the resulting paper and approve its contents prior to publication.

*[INSERT FIGURE 2 NEAR HERE]*

### *2.1. Literature reviews*

A literature review was conducted to identify the potential biodiversity and ecosystem effects of climate engineering techniques. As the scope of the existing literature was uncertain, the recent reports of the Royal Society (2009) and the Secretariat to the Convention on Biological Diversity (2012) were used as a starting point. An approach based on snowball sampling (Biernacki & Waldork 1981) was used to identify further relevant literature from their citations, and then from the citations of these citations, and so on. Seventeen geoengineering techniques were included in the review (Figure 1) based on those discussed in prominent literature at the time (Rickels et al. 2011; The Royal Society 2009). Overall, the review found 154 environmental changes predicted to result from the techniques, each with a range of associated potential biodiversity and ecosystem effects (Supporting Information S1). Additional environmental changes were added by participating experts so that a total of 192 changes and their associated effects were assessed in total. The focus was on the side-effects of the implementation of the techniques, rather than the effects they would cause by counteracting climate change, which is beyond the scope of the current study. In a separate literature review, assessments of the technical feasibility and anticipated effectiveness of the techniques were identified using the same literature sampling technique as above, and used to shortlist five techniques about which research questions were formulated.

### *2.2. Scoring round 1: Survey*

The assessment was conducted by a working group of 34 senior academic scientists with expertise in biodiversity, ecosystems and environmental and climatic change. Participants were identified through internet searches and selected to ensure an even split between terrestrial and marine expertise, and a global scope;  the majority of experts were based at European institutions but there were also representatives from Canada, North America, Mexico and South Africa, and all had extensive knowledge of ecosystems beyond their institution's country.

Each participant first completed an Excel-based survey exercise. They read the report of the literature review of biodiversity and ecosystem effects of climate engineering (Supporting Information S1), and used the information to score a list of environmental changes for each of the techniques between 0 and 100, to reflect the relative importance of their potential effects on biodiversity and ecosystems. They added comments to explain their scores. Each climate engineering technique was considered separately. At the end of the survey, the participants compared their top prioritised environmental changes from each technique and scored them between 0 and 100. These values were used as 'swing weights' to calibrate the earlier scores, making them comparable across the techniques (Holt 1996). In a second Excel-based survey, participants used the literature review report in combination with their own experience and expertise to score the environmental changes between 0 and 100 to reflect the extent of scientific knowledge about their biodiversity and ecosystem effects. They also suggested priority research questions. Detailed guidelines and definitions were provided for both survey exercises to ensure that scores were comparable amongst participants. They were asked to assume deployment of the technique at a 'climatically-significant scale' (Lenton & Vaughan 2009; Williamson et al. 2012) and against a background of climate change causing a warming world with an acidifying ocean. SRM-induced climate changes were considered independently of the concurrent greenhouse gas-induced climate changes. Nevertheless, the biodiversity and ecosystem consequences identified are equally applicable when the two drivers are considered together.

### *2.3. Re-scoring*

A summary of the survey responses was sent to each expert for them to review ahead of a two day workshop in May 2013. At the workshop, participants shared reasons for their scores, and heard perspectives from others in the group. Parallel groups discussed a subset of the climate engineering techniques and their associated environmental changes and biodiversity and ecosystem effects. Following discussion, the experts then individually re-scored using the same 0-100 scale or kept their original score based on the discussion.

In a final session, the research questions suggested during the second survey were reviewed and refined.

### *2.4. Calculating an 'index of priority'*

A median was calculated from the group's final importance and scientific understanding scores (both using range of 0-100). This was used to calculate an 'index of priority' for each of the environmental changes across all of the climate engineering techniques, using the equation: (Importance score + (100 – Understanding score))*0.5.

The index of priority was used to rank the environmental changes; a change is of greater priority if it has more important potential effects on biodiversity and ecosystems and/or there is less understanding about its effects. A list of the top 20 changes across all of the techniques was identified form the results of this scoring.

### *2.5. Shortlisted techniques and research questions*

In parallel with assessing the impact of all changes we assessed how likely each technique was likely to occur. This then identifies the research priorities allowing for the likelihood of the different options being adopted. Five of the 17 climate engineering techniques were identified from a review of existing assessments (e.g. (Caldeira et al. 2013; Lenton & Vaughan 2009; The Royal Society 2009) as having relatively higher anticipated efficacy (potential climate change forcing when deployed at maximum scale) and technical feasibility (availability of materials, technology and knowledge to implement) than the other techniques (Table 1). This was taken to indicate that they are more plausible options for implementation, meaning that their potential effects are most pertinent to consider.

The index of priority was therefore used to identify two or three highest priority environmental changes associated with each of these five techniques. The expert group identified key knowledge gaps and research questions about the potential biodiversity and ecosystem effects, using the questions suggested during the survey as a starting point.

*[INSERT TABLE 1 NEAR HERE]*

## 3. Results and Discussion

### *3.1. Key themes for research – across all techniques*

The 'index of priority' was used to rank all of the environmental changes across all of the 17 climate engineering techniques. A full list of the median scores and index of priority values is given in Supporting Information S4. The top 20 (Table 2), and patterns within the rest of the ranked list, reveals interesting themes in the types of environmental changes that were judged by the expert group to have important biodiversity and ecosystem consequences but limited scientific understanding.

*(INSERT TABLE 2 NEAR HERE)*

#### *3.1.1. Climatic changes*

The top seven of the 20 prioritized environmental changes (Table 2) recognize the potentially substantial and complex biodiversity and ecosystem implications of global-scale alterations to climatic processes associated with solar radiation management 'dimming' techniques - sunshades, sulfate aerosols and enhanced marine cloud albedo. These techniques reduce incoming shortwave radiation to the earth, reducing global mean surface temperature, but causing regionally variable changes in climatic conditions (Caldeira et al. 2013), such as potential enhancement of increases or decreases in precipitation caused by climate change (Irvine et al. 2010; Kravitz, Robock, et al. 2013; Ricke et al. 2010). 'Novel' regional climatic states could occur (Irvine et al. 2010). The ecological effects of these are challenging to predict (Williams et al. 2007).

Changes to temperature and precipitation patterns were considered by the group to be highly important for biodiversity and ecosystems as they are strong determinants of species' life history, phenology, physiological performance, distribution and interactions (Cahill et al. 2013; Pörtner & Farrell 2008). A reduction in the equator-to-pole temperature gradient, for example, would shift species' climatic ranges (Couce et al. 2013), which would lead to altered ecological community assemblages and a change in the distribution of biomes (Burrows et al. 2011; Walther et al. 2002). Changes in the amplitude of seasonal temperature variation could strongly influence the timing of ecological processes such as migration, breeding, flowering and phytoplankton blooms (Edwards & Richardson 2004; Menzel et al. 2006; Sims et al. 2001). Both the climatic effects and the biodiversity impacts they cause are likely to be highly regionally variable, due to factors such as local microclimatic conditions (De Frenne et al. 2013), or circulation patterns in the marine environment, meaning there are large gaps in knowledge and understanding of the effects and a need for research.

Changes affecting precipitation and surface water availability were also prioritized; regionally variable changes to precipitation patterns, the slowing of the global hydrological cycle(Tilmes et al. 2013), and a potential reduction in continental rainfall associated with enhanced desert albedo (Irvine et al. 2011), were all included in the top 20 (Table 2). Water availability influences rates of primary productivity and the composition of plant communities that underpin terrestrial habitats (Cleland et al. 2013). Determining the trajectory of the ecological effects of changing precipitation patterns is subject to uncertainty due to differences in individual and species responses, which compound uncertainties over the likely direction and magnitude of the precipitation change (Hoffmann & Sgro 2011; Mustin et al. 2007). Paleoecological records of responses to past precipitation changes – for example, the 'greening' of the Sahara – can offer some indication of potential effects (e.g. Willis et al. 2013), as can ongoing research on effects of precipitation changes associated with climate change, but specific research needs to be conducted in the context of climate engineering scenarios.

### *3.1.2. Changes affecting marine ecosystems*

Many of the prioritized environmental changes are associated with ocean systems (Table 2). Already, anthropogenic emissions of $CO_2$ are causing ocean acidification due to increased dissolved inorganic carbon in ocean waters. Such chemical changes have potential impacts on the acid-base balance, metabolic energy allocation and calcification of marine organisms (Bopp et al. 2013; Kroeker et al. 2013). Solar radiation management techniques would not address atmospheric $CO_2$, so in the absence of additional actions to reduce greenhouse gas levels, concentrations will almost certainly increase relative to present day, which could lead to worsening acidification (Keller et al. 2014). However, there is uncertainty about the net effect; for the same emission rates, solar radiation management could lessen $CO_2$ rise in the atmosphere by causing enhanced terrestrial $CO_2$ uptake and by avoiding positive feedbacks (e.g. carbon release from thawing tundra, fire etc.; see Matthews et al. 2009). The net effect of SRM on ocean acidification could therefore be slightly beneficial compared to a non-SRM scenario. However, SRM will also reduce sea-surface temperatures, which affect $CO_2$ dissolution rates, ocean circulation and other poorly-understood feedback processes, so the overall effect is uncertain (Williamson & Turley 2012). The relationship between temperature and ocean acidification impacts on marine calcifiers, and ecosystems dependent on carbonate structures (e.g. coral reefs), is an area of active research (e.g. Anthony et al. 2011) but has so far received little attention in the climate engineering context. To date, only one study (Couce et al. 2013) has investigated these potential implications of SRM, and finds that moderate deployment could reduce degradation of global coral reef habitat compared to no SRM, according to model simulations.

SRM 'dimming' techniques will affect global ocean circulation through changes to the energy exchanges between the ocean and the atmosphere (McCusker et al. 2012). Light availability (partially determined by incoming solar irradiance), temperature, and nutrient patterns fundamentally determine marine ecological communities, and are responsible for diversity both between ocean strata and across latitudes. Changes to circulation will alter these factors, with the potential for biodiversity consequences throughout the entire marine system (Drinkwater et al. 2010; Hardman-Mountford et al. 2013). The group's scores indicate there is limited scientific understanding of the likely biodiversity and ecosystem effects, particularly as they will vary regionally (Secretariat of the Convention on Biological Diversity 2012). The group acknowledged that oceanic islands would be highly vulnerable to changes in ocean-atmosphere dynamics (e.g. Loope & Giambelluca 1998). These habitats often support a high concentration of endemic species and their populations are generally small and geographically isolated, restricting their ability to adapt. Novel impacts of climate engineering could also affect them, such as possible deposition of sea water used for enhanced cloud albedo; this could further reduce freshwater availability, which is often limited on islands (Meehl 1996).

Increased primary productivity in the surface ocean due to artificially enhanced fertilization is judged to be a highly important change across the CDR fertilization methods (Table 2). The phytoplankton communities that would be directly impacted underpin a significant proportion of ocean ecological communities and determine parameters such as light penetration, nutrient cycling, and the supply of organic material to benthic systems (Falkowski et al. 1998; Kirk 2011). Ocean fertilization could therefore have profound effects throughout marine ecosystems, particularly in currently low-productivity areas (Falkowski et al. 1998). 'Knock-on' trophic effects observed in open-ocean fisheries, whereby changes in one group of species has broad effects throughout the ecosystem (e.g. Bailey et al. 2009), would very likely occur. Effects are likely to be widely spread by global ocean circulation (Williamson et al. 2012). Although their effects are sometimes conflated in the climate engineering literature, we suggest that it is critical to distinguish iron fertilization in high nutrient low chlorophyll ocean regions from nitrogen or phosphorous fertilization in low nutrient low chlorophyll regions. Field trials of iron fertilization have shown varying impacts on phytoplankton communities and the marine ecosystem (Williamson et al. 2012) and a diversity of effects can also be anticipated to result from nitrogen or phosphorus fertilization (Lampitt et al. 2008). Increased productivity caused by enhanced upwelling/downwelling was judged to be less well understood and so was the highest prioritized; modeling suggests that intended effects of enhanced vertical mixing may be less strong than anticipated, will vary greatly from place to place, and may even be opposite from that desired (Dutreuil et al. 2009). The engineered structures required for enhanced upwelling were also judged to have important biodiversity and ecosystem implications, creating artificial reefs or acting as 'stepping stones' for species migration, distribution, and aggregation  (Mineur et al. 2012).

### *3.1.3. Changes affecting the deep ocean*

Environmental changes with effects in the deep ocean were repeatedly identified as priorities for further research by the group (Table 2). There is a general lack of knowledge about these environments(Costello et al. 2010) but fisheries research indicates that deep sea species are sensitive to disturbance and slow to recover (e.g. Devine et al. 2006). It is therefore likely that effects of climate engineering techniques on the deep sea would be long-lasting. Large-scale coverage of the deep-ocean seabed, associated with the technique biomass storage in the ocean (Table 1), would be a significant alteration of relatively undisturbed habitats. Reduced oxygen and enhanced nutrient levels due to decaying organic matter could impact species richness, physiological processes and community composition (Lampitt et al. 2008; Levin et al. 2001). There is a need to increase fundamental understanding of these environments before deployment of any climate engineering technique that might impact them.

### *3.1.4. Large-scale terrestrial habitat disturbance or destruction*

Large-scale disturbance of terrestrial habitats was a topic prioritized by the group, and could result from a number of climate engineering techniques (Supporting Information S1).

Although the effects of such habitat change are considered to be relatively well understood (Table 2), the anticipated scale associated with climate engineering on a 'climatically significant' scale is considerable and would be additional to current processes. Specifically, the replacement of (semi-)natural grassland and shrubland, or forest habitats, with reflective plants to increase surface albedo for SRM was included in the 20 priority changes (Table 2). This conversion of existing habitat constitutes complete habitat loss for inhabitant species (Secretariat of the Convention on Biological Diversity, 2012). Detrimental effects could be reduced by limiting planting to degraded land (e.g. Tilman et al. 2009). However, the area required in order for the technique to impact the global climate would inevitably exceed this resulting in conversion of natural or semi-natural habitats (see Lenton & Vaughan 2009; Tilman et al. 2009).

Alteration or loss of desert habitats through coverage with manmade reflective materials (an SRM technique) is also included within the 20 prioritized changes (Table 2). It is estimated that to offset the warming from a doubling of atmospheric $CO_2$ concentrations, an area of approximately 12 million square kilometers – roughly 1.2 times the area of the Saharan desert – would need to be covered (Lenton & Vaughan 2009; Vaughan & Lenton 2011). Although considered to have low biodiversity, desert regions contain many endemic species that are highly adapted to the local conditions. They are likely to be significantly affected by a long-term increase in shading and change in regional temperatures caused by man-made structures (Stahlschmidt et al. 2011). Alteration of the habitats may allow other species to become established in desert regions, leading to changes in the unique ecological community composition (Steidl et al. 2013).

#### *3.1.5. Alteration of soil properties*

Another essential area for research was the impact of climate engineering on soils. Specifically, changes in soil properties due to the addition of powdered alkali rocks for enhanced weathering (a CDR technique) was included in the top 20 (Table 2). This would cause a fundamental alteration of biogeochemical properties of the soil (pH, structure, etc.) with the potential to reduce soil biodiversity and disrupt the activity of the soil organisms that underpin overlying ecological communities (Jensen et al. 2003). An associated increase in the availability of nutrients could also feedback to alter the composition and productivity of plant communities (Dawson et al. 2012). The overall combined effects of changes to interdependent abiotic soil properties —such as temperature, physical structure and biogeochemistry — are difficult to predict (Davidson et al. 1998) and understanding of soil dynamics and biota, and their interactions with above-ground systems, requires more research (De Deyn & van der Putten 2005). Similar concerns were raised in relation to the application of biochar to soil as a means to increase carbon sequestration (another CDR technique), as the effects of this technique on soil biodiversity are poorly understood (Lehmann et al. 2011).

### ***3.2. Priority areas for research***

Five climate engineering techniques (Table 1) were found in existing assessments to have higher anticipated technical feasibility and efficacy than other techniques (e.g. The Royal Society, 2009; Vaughan and Lenton, 2011). Of the solar radiation management techniques, stratospheric sulfate aerosols and enhanced marine cloud albedo are relatively well-studied through model simulations and inter-comparisons, and both anticipated to have high potential effectiveness in counteracting climate change (Kravitz *et al.*, 2013b). Of the carbon dioxide removal techniques, bioenergy with carbon capture and storage (BECCS) uses techniques that are already well developed (International Energy Agency, 2011) and has good carbon sequestration potential (Caldeira *et al.*, 2013). It is also included in mitigation scenarios in the recent IPCC Fifth Assessment report (van Vuuren et al., 2011; IPCC, 2014). Ocean fertilization with iron is receiving ongoing commercial interest and field trials demonstrate that it is possible, even if its ability to absorb and store atmospheric carbon dioxide over the long-term appears to be low (Strong et al. 2009; Williamson et al. 2012). Direct air capture (DAC) was also found to be pertinent to consider as there is ongoing research and development of potential technology designs (e.g. Choi 2011).

For each of these techniques, the index of priority was used to identify the highest priority environmental changes that they could cause if implemented. For each change, the expert group identified key knowledge gaps and research questions about its biodiversity and ecosystem effects, detailed in Table 3.

*[INSERT TABLE 3 NEAR HERE – UNLESS INCLUDING AS AN APPENDIX INSTEAD]*

### *3.2.1. Reinforcing current research priorities*

Many of the questions are relevant to existing research priorities in ecological science, but climate engineering presents an important and unique context for investigation. For example, ‘What are the rates of warming that species can tolerate by means of adaptation or migration…?’ (Table 3) is a key area of research in relation to climate change (e.g. (Peck et al. 2014; Quintero & Wiens 2013; Schloss 2012). It is also critical to consider within the context of climate engineering. Atmospheric and stratospheric solar radiation management (‘dimming’) techniques will cause global-scale reduction in incoming radiation leading to stabilized or reduced rates of warming. Abrupt termination of the techniques would be expected to cause a rapid rise in global mean temperatures - the ‘termination effect’ - unless additional actions had been used in the interim to reduce atmospheric $CO_2$ (Jones et al. 2013; Matthews & Caldeira 2007). Some of the ecological impacts of the ‘termination effect’ can be anticipated from ongoing research into the effects of ongoing climate change which indicates that warming could alter species distributions, migration patterns, breeding etc. (Cotton 2003; Hurlbert 2012). However, the rate of temperature increase associated with the termination effect is likely to be much more rapid. Rates of change could exceed the ability of many species to adapt or migrate (Bellard et al. 2012; Cahill et al. 2013; Quintero & Wiens 2013) which could lead to local extinctions and substantial changes in community assemblages (Willis et al. 2010). Palaeoecological records suggest that global biodiversity showed resilience to similar rapid temperature changes during the last glacial-interglacial transition (Willis et al. 2010), but modern pressures including habitat fragmentation and degradation may now limit the capacity of species to track changes. Overall, there still remain large uncertainties about the exact nature of the ecological impacts of global temperature rises and scientific understanding of the biodiversity and ecosystem effects of the termination effect was judged by the group to be low (Table 3).

Similarly, several of the research questions identified in relation to bioenergy with carbon capture and storage (BECCS) (Table 3) are existing priority topics of research in relation to biofuels for energy (Fletcher 2011; Gove et al. 2010; Wiens et al. 2011). Overall, the effects of biomass production was considered to be well understood compared to other environmental changes assessed (scores in Supporting Information S4). However, the significant scale of production required for BECCS as a climate engineering technique represents a significant additional demand for feedstocks, reinforcing the importance of research effort on the ecological effects of such production.

### *3.2.2. Novel research areas*

Other environmental changes predicted to be caused by climate engineering create relatively novel conditions compared both to conditions observed in the past, and to projected trajectories of ongoing climate and environmental change. The ecological effects of these changes are relatively less well understood. For example, reduced incoming solar radiation caused by atmospheric and stratospheric solar radiation management techniques will lead to reduced rates of global warming. However, in the absence of measures to address greenhouse gas emissions, atmospheric $CO_2$ levels would remain high. This high $CO_2$, low temperature climate differs from both current conditions and the high temperature, high $CO_2$ conditions projected under future emissions scenarios (Secretariat of the Convention on Biological Diversity 2012) and represents a relatively novel global climate compared to current, historical or paleo-historical conditions (Tilmes et al. 2013; Williams et al. 2007). Temperature and $CO_2$ control fundamental ecological processes and the relative influence of the two parameters is highly complex (Long et al. 2004). Climate and vegetation models suggest that elevated $CO_2$ would be the dominant influence and could reduce water stress of plants leading to enhanced terrestrial primary productivity in almost all regions(Donohue et al. 2013; Long et al. 2004; Wiens et al. 2011), but there is a large degree of uncertainty in these projections (Jones et al. 2013; Kravitz, Caldeira, et al. 2013). Individual species, functional groups and biomes will also vary in their response to temperature and $CO_2$ levels(De Frenne et al. 2013; Higgins & Scheiter 2012). The potential to predict these effects is currently limited by factors including the low-resolution representation of ecological interactions in integrated global scale models (Mustin et al. 2007; Ostle & Ward 2012). Scientific understanding of the effects was judged to be low (see Supporting Information S4).

Even when environmental changes have historical natural proxies, there often remain knowledge gaps about their biodiversity and ecosystem effects. For example, implications of increased primary productivity in high nutrient low chlorophyll ocean regions with iron fertilization can be anticipated to some extent from observations of natural fertilization from deep water upwelling (Blain et al. 2007) or deposition of air borne dust (Martinez-Garcia et al. 2014). However, the complexity of ocean systems and possible feedbacks mean that certainty about the ecological effects remains low, reflected in the expert group scientific understanding score (Table 3). Questions like ‘What ecosystem effects might occur beyond the fertilization zone…?’ would require dedicated investigation should this climate engineering technique be implemented.

The suggested research questions (Table 3) demonstrate critical knowledge gaps about ecological effects of climate engineering, which will need to be addressed if the techniques are pursued. Many relate to topics already recognized by the ecological research community as priority knowledge gaps, but in the climate engineering context, may require investigation over different scales, timeframes and locations. Others relate to novel conditions that could be created by climate engineering, which raise new questions about potential biodiversity and ecosystem impacts.

### *3.3. Concluding remarks*

#### *3.3.1. Inclusion of biodiversity and ecosystem effects in climate engineering research and decision making*

In the discussion about climate engineering to date, potential biodiversity and ecosystem impacts of the techniques have received little attention and there has been very limited work by the ecological research community on this topic. We believe it has thus far been challenging to identify discrete research questions due to the scale, number, range and complexity of potential biodiversity and ecosystem effects. In addition, there is perhaps reluctance to engage with climate engineering, given that it involves large-scale manipulation of the earth system and is viewed by some as a distraction from reducing greenhouse-gas emissions.

In an effort to encourage timely research into the biodiversity and ecosystem impacts of climate engineering, we have reviewed a comprehensive range of potential effects and made a critical first attempt to prioritize them based on assessment of the importance of their biodiversity and ecosystem effects and the degree of scientific understanding about them. In doing so, we have identified some key knowledge gaps and questions. Some of these fit within research priorities already identified by ecological science, but climate engineering presents a novel application and extension of the investigations and reinforces the need to investigate these topics further. Others relate to conditions potentially created by climate engineering that differ from past conditions and from those projected under underlying climate and environmental change.

Discussions – and decisions – on the governance of climate engineering are already occurring, e.g. recent amendments to the London Protocol (International Maritime Organization 2013; Schafer et al. 2013). For sound policy decisions to be made, it is critical that they are based on good scientific understanding. We hope our identification of key knowledge gaps and suggested research questions will act as a platform for more detailed consideration of the ecological implications of climate engineering from now on, both from the ecological research community, and from those working on climate engineering and related policy.

#### *3.3.2. Expert consultation and uncertainty*

Expert elicitation can help enhance limited information available from scientific study (Martin et al. 2012). It is useful in the case of climate engineering as empirical studies of the techniques are logistically difficult or impossible to conduct at the scales necessary (Secretariat of the Convention on Biological Diversity 2012). Extrapolation from analogous natural processes (for example, global dimming caused by volcanic eruptions;  Robock et al. 2013) and climate envelope modeling (Couce et al. 2013) can inform expectations of future scenarios to some extent (Robock et al. 2013), but are less effective when conditions will be novel relative to the past (Sutherland 2006).

The expert group used their collective knowledge to interpret avialble information to identify which biodiversity and ecosystem effects of climate engineering from a long and diverse list are important to investigate further. They acknowledged complexities of the potential ecological effects of climate engineering not previously acknowledged in the climate engineering literature. For example, the importance of distinguishing the effects of ocean fertilization with iron from those associated with nitrogen or phosphorus, and the need to particularly consider vulnerability of island biodiversity.

Inevitably, there are sources of uncertainty and variability inherent in expert consultation. Our outcomes may have been different with a different group of experts due to varying knowledge and opinion on the ecological impacts being discussed. Outcomes also depend very much on how the issues are framed, such as the context in which climate engineering is considered. For example, whilst it was specified that the working group should consider the effects against a background of a warming world with an acidifying ocean, it was left up to the individual to interpret whether that should be a ‘business as usual’ scenario or one with low, medium or high global mitigation effort. As noted in the introduction, we also did not consider the effects of the overall climate amelioration that would occur if climate engineering were effective, which would also have considerable biodiversity and ecosystem effects, including some likely benefits.

There are also many uncertainties related to climate engineering that make anticipating biodiversity and ecosystem effects challenging. Most technologies are in the early stages of design and it is difficult to predict how they might evolve. The location, timing and scale of any future deployment of such techniques are all theoretical (Keith 2000), making it difficult to identify the specific circumstances under which the environmental changes would occur (Russell et al. 2012; The Royal Society 2009). This significant topic of ongoing research should occur in parallel with attempts to project biodiversity and ecosystem effects of climate engineering. Biodiversity experts and climate engineering impact modelers should collaborate in order to produce reasonable scenarios of deployment (Carey & Burgman 2008) (and see Cusack et al. 2014).

## 4. Conclusion

Any climate engineering technique designed to alter the global climate will have significant implications for biodiversity and ecosystems. This study makes a first attempt to identify effects related to currently-discussed techniques that are priorities for detailed investigation.

The outcomes  should be considered for what it is: an assessment by a group of experienced researchers based on currently available information. It is not an evaluation of the relative benefits or risks of climate engineering. It is a scoping of knowledge gaps and research priorities related to the biodiversity and ecosystem effects of implementing the techniques. The major themes identified show the types of ecological impacts that are particularly critical to consider, and highlight both important overlaps with existing research priorities and knowledge gaps that require new research focus. If interest in climate engineering continues, biodiversity and ecosystem consequences must be comprehensively considered so that unintended consequences are avoided and any potential co-benefits are realized. Further horizon scanning and expert consultation processes similar to those used here could be valuable in identifying emerging issues.

## Acknowledgements

This work was funded by the Institute for Advanced Sustainability Studies, who we thank for their efficient organization and hospitality for the workshop. We also thank the various experts who completed the survey but could not attend the workshop: Tom Battin, Richard T. Conant, Jason Hall-Spencer, Sandra Lavorel and Klaus Lorenz. We are also grateful to the Cambridge Conservation Initiative (CCI) Shared Challenges Programme who funded the initial literature review, and to Rosamunde Almond (CCI) who was involved in the conception of the project. WJS is funded by Arcadia

## Figure legends

**Figure 1**. **Schematic of climate engineering techniques considered in this review, covering Carbon Dioxide Removal (CDR) techniques and Solar Radiation Management (SRM) techniques**

**Figure 2. Flow diagram of study methodology.**

## Supporting information captions

**Supporting Information S1. Report of literature review to identify environmental changes and potential biodiversity and ecosystem effects caused by currently discussed climate engineering techniques**. This provides an extensive list of potential ecological effects of climate engineering, supported by references where available. Although extensive, it cannot detail every possible effect of climate engineering, as this is far beyond its scope.

**Supporting Information S2. Summary of the survey guidelines provided to members of the working group when completing the initial scoring exercise.**

**Supporting Information S3.** Description of process used to adjust scores to remove potentially influential scorer bias.

**Supporting Information S4.** Table of the full list of environmental changes from all climate engineering techniques assessed, with median importance and scientific understanding scores and index of priority values.

**Authors and contributors:** RS and SS conducted the initial literature review of climate engineering effects, with subsequent input from CGM, WB and PI. CGM and WJS designed the study process and delivered the workshop along with WB, PI and JJB. JJB contributed significantly to the literature review of the technical feasibility of climate engineering techniques. All other authors (except TA) completed the survey scoring task and attended the workshop. TA analyzed the output data. CM wrote the first draft of the manuscript, and all authors contributed substantially to revisions. WJS, WB and PI in particular made significant contributions to the direction and content of the manuscript.

## References


Anthony, KRN, A. Kleypas, J, & Gattuso, J-P. 2011. Coral reefs modify their seawater carbon chemistry – implications for impacts of ocean acidification. Glob Change Biol, 17: 3655-3666. doi: 10.1111/j.1365-2486.2011.02510.x

Bailey, DM, Collins, MA, Gordon, JDM, Zuur, AF, & Priede, IA. 2009. Long-term changes in deep-water fish populations in the northeast Atlantic: a deeper reaching effect of fisheries? Proc R Soc B, 276: 1965-1969.

Bellard, C, Bertelsmeier, C, Leadley, P, Thuiller, W, & Courchamp, F. 2012. Impacts of climate change on the future of biodiversity. Ecol Lett, 15: 365-377.

Biernacki, P & Waldorf, D. 1981. Snowaball Sampling: problems and techniques of chain referral sampling. Socio Meth Res. 10: 141 -153.

Blain, S, Queguiner, B, Armand, L, Belviso, S, Bombled, B, Bopp, L, Bowie, A, Brunet, C, Brussaard, C, Carlotti, F, et al. 2007. Effect of natural iron fertilization on carbon sequestration in the Southern Ocean. Nature, 446: 1070-1074. doi: http://www.nature.com/nature/journal/v446/n7139/suppinfo/nature05700_S1.html

Bopp, L, Resplandy, L, Orr, JC, Doney, SC, Dunne, JP, Gehlen, M, Halloran, P, Heinze, C, Ilyina, T, Séférian, R, et al. 2013. Multiple stressors of ocean ecosystems in the 21st century: projections with CMIP5 models. Biogeosciences, 10: 6225-6245. doi: 10.5194/bg-10-6225-2013

Burrows, MT, Schoeman, DS, Buckley, LB, Moore, P, Poloczanska, ES, Brander, KL, Brown, C, Bruno, JF, Duarte, CM, Halpern, BSH, J., Kappel, CV, Kiessling, W, O'Connor, MI, Pandolfi, JM, Parmesan, C, Schwing, FB, Sydeman, W.J. & Richardson, A.J. 2011. The Pace of Shifting Climate in Marine and Terrestrial Ecosystems. Science, 334.

Cahill, AE, Aiello-Lammens, ME, Fisher-Reid, MC, Hua, X, Karanewsky, CJ, Ryu, HY, Sbeglia, GC, Spagnolo, F, Waldron, JB, Warsi, O, & Wiens, JJ. 2013. How does climate change cause extinction? Proc R Soc B, 280.

Caldeira, K, Govindasamy, B, & Cao, L. 2013. The Science of Geoengineering. Annu Rev Earth Planet Sci, 41: 231-256.

Carey, JM, & Burgman, MA. 2008. Linguistic Uncertainty in Qualatative Risk Analysis and How to Minimize It. Ann NY Acad Sci, 1128: 13-17.

Chen, IC, Hill, JK, Ohlemuller, R, Roy, DB, & Thomas, CD. 2011. Rapid range shifts of species associated with high levels of climate warming. Science, 333: 1024-1026.

Choi, S, Drese, JH, Eisenberger, PM, and Jones, CW. 2011. Application of Amine-Tethered solid sorbents for direct $CO_2$ capture from the ambient air. Environ Sci Tech, 45: 2420-2427.

Cleland, EE, Collins, SL, Dickson, TL, Farrer, EC, Gross, KL, Gherardi, LA, Hallett, LM, Hobbs, RJ, Hsu, JS, Turnbull, L, & Suding, KN. 2013. Sensitivity of grassland plant community composition to spatial vs. temporal variation in precipitation. Ecology, 94: 1687-1696. doi: 10.1890/12-1006.1

Costello, MJ, Coll, M, Danovaro, R, Halpin, P, Ojaveer, H, & Miloslavich, P. 2010. A Census of Marine Biodiversity Knowledge, Resources, and Future Challenges. PLoS ONE, 5: e12110. doi: 10.1371/journal.pone.0012110

Cotton, PA. 2003. Avian migration phenology and global climate change. PNAS, 100: 12219-12222.

Couce, E, Irvine, PJ, Gregorie, LJ, Ridgwell, A & Hendy, EJ. 2013. Tropical coral reef habitat in a geoengineered, high-$CO_2$ world. Geophys Res Lett, 40: 1799-1805. doi: 10.1002/grl.50340

Cusack, DF, Axsen, J, Shwom, R, Hartzell-Nichols, L, White, S, & Mackey, KRM. 2014. An interdisciplinary assessment of climate engineering strategies. Front Ecol Environ, 12: 280-287. doi: 10.1890/130030

Davidson, EA, Belk, E, & Boone, RD. 1998. Soil water content and temperature as independent or confounded factors controlling soil respiration in a temperate mixed hardwood forest. Glob Change Biol, 4: 217 - 227.

Dawson, W, Fischer, M, & van Kleunen, M. 2012. Common and rare plant species respond differently to fertilisation and competition, whether they are alien or native. Ecol Lett, 15: 873-880.

De Deyn, GB, & van der Putten, W. 2005. Linking aboveground and belowground diversity. TREE, 20.

De Frenne, P, Rodríguez-Sánchez, F, Coomes, DA, Baeten, L, Verstraeten, G, Vellend, M, Bernhardt-Römermann, M, Brown, CD, Brunet, J, Cornelis, J, et al. 2013. Microclimate moderates plant responses to macroclimate warming. PNAS, 110: 18561-18565. doi: 10.1073/pnas.1311190110

Devine, JA, Baker, KD, & Haedrich, RL. 2006. Fisheries: Deep-sea fishes qualify as endangered. Nature, 439: 29.

Donohue, RJ, Roderick, MJM, T.R., & Farquhar, GD. 2013. Impact of $CO_2$ fertilization on maximum foliage cover across the globe's warm, dry environments. Geophys Res Lett 40: 3031-3035.

Drinkwater, K, Hunt, G, Lehodey, P, Lluch-Cota, S, Murphy, EJ, Sakuri, Y, Schwing, F, Beaugrand, G & Svein, S. 2010. Climate forcing on marine ecosystems. In M. Barange, J. G. Field, R. P. Harris, E. E. Hofmann, I. Perry & F. Werner (M. Barange, J. G. Field, R. P. Harris, E. E. Hofmann, I. Perry & F. Werner(M. Barange, J. G.

Field, R. P. Harris, E. E. Hofmann, I. Perry & F. Werners.), Marine Ecosystems and Global Change: Oxford Scholarship Online.

Dutreuil, S, Bopp, L, & Tagliabue, A. 2009. Impact of enhanced vertical mixing on marine biogeochemistry: lessons for geo-engineering and natural variability. Biogeosciences, 6: 901-912. doi: 10.5194/bg-6-901-2009

Edwards, M, & Richardson, AJ. 2004. Impact of climate change on marine pelagic phenology and trophic mismatch. [10.1038/nature02808]. Nature, 430: 881-884. doi: http://www.nature.com/nature/journal/v430/n7002/suppinfo/nature02808_S1.html

Falkowski, P, Barber, RT, & Smetacek, V. 1998. Biogeochemical Controls and Feedbacks on Ocean Primary Productivity. Science, 281: 200-206.

Fletcher, RJ, Robertson, BA, Evans, J, Doran, PJ, Alavalapati, JRR, & Schemske, DW. 2011. Biodiversity conservation in the era of biofuels: risks and opportunities. Front Ecol Environ, 9: 161-168.

Foster, J, Cooper, G, & Galbraith, L. 2013. Patent application: Salt water spray systems for cloud brightening droplets and nano-particle generation. US patent application PCT/US2013/020589. Washington, DC: U.S. Patent and Trademark Office

Gove, B, Flower, KA, & Bradbury, RB. 2010. A review of environmental consequences of biomass production for UK energy consumption. Sandy, Bedfordshire: RSPB.

Hardman-Mountford, NJ, Polimene, L, Hirata, T, Brewin, RJ, & Aiken, J. 2013. Impacts of light shading and nutrient enrichment geoengineering approaches on the productivity of a stratified, oligotrophic ocean ecosystem. J R Soc Interface, 10: 20130701.

Hartmann, J, West, AJ, Renforth, P, Kohler, P, De la Rocha, CL, Wolf-Gladrow, DA, Durr, HH, & Scheffran, J. 2013. Enhanced chemical weathering as a geoengineering strategy to reduce atmospheric carbon dioxide, supply nutrients, and mitigate ocean acidification. Rev Geophys, 51: 113-149.

Higgins, SI, & Scheiter, S. 2012. Atmospheric $CO_2$ forces abrupt vegetation shifts locally, but not globally. Nature, 488: 209-212.

Hoffmann, AA, & Sgro, CM. 2011. Climate change and evolutionary adaptation. Nature, 470: 479 - 485.

Holt, J. 1996. Balancing task allocation in teams. In: Robertson, S, editor Contemporary Ergonomics. London: Taylor and Francis, p351.

Hurlbert, AHL, Z. 2012. Spatiotemporal Variation in Avian Migration Phenology: Citizen Science Reveals Effects of Climate Change. PLoS ONE, 7.

Hutchings, A, & Raine, R. 2006. A systematic review of factors affecting the judgements produced by formal consensus development methods in health care. J Health Serv Res Policy, 11: 172-179.

International Energy Agency. (2013). Redrawing the Energy-Climate Map: World Energy Outlook Special Report. Paris: International Energy Agency.

International Maritime Organization. (2013). Marine geoengineering including ocean fertilization to be regulated under amendments to international treaty  Retrieved 7th November, 2013, from http://www.imo.org/MediaCentre/PressBriefings/Pages/45-marine-geoengieneering.aspx

IPCC. 2005. IPCC Special Report on Carbon Dioxide Capture and Storage. In B. Metz, Davidson, O., de Coninck, H., Loos, M., Meyer, L. (Ed.). Cambridge: Cambridge University Press.

IPCC. 2013. Working Group I Contribution to the IPCC Fifth Assessment Report Climate Change 2013: The Physical Science Basis Summary for Policymakers. Cambridge, UK: Cambridge University Press.

Irvine, PJ, Ridgwell, A, & Lunt, DJ. 2010. Assessing the regional disparities in geoengineering impacts. Geophys Res Lett, 37: L18702. doi: doi:10.1029/2010GL044447

Irvine, PJ, Ridgwell, A, & Lunt, DJ. 2011. Climatic impacts of surface albedo geoengineering. J Geophys Res, 116: D24112. doi: doi:10.1029/2011JD016281

Jensen, KD, Beier, C, Michelsen, A, & Emmett, BA. 2003. Effects of experimental drought on microbial processes in two temperate heathlands at contrasting water conditions. Applied Soil Ecology, 24: 165-176. doi: http://dx.doi.org/10.1016/S0929-1393(03)00091-X

Jones, A, Haywood, JM, Alterskjær, K, Boucher, O, Cole, JNS, Curry, CL, Irvine, PJ, Ji, D, Kravitz, B, Egill Kristjánsson, J, et al. 2013. The impact of abrupt suspension of solar radiation management (termination effect) in experiment G2 of the Geoengineering Model Intercomparison Project (GeoMIP). J Geophys Res: Atmospheres, 118: 9743-9752. doi: 10.1002/jgrd.50762

Keith, DW. 2000. Geoengineering the Climate: History and Prospect. Ann Rev Energy Env, 25: 245-284.

Keller, DP, Feng, EY, & Oschlies, A. 2014. Potential climate engineering effectiveness and side effects during a high carbon dioxide-emission scenario.Nat Commun, 5. doi: 10.1038/ncomms4304

Kirk, JTO. 2011. Light and photosynthesis in aquatic ecosystems (3rd ed.). Cambridge: Cambridge University Press.

Kravitz, B, Caldeira, K, Boucher, O, Robock, A, Rasch, PJ, Alterskjær, K, Karam, DB, Cole, JNS, Curry, CL, Haywood, JM, et al. 2013. Climate model response from the Geoengineering Model Intercomparison Project (GeoMIP). J Geophys Res: Atmospheres, 118: 8320-8332. doi: 10.1002/jgrd.50646

Kravitz, B, Robock, A, & Irvine, P. 2013. Robust Results From Climate Model Simulations of Geoengineering. Eos, Trans Amer Geophy Union, 94: 292-292. doi: 10.1002/2013eo330005

Kroeker, KJ, Kordas, RL, Crim, R, Hendriks, IE, Ramajo, L, Singh, GS, Duarte, CM, & Gattuso, J-P. 2013. Impacts of ocean acidification on marine organisms: quantifying sensitivities and interaction with warming. Glob Change Biol, 19: 1884-1896. doi: 10.1111/gcb.12179

Lampitt, RS, Achterberg, EP, Anderson, TR, Hughes, JA, Iglesias-Rodriguez, MD, Kelly-Gerreyn, BA, Lucas, M, Popova, EE, Sanders, R, Shepherd, JG, et al. 2008. Ocean fertilization: a potential means of geoengineering? Philos Trans R Soc A, 366: 3919–3945.

Latham, J, Bower, K, Choularton, T, Coe, H, Connolly, P, Cooper, G, Craft, T, Foster, J, Gadian, A, & Galbraith, L. 2012. Marine cloud brightening. Philos Trans R Soc A, 370: 4217-4262.

Lehmann, J, Rillig, MC, Thies, J, Masiello, CA, Hockaday, WC, & Crowley, D. 2011. Biochar effects on soil biota - a review. Soil Biol Biochem, 43: 1812-1836.

Lenton, TM, & Vaughan, NE. 2009. The radiative forcing potential of different climate geoengineering options. Atmos Chem Phys, 9: 5539–5561.

Levin, LA, Etter, RJ, Rex, MA, Gooday, AJ, Smith, CR, Pineda, J, Stuart, CT, Hessler, RR, & Pawson, D. 2001. Environmental influences on regional deep-sea species diversity. Annu Rev Ecol Syst, 32: 51–93.

Long, SP, Ainsworth, AE, Rogers, A, & Ort, DR. 2004. Rising atmospheric carbon dioxide: Plants FACE the future. Annu Rev Plant Biol, 55.

Loope, L, & Giambelluca, T. 1998. Vulnerability of Island Tropical Montane Cloud Forests to Climate Change, with Special Reference to East Maui, Hawaii. Clim Chang, 39: 503-517. doi: 10.1023/a:1005372118420

MacMynowski, DG, Keith, DW, Caldeira, K, & Shin, H-J. 2011. Can we test geoengineering? Energy Env Sci, 4: 5044-5052.

Martin, TG, Burgman, MA, Fidler, F, Kuhnert, PM, Low-Choy, S, McBride, M, & Mengersen, K. 2012. Eliciting Expert Knowledge in Conservation Science. Cons Biol, 26: 29-38. doi: 10.1111/j.1523-1739.2011.01806.x

Martinez-Garcia, A, Sigman, DM, Ren, H., Anderson, R.F., Straub, M., Hodell, D.A., Jaccard, S.L., Eglinton, T.I., and Haug, G.H. 2014. Iron fertilization of the Subantarctic Ocean during the last ice age. Science, 6177: 1347-1350.

Matthews, HD, & Caldeira, K. 2007. Transient climate-carbon simulations of planetary geoengineering. PNAS, 104: 9949–9954.

Matthews, HD, Cao, L, & Caldeira, K. 2009. Sensitivity of ocean acidification to geoengineered climate stabilisation. Geophys Res Lett, 36.

Matthews, S, O'Connor, R, & Plantinga, AJ. 2002. Quantifying the impacts on biodiversity of policies for carbon sequestration in forests. Ecol Econ, 40: 71-87. doi: http://dx.doi.org/10.1016/S0921-8009(01)00269-5

McCusker, K, Battisti, DS, & Bitz, CM. 2012. The climate response to stratospheric sulfate injections and implications for addressing climate emergencies. J Clim, 25.

Meehl, GA. 1996. Vulnerability of freshwater resources to climate change in the tropical pacific region. Water Air Soil Pollut, 92: 203-213. doi: 10.1007/bf00175566

Menzel, A, Sparks, TH, Estrella, N, Koch, E, Aasa, A, Ahas, R, Alm-KÜBler, K, Bissolli, P, BraslavskÁ, OG, Briede, A, et al. 2006. European phenological response to climate change matches the warming pattern. Glob Change Biol, 12: 1969-1976. doi: 10.1111/j.1365-2486.2006.01193.x

Mineur, F, Cook, E, Minchin, D, Bohn, K, Macleod, A, & Maggs, C. 2012. Changing coasts: marine aliens and artificial structures. Oceanogr Mar Biol, 50: 189-234

Mustin, K, Sutherland, WJ, & Gill, JA. 2007. The complexity of predicting climate-induced ecological impacts. Clim Res, 35: 165-175. doi: 10.3354/cr00723

Ostle, N, & Ward, S. 2012. Climate change and soil biotic carbon cycling Soil Ecology and Ecosystem Services. (pp. 241-255). Oxford: Oxford University Press.

Peck, LS, Morley, SA, & Richard, JC, M.S. 2014. Acclimation and thermal tolerance in Antarctic marine ectotherms. J Exp Biol, 217: 16-22.

Peters, GP, Marland, G, Le Quéré, C, Boden, T, Canadell, JG, & Raupach, MR. 2012. Rapid growth in $CO_2$ emissions after the 2008-2009 global financial crisis. Nat Clim Chang, 2 2–4. doi: doi. 10.1038/nclimate1332

Pörtner, HO, & Farrell, AP. 2008. Physiology and Climate Change. Science, 322: 690-692.

Quintero, I, & Wiens, JJ. 2013. Rates of projected climate change dramatically exceed past rates of climatic niche evolution among vertebrate species. Ecol Lett, 16: 1095-1103.

Ricke, K, Morgan, G, & Allen, M. 2010. Regional climate response to solar-radiation management. Nat Geosci, 3: 537-541.

Rickels, W, Klepper, G, Dovern, J, Betz, G, Brachatzek, N, Cacean, S, Gussow, K, Heintzenberg, J, Hiller, S, Hoose, C, et al. (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: Kiel Earth Institute.

Robock, A, MacMartin, D, Duren, R, & Christensen, M. 2013. Studying geoengineering with natural and anthropogenic analogs. Clim Chang, 121: 445-458. doi: 10.1007/s10584-013-0777-5

Russell, LM, Rasch, PJ, Mace, GM, Jackson, RB, Shepherd, J, Liss, P, Leinen, M, Schimel, D, Vaughan, NE, Janetos, AC, et al. 2012. Ecosystem impacts of geoengineering: A review for developing a science plan. Ambio: DOI 10.1007/s13280-13012-10258-13285.

Schafer, S, Irvine, PJ, Hubert, A-M, Reichwein, D, Low, S, Stelzer, H, Maas, A, & Lawrence, MG. 2013. Field tests of solar climate engineering. Nature Clim Chang, 3: 766-766. doi: 10.1038/nclimate1987

Schloss, CA, Nunez, TA & Lawler, JJ. 2012. Dispersal will limit ability of mammals to track climate change in the Western Hemisphere. PNAS. doi: 101073/pnas1116791109

Secretariat of the Convention on Biological Diversity. 2012. Geoengineering in relation to the Convention on Biological Diversity: Technical and Regulatory Matters. CBD Technical Series No 66. (pp. 152). Montreal.

Sims, DW, Genner, MJ, Southward, AJ, & Hawkins, SJ. 2001. Timing of squid migration reflects North Atlantic climate variability. Proc R Soc B, 268: 2067-2611.

Singarayer, JS, Ridgwell, A, & Irvine, PJ. 2009. Assessing the benefits of crop albedo bio-geoengineering. Env Res Lett, 4.

Stahlschmidt, ZR, DeNardo, DF, Holland, JN, Kotler, BP, & Kruse-Peeples, M. 2011. Tolerance mechanisms in North American deserts: Biological and societal approaches to climate change. J Arid Environ, 75: 681-687.

Steidl, RJ, Litt, AR, & Matter, WJ. 2013. Effects of plant invasions on wildlife in desert grasslands. Wildlife Soc B, 37: 527-536. doi: 10.1002/wsb.308

Strong, A, Chisholm, S, Miller, C, & Cullen, J. 2009. Ocean fertilization: time to move on. Nature, 461: 347-348.

Sutherland, WJ. 2006. Predicting the ecological consequences of environmental change: a review of the methods. J Appl Ecol, 43: 599-616. doi: 10.1111/j.1365-2664.2006.01182.x

Sutherland, WJ, Bardsley, S, Clout, M, Depledge, MH, Dicks, LV, Fellman, L, Fleishman, E, Gibbons, DW, Keim, B, Lickorish, F, et al. 2012. A horizon scan of global conservation issues for 2013. TREE, 28: 16-22.

Sutherland, WJ, & Woodroof, HJ. 2009. The need for environmental horizon scanning. TREE, 24: 523 - 527. doi: doi:10.1016/j.tree.2009.04.008

The Royal Society. 2009. Geoengineering the climate - Science, governance and uncertainty. RS Policy document 10/09. London: The Royal Society.

Tilman, D, Socolow, R, Foley, JA, Hill, J, Larson, E, Lynd, L, Pacala, S, Reilly, J, Searchinger, T, Somerville, C, & Williams, R. 2009. Beneficial Biofuels—The Food, Energy, and Environment Trilemma. Science, 325: 270-271. doi: 10.1126/science.1177970

Tilmes, S, Fasullo, J, Lamarque, J-F, Marsh, DR, Mills, M, Alterskjær, K, Muri, H, Kristjánsson, JE, Boucher, O, Schulz, M, et al. 2013. The hydrological impact of geoengineering in the Geoengineering Model Intercomparison Project (GeoMIP). J Geophys Res: Atmos, 118: 11,036-011,058. doi: 10.1002/jgrd.50868

Vaughan, NE, & Lenton, TM. 2011. A review of climate geoengineering proposals. Clim Chang, 109: 745-790.

Walther, G-R, Post, E, Convey, P, Menzel, A, Parmesan, C, Beebee, TJC, Fromentin, J-M, Hoegh-Guldberg, O, & Bairlein, F. 2002. Ecological responses to recent climate change. Nature, 416: 389-395.

Warren, R, VanDerWal, J, Price, J, Walbergen, JA, Atkinson, I, Ramirez-Villegas, J, Osborn, TJ, Jarvis, A, Shoo, LP, Williams, SE, & Lowe, J. 2013. Quantifying the benefit of early climate change mitigation in avoiding biodiversity loss. Nat Clim Chang, 3.

Wiens, JJ, Fargione, J, & Hill, J. 2011. Biofuels and biodiversity. Ecol Appl, 21.

Williams, JW, Jackson, ST, & Kutzbach, JE. 2007. Projected distributions of novel and disappearing climates by 2100 AD. Proc Natl Acad Sci USA, 104: 5738-5742. doi: 10.1073/pnas.0606292104

Williamson, P, & Turley, C. 2012. Ocean acidification in a geoengineering context. Philos Trans R Soc A, 370: 4317-4342. doi: 10.1098/rsta.2012.0167

Williamson, PW, D.W.R., Law, CS, Boyd, PW, Collos, Y, Croot, P, Denman, K, Riebesell, U, Takeda, S, & Vivian, C. 2012. Ocean fertilisation for geoengineering: A review of effectiveness, environmental impacts and emerging governance. Process Saf Environ, 90: 475-488.

Willis, KJ, Bailey, RM, Bhagwat, SA, & Birks, HJB. 2010. Biodiversity baselines, thresholds and resilience: testing predictions and assumptions using palaeecological data. TREE, 25: 583-591.

Willis, KJ, Bennett, KD, Burrough, SL, Macias-Fauria, M, & Tovar, C. 2013. Determining the response of African biota to climate change: using the past to model the future. Philos Trans R Soc B: Biological Sciences, 368.

Winder, MS, D.E. 2004. Climate change uncouples trophic interactions in an aquatic ecosystem. Ecology, 85: 2100-2106.

Zhou, S, & Flynn, PC. 2005. Geoengineering downwelling ocean currents: a cost assessment. Clim Chang, 71: 203–220.

# Tables

**Table 1**. Description of climate engineering techniques and shortlisting on the basis of technical feasibility, affordability and/or anticipated effectiveness.

| Climate engineering technique | SRM or CDR | Description | Prioritization | Reasons for prioritization |
|---|---|---|---|---|
| **High priority techniques** | | | | |
| Ocean fertilization - iron | CDR | Soluble iron minerals added to regions of the ocean where availability limits productivity. Cover c. 30% of the ocean surface, including the Southern Ocean, and the equatorial and northern Pacific[1] | High | Field experimentation[2] shows enhanced $CO_2$ uptake can be achieved. Iron has greater potential $CO_2$ sequestration per amount of nutrient added compared to macronutrient fertilization[2], so is prioritized over nitrogen/phosphorus (below). |
| Bio-energy with carbon capture and storage (BECCS) | CDR | Biomass burned for fuel and $CO_2$ emissions produced during processing and combustion captured and transferred to long-term geological or ocean storage[1,3]. | High | Techniques for bioenergy production, processing, combustion, and capture and storage of $CO_2$ already developed[1, 3]. Relatively high anticipated $CO_2$ sequestration potential[1,4,5]. |
| Marine cloud albedo | SRM | Reflectivity of clouds over the ocean is enhanced by increasing the number of particles which act as cloud condensation nuclei, by spraying seawater into clouds[1,5]. | High | Potential for large radiative forcing effect[5,6];. Potentially technically feasible and relatively affordable technology[1,7,8] |
| Stratospheric sulfate aerosols | SRM | Sulfur dioxide or hydrogen sulfide injected into the lower stratosphere to form sulfate aerosol particles which scatter incoming shortwave radiation[4]. | High | Potential for large radiative forcing effect[5,6]. Potentially technically feasible and relatively affordable technology[4]. |
| Direct air capture (DAC) | CDR | Free-standing structures constructed in areas with good airflow. Sorbent materials on surfaces selectively trap $CO_2$ from ambient air. Isolated $CO_2$ transferred to a long-term geological or ocean store[4]. | High | High anticipated $CO_2$ sequestration potential[5,6]. Relatively achievable technological requirements[1]. |
| **Lower priority techniques** | | | | |
| Ocean fertilization – nitrogen/phosphorus | CDR | Soluble phosphorus or nitrogen minerals added to regions of the ocean where availability limits productivity. These regions cover 40% | Low | Limited carbon sequestration potential[2,6]. Significant volumes of mined minerals required[1]. |

| | | | | |
|---|---|---|---|---|
| | | of the ocean surface including tropical and subtropical gyres[1, 2]. | | |
| Biomass – storage in the ocean | CDR | Terrestrial biomass harvested, baled and deposited onto the sea floor below 1000-1500m where conditions limit decomposition[1,9] | Low | Unlikely to be viable at a scale to appreciably offset global $CO_2$ emissions[1]. Requires novel techniques and equipment. |
| Biochar | CDR | Biomass burned in low oxygen ('pyrolysis') to form solid product similar to charcoal. This is dug into soils where it acts as a carbon reservoir[1,9]. | Low | Feasibility and anticipated effectiveness in achieving net $CO_2$ reduction limited by significant land use requirements[1,6]. |
| Enhanced weathering *in situ* | CDR | $CO_2$ dissolved in solution and injected into basic rocks in the Earth's crust to react with basic minerals such as olivine to form mineral compounds[1]. | Low | Significant logistical challenges and uncertainty over chemical feasibility and energy requirements[1]. |
| Afforestation or reforestation | CDR | Forest established on currently non-forested land to increase $CO_2$ uptake and storage through photosynthesis[1,9]. | Low | Biodiversity and ecosystem effects of afforestation and reforestation have previously been subject to detailed reviews so are not considered here (e.g. 10) |
| Enhanced weathering: to land | CDR | Basic rock minerals —such as olivine— are quarried, ground into fine particles and spread on soils to undergo accelerated weathering, reacting with atmospheric $CO_2$ and converting it to mineral compounds[9,11] | Low | Relatively good technical feasibility but high energy requirements and $CO_2$ emissions associated with quarrying, processing and spreading materials[1,9,11]. |
| Enhanced weathering: to ocean | CDR | Quarried and processed carbonate or silicate materials are added to the surface ocean. The basic/alkaline materials react with $CO_2$ in the water, converting it to bicarbonate ions. $CO_2$ content of the ocean is reduced allowing more to be absorbed from the atmosphere[9]. | Low | *[See. Enhanced weathering: to land]* |
| Enhanced upwelling/downwelling | CDR | The natural process of upwelling — deep-ocean waters brought to the surface by ocean circulation— is enhanced using man-made pipes and pumps. Water brought to the surface is rich in nutrients and cooler than existing surface waters, leading to increased uptake of atmospheric $CO_2$. Alternatively, natural | Low | Very limited potential to achieve net drawdown of $CO_2$ due to high $CO_2$ content of waters brought to surface by both techniques[2]. Significant logistical and engineering challenges[12] |

| | | | | |
|---|---|---|---|---|
| | | downwelling would be enhanced by cooling $CO_2$ -rich ocean surface waters, causing them to sink to the deep ocean[1,12]. | | |
| Surface albedo - urban | SRM | Albedo of urban structures increased using bright paint or materials[1,13]. | Low | Very low anticipated radiative forcing potential and therefore low cost-effectiveness[1,5,6]. |
| Surface albedo - desert | SRM | Albedo of desert regions —which receive a high proportion of incoming solar radiation—increased by covering areas in man-made reflective materials[5,6]. | Low | Very low anticipated affordability and very large land requirements[1]. |
| Surface albedo - crop | SRM | Plants selected for high surface albedo are established over large areas of cropland or grassland/shrubland[1,13,14] | Low | Low anticipated radiative forcing potential[4,5] Vaughan & Lenton 2011), scale of implementation required for measurable effect prohibitively large[5,6]. |
| Sunshades | SRM | Sun shields or deflectors are installed in space to reflect a proportion of sunlight away from the Earth[1,4]. | Low | Very low timeliness and affordability[1,4]. |
| 1. The Royal Society 2009, 2. Williamson et al. 2012, 3. IPCC 2005, 4. Caldeira et al. 2013, 5. Lenton & Vaughan 2009, 6. Vaughan & Lenton 2011, 7. Foster et al. 2013, 8. Latham et al. 2012, 9. Secretariat of the Convention on Biological Diversity 2012, 10. Matthews et al. 2002, 11. Hartmann et al. 2013, 12. Zhou & Flynn 2005, 13. Irvine et al 2011, 14. Singarayer et al. 2009 | | | | |

**Table 2.** Top environmental changes across all techniques presented in rank order according to an 'index of priority'*. A higher value indicates a greater priority for research due to higher judged importance and/or lower scientific understanding of potential biodiversity and ecosystem effects. See Supporting Information S4 for a full list of environmental changes and scores.

| Rank | Technique | SRM or CDR | Environmental change | Median importance score (interquartile range) 100 = highest importance | Median scientific understanding score (interquartile range) 0 = no scientific understanding; 100 = complete scientific understanding | Index of priority* (100 = highest priority) |
|---|---|---|---|---|---|---|
| 1 | Solar radiation management 'dimming' techniques† | SRM | The 'termination effect'‡: Rapid increase of global temperatures if solar radiation management failed or was terminated | 99.9 (6) | 20 (5) | 90 |
| 2 | Solar radiation management 'dimming' techniques† | SRM | Regionally-variable changes in precipitation due to altered atmospheric circulation. Increase in some areas, decrease in others | 80 (18) | 30 (10) | 75 |
| 3 | Solar radiation management 'dimming' techniques† | SRM | Creation of high $CO_2$/low temperature climate (unlike either the current low $CO_2$/low temperature conditions or high $CO_2$/high temperature conditions of projected climate change) | 70 (27) | 20 (8) | 75 |
| 4 | Solar radiation management 'dimming' techniques† | SRM | Reduced amplitude of seasonal temperature range with warmer winters and cooler summers | 75 (20) | 30 (10) | 73 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 5 | Solar radiation management ‘dimming’ techniques† | SRM | Small but detectable global cooling within ~5 years of solar radiation management deployment (relative to elevated temperatures caused by global warming effect) | 74 (11) | 30 (5) | 72 |
| 6 | Solar radiation management ‘dimming’ techniques† | SRM | Reduced equator-to-pole temperature gradient due to greater reduction in incoming solar radiation at the tropics than at higher latitudes | 70 (19) | 30 (6) | 70 |
| 7 | Solar radiation management ‘dimming’ techniques† | SRM | Slowing of the global hydrological cycle (reduced evaporation and precipitation) | 70 (15) | 30 (10) | 70 |
| 8 | Enhanced desert albedo | SRM | Potentially strong reduction in continental rainfall, particularly in monsoon regions | 64 (15) | 30 (8) | 68 |
| 9 | Enhanced upwelling/ downwelling | CDR | Increased primary productivity in surface ocean as a result of artificially enhanced upwelling of nutrient-rich deep waters (in mid-ocean locations) | 63 (25) | 30 (23) | 67 |
| 10 | Solar radiation management ‘dimming’ techniques† | SRM | Changes in ocean circulation patterns due to changes in energy into and out of the ocean due to reduced atmospheric temperature | 63 (17) | 30 (10) | 67 |
| 11 | Ocean fertilization with iron | CDR | Increased primary productivity in high nutrient low chlorophyll regions of the ocean due to iron fertilization | 70 (30) | 40 (15) | 66 |
| 12 | Enhanced upwelling/downwelling | CDR | Increased area of man-made structures in the ocean for artificial enhancement of upwelling or downwelling | 55 (20) | 25 (16) | 65 |
| 13 | Biomass: storage in the ocean | CDR | Increased nutrient availability in deep ocean and on sea floor due to deposition of harvested terrestrial biomass | 50 (23) | 15 (18) | 65 |
| 14 | Enhanced cropland or grassland albedo | SRM | Establishment of monocultures of high-reflectivity vegetation over several million $km^2$ to replace natural and semi-natural grassland and shrubland habitats | 80 (17) | 50 (28) | 65 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 15 | Biomass: storage in the ocean | CDR | Reduced oxygen in deep ocean due to decomposition of introduced organic matter (harvested terrestrial biomass) | 55 (33) | 30 (28) | 65 |
| 16 | Enhanced cropland or grassland albedo | SRM | Conversion of (dark) forest habitats to establish (lighter) grassland or cropland | 79 (25) | 50 (30) | 63 |
| 17 | Biomass: storage in the ocean | CDR | Large-scale coverage (smothering) of deep-ocean seabed with harvested terrestrial biomass | 52 (47) | 25 (15) | 63 |
| 18 | Enhanced weathering: base materials to land | CDR | Change in soil properties with addition of powdered basic rock (soil structure, density, aggregation and water retention) | 9 (9) | 30 (10) | 63 |
| 19 | Enhanced desert albedo | SRM | Large-scale covering of desert surface with man-made materials | 50 (13) | 25 (23) | 61 |
| 20 | Ocean fertilization: nitrogen or phosphorus | CDR | Increased primary productivity in low nutrient low chlorophyll regions of the ocean due to nitrate or phosphate fertilization | 60 (20) | 40 (13) | 60 |

* The 'Index of priority' is calculated by: (Importance score + (100 – Understanding score))*0.5

† Solar radiation management 'dimming' techniques refers to sunshades, stratospheric sulfate aerosols and enhanced marine cloud albedo, which reflect a proportion of incoming solar radiation back into space. Environmental changes under this heading are taken to be common to these three techniques.

‡ The termination effect is associated with the possible failure or termination of SRM 'dimming' techniques, rather than their implementation or functioning.

**Table 3.** Priority research questions relating to the highest priority environmental changes associated with each of the five shortlisted climate engineering techniques. The 'Index of priority' combines their importance score and scientific understanding score; environmental changes with high importance and low scientific understanding of the biodiversity and ecosystem consequences were considered priorities for research.

| Technique | Prioritized Environmental Changes | Index of Priority | Suggested Priority Research Questions |
|---|---|---|---|
| 1. Stratospheric sulfate aerosols | Termination effect: Rapid increase of global temperatures if solar radiation management fail or are terminated | 89.9 | 1. What are the rates of warming that species can tolerate by means of adaptation or migration and which key species and ecosystem-level processes are most vulnerable to such rapid changes? |
| | | | 2. Does a rapid increase in temperature modify the effects of other important stressors, and what are the synergistic effects of these multiple stressors on biodiversity and ecosystems? |
| | | | 3. What consequences does an abrupt change from cooling to rapid warming have for evolutionary adaptation to warming? |
| | Creation of high $CO_2$/low temperature climate (relative to current low $CO_2$/low temperature baseline and high $CO_2$/high temperature of projected climate change) | 75 | 1. What is the effect on primary productivity of the combined influence of increased $CO_2$ concentrations and reduced temperatures for the dominant plant species in major terrestrial biomes and for oceanic phytoplankton? |
| | | | 2. How will enhanced $CO_2$ concentrations and reduced global temperatures impact on ocean uptake of $CO_2$ and acidification rates and what are the implications for calcifying organisms and their role in transferring particulate organic carbon to the deep ocean? |
| | | | 3. What are the indirect effects of high atmospheric $CO_2$ levels and reduced temperature on biodiversity and ecosystem structure and function, including the effects on taxa other than primary producers and as a result of impacts cascading through food webs? |
| | Regionally-variable changes in precipitation due to altered atmospheric circulation. Increase in some areas, decrease in others. | 75 | 1. How will changes in precipitation affect aridification and regional distributions of species and communities, especially trophic levels other than primary producers, and what implications does this have for ecosystem processes they control? |
| | | | 2. What impacts do variations in precipitation regimes have on belowground processes, including water uptake and root structure, over the medium to long term? |
| | | | 3. In marine habitats, how might changes in freshwater inputs to the ocean affect the intensity and distribution of acidification in the marine surface layer and ocean interior, and how does this affect ocean biodiversity and ecosystem function in various regions? |
| 2. Enhanced marine cloud | *[Prioritized environmental changes for this technique are the same as for 1. Stratospheric sulfate aerosols – they are common to both]* | | |

| | | | |
|---|---|---|---|
| albedo | | | |
| 3. Ocean fertilization with iron | Increased primary productivity in high nutrient low chlorophyll regions of the ocean | 66 | 1. What are the taxon-specific responses of phytoplankton to fertilization in terms of their growth and chemical composition (C, N, P, Si and Fe stoichiometry) under different states of nutrient (in)sufficiency, and how should these responses be included in models of community and ecosystem response? |
| | | | 2. What ecosystem effects might occur beyond the fertilization zone (e.g. through changes in downstream nutrient regimes, changes in flux to deeper ocean communities)? |
| | | | 3. How might higher trophic levels (including zooplankton, fish and mammals) respond to enhanced throughput of organic material, due to large-scale and long-term fertilization, and how might such effects influence areas beyond the fertilization zone? |
| | Increase in anoxic or hypoxic regions in mid and deep oceans due to increased respiration during decomposition of additional organic matter | 55 | 1. What are the likely rates of biological degradation of the organic matter generated by iron fertilization in deep, cold ocean environments and would the character of the material (e.g. carbon:nitrogen ratio) make a difference to mineralization rates? |
| | | | 2. What is the anticipated scale of the impact of substantially increased input of organic matter (and its subsequent decomposition) on mid-water oxygen levels; will existing oxygen minimum zones be expanded or new ones created? |
| | | | 3. How might increased volumes of anoxic water directly or indirectly impact higher trophic levels, for example, fish and mammals (e.g. on geographical and depth ranges, migration routes, physiological processes, prey availability and foraging etc.)? |
| 4. Biofuels with carbon capture and storage (BECCS) | Conversion of habitats to large-scale production of biofuel feedstocks | 56 | 1. What strategies for feedstock production - in terms of location and size of production, type of existing land-use or habitat replaced, and size and connectivity of remaining natural areas - could we use such that biodiversity and/or ecosystem service loss is minimized per unit energy produced for different biofuel types? |
| | | | 2. Which management regimes used for planting, growing and harvesting each type of biofuel feedstock will have the smallest impact on biodiversity and ecosystem services? |
| | | | 3. Which biofuel crops in which location will provide the most energy whilst having the least impact on biodiversity and ecosystem services per unit area, and how can we properly assess the trade-off between the value of biofuel production and the loss of biodiversity/ecosystem services? |
| | Biodiversity and ecosystem impacts of species used in | 52 | 1. Can structurally complex, multispecies biofuel plantations be established that have adequate biomass production for economic viability, whilst also providing habitat for native species and other non-biofuel ecosystem services? |

| | | | |
|---|---|---|---|
| | feedstocks (e.g. introduced fast-growing tree varieties, invasive species etc.) | | 2. Is the long term net impact on biodiversity and ecosystem services less if a small area of highly productive, high water demanding, agrochemical dependent and potentially invasive biofuel crops is established, relative to the impact of developing a larger area for biofuels, which although less productive, are also less water-demanding, agrochemical dependent and less likely to become invasive? |
| | | | 3. Which genetic and agronomic methods could be used to reduce the risk of invasiveness and the need for agrochemicals, whilst increasing productivity and water use efficiency of biofuel crops? |
| 5. Direct air capture (DAC) | Construction of large air-capturing structures on open areas of land | 33 | 1. Which locations could be most suitable for the placement of the DAC structures and what is the profile of the ecosystems and biodiversity that currently exist there? (i.e. are species rare/unique/endemic? How resilient are communities to disturbance?) |
| | | | 2. How large will the footprint of the DAC structures be and will they present an influential obstacle in the landscape, causing potential interference to species' feeding, nesting or migratory activity? |
| | | | 3. To what degree will habitats be altered and disturbed by the construction and maintenance of direct air capture structures? (e.g. will land need to be cleared? Will permanent access routes be established and frequently used?) |
| | Contamination of air 'downstream' of DAC if reactive chemicals used to capture $CO_2$ evaporate | 42 | 1. Will the likely concentration of chemicals in air passing through the DAC structure represent a biologically-significant level to species in surrounding ecosystems? |
| | | | 2. How far from direct air capture structures might species be impacted by air contamination effects? |
| | | | 3. How will contamination impact species' fitness and the structure of communities in habitats where DAC structures are established? |