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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

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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.

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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 (Chen et al. 2011; Bellard et al. 2012; Warren et al. 2013). With continued high greenhouse gas emissions (Jackson et al. 2016; International Energy Agency 2015), 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): (a) carbon dioxide removal (CDR) techniques, designed to reduce atmospheric carbon dioxide concentrations, and (b) solar radiation management (SRM), designed to reflect solar radiation away from Earth (The Royal Society 2009; Secretariat of the Convention on Biological Diversity 2012; Caldeira et al. 2013). 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).

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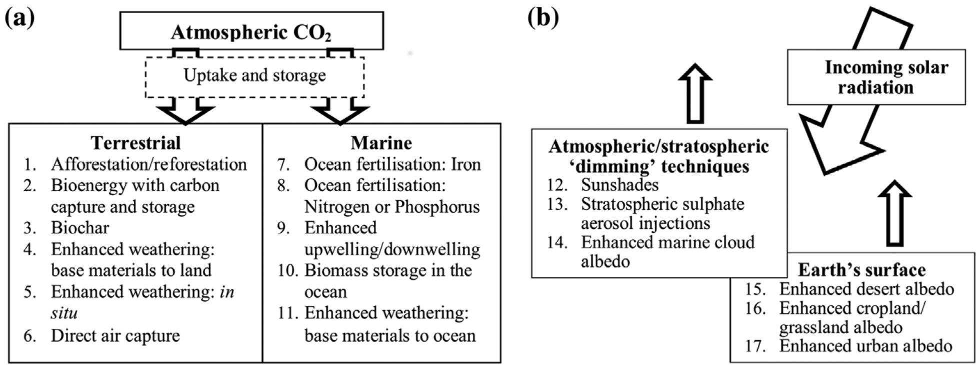

Figure 1. Schematic of climate engineering techniques considered in this review, covering CDR techniques and SRM techniques.

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 challenging. 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 (Secretariat of the Convention on Biological Diversity 2012; International Maritime Organization 2013; IPCC 2013) 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 (Sutherland 2006; Sutherland & Woodroof 2009; Martin et al. 2012; Sutherland et al. 2012). 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.

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 of the Convention on Biological Diversity (2012) were used as a starting point. An approach based on snowball sampling (Biernacki & Waldorf 1981) was used to identify further relevant literature from

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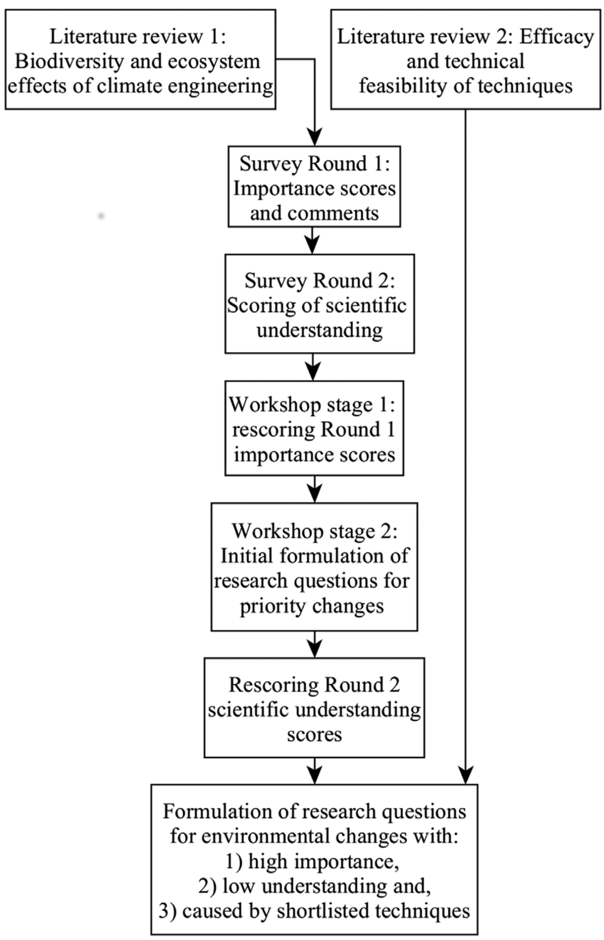

Figure 2. Flow diagram of study methodology.

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 (The Royal Society 2009; Rickels et al. 2011). 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 the participating group of researchers 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.

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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 pre-workshop 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 from the results of this scoring.

2.5. Shortlisted techniques and research questions

As well as assessing the effects across all 17 climate engineering techniques, we specifically assessed effects associated with techniques that we concluded were more plausible for implementation than others; five of the 17 climate engineering techniques were identified from a review of existing assessments 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) (e.g. (Lenton & Vaughan 2009; The Royal Society 2009; Caldeira et al. 2013). This was taken to indicate that they are more plausible options for implementation, meaning that potential effects associated with them are the most pertinent to consider.

The index of priority was 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.

3. Results and discussion

3.1. Key themes for research – across all techniques

The 'index of priority' was used to first rank all of the environmental changes across all of the 17 climate engineering techniques, assuming equal likelihood of implementation. A full list of the median scores and index of priority values is given in Supporting Information S4. The top 20 of these environmental changes (Table 2), and patterns within the rest of the ranked list, reveals interesting themes in the types of changes that were judged by

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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[a]	High	Field experimentation[b] shows enhanced CO_2 uptake can be achieved. Iron has greater potential CO_2 sequestration per amount of nutrient added compared to macronutrient fertilization,[b] 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[a,c]	High	Techniques for bioenergy production, processing, combustion, and capture and storage of CO_2 already developed,[a,c]. Relatively high anticipated CO_2 sequestration potential[a,d,e]
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[a,e]	High	Potential for large radiative forcing effect.[e,f] Potentially technically feasible and relatively affordable technology[a,g,h]
Stratospheric sulfate aerosols	SRM	Sulfur dioxide or hydrogen sulfide injected into the lower stratosphere to form sulfate aerosol particles which scatter incoming shortwave radiation[d]	High	Potential for large radiative forcing effect.[e,f] Potentially technically feasible and relatively affordable technology[d]
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[a]	High	High anticipated CO_2 sequestration potential.[e,f] Relatively achievable technological requirements[a]
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% of the ocean surface including tropical and subtropical gyres[a,b]	Low	Limited carbon sequestration potential.[b,f] Significant volumes of mined minerals required[a]
Biomass – storage in the ocean	CDR	Terrestrial biomass harvested, baled and deposited onto the sea floor below 1000–1500 m where conditions limit decomposition[a,i]	Low	Unlikely to be viable at a scale to appreciably offset global CO_2 emissions.[a] 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[a,i]	Low	Feasibility and anticipated effectiveness in achieving net CO_2 reduction limited by significant land use requirements[a,f]
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[a]	Low	Significant logistical challenges and uncertainty over chemical feasibility and energy requirements[a]
Afforestation or reforestation	CDR	Forest established on currently non-forested land to increase CO_2 uptake and storage through photosynthesis[a,i]	Low	Biodiversity and ecosystem effects of afforestation and reforestation have previously been subject to detailed reviews so are not considered here
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[i,k]	Low	Relatively good technical feasibility but high energy requirements and CO_2 emissions associated with quarrying, processing and spreading materials[a,i,k]

(*Continued*)

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Table 1. (*Continued*)

Climate engineering technique	SRM or CDR	Description	Prioritization	Reasons for prioritization
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[i]	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 downwelling would be enhanced by cooling CO_2 -rich ocean surface waters, causing them to sink to the deep ocean[a,l]	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.[b] Significant logistical and engineering challenges[l]
Surface albedo – urban	SRM	Albedo of urban structures increased using bright paint or materials[a,m]	Low	Very low anticipated radiative forcing potential and therefore low cost-effectiveness[a,e,f]
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[a,f]	Low	Very low anticipated affordability and very large land requirements[a]
Surface albedo – crop	SRM	Plants selected for high surface albedo are established over large areas of cropland or grassland/shrubland[a,m,n]	Low	Low anticipated radiative forcing potential,[d,e,f] scale of implementation required for measurable effect prohibitively large[e,f]
Sunshades	SRM	Sun shields or deflectors are installed in space to reflect a proportion of sunlight away from the Earth[a,d]	Low	Very low timeliness and affordability[a,d]

[a]The Royal Society 2009.
[b]Williamson et al. 2012.
[c]Metz et al. 2005.
[d]Caldeira et al. 2013.
[e]Lenton & Vaughan 2009.
[f]Vaughan & Lenton 2011.
[g]Foster et al. 2013.
[h]Latham et al. 2012.
[i]Secretariat of the Convention on Biological Diversity 2012.
[j]Matthews et al. 2002.
[k]Hartmann et al. 2013.
[l]Zhou & Flynn 2005.
[m]Irvine et al. 2011.
[n]Singarayer et al. 2009.

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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[a]	SRM	The 'termination effect'[b]: 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[a]	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[a]	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[a]	SRM	Reduced amplitude of seasonal temperature range with warmer winters and cooler summers	75 (20)	30 (10)	73
5	Solar radiation management 'dimming' techniques[a]	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[a]	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[a]	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[a]	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

(*Continued*)

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Table 2. (*Continued*)

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)
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.

[a]SRM '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.

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

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the expert group to have important biodiversity and ecosystem consequences but limited scientific understanding.

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 SRM '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; Ricke et al. 2010; Kravitz, Robock, et al. 2013). '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 (Pörtner & Farrell 2008; Cahill et al. 2013). 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 (Walther et al. 2002; Burrows et al. 2011). Changes in the amplitude of seasonal temperature variation could strongly influence the timing of ecological processes such as migration, breeding, flowering and phytoplankton blooms (Sims et al. 2001; Edwards & Richardson 2004; Menzel et al. 2006). 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 (Mustin et al. 2007; Hoffmann & Sgro 2011). 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). SRM techniques would not address atmospheric

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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, SRM 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 various 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 (Levin et al. 2001; Lampitt et al. 2008). 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

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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 & Lenton 2011). Of the SRM 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, Caldeira et al. 2013). Of the CDR 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 et al. 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.

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.

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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 albedo		*[Prioritized environmental changes for this technique are the same as for 1. Stratospheric sulfate aerosols – they are common to both]*	
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)?

(*Continued*)

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Table 3. (*Continued*)

Technique	Prioritized environmental changes	Index of priority	Suggested priority research questions
			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 feedstocks (e.g. introduced fast-growing tree varieties, invasive species etc.)	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?
			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?)

(*Continued*)

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Table 3. (*Continued*)

Technique	Prioritized environmental changes	Index of priority	Suggested priority research questions
			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?

(Schloss et al. 2012; Quintero & Wiens 2013; Peck et al. 2014). It is also critical to consider within the context of climate engineering. Atmospheric and stratospheric SRM ('dimming') techniques will cause global-scale reduction in incoming radiation leading to stabilized or reduced rates of warming. With intensive implementation, 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 (Matthews & Caldeira 2007; Jones et al. 2013). 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 at intensive SRM implementation 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). The intensity of the effects could however be much less if a more moderate approach to SRM implementation was used. For example, if techniques were implemented at a scale to induce only a small degree of cooling (Kosugi 2013) or to curtail the rate of warming in parallel with emissions reduction efforts (MacMartin et al. 2014)

Similarly, several of the research questions identified in relation to BECCS (Table 3) are existing priority topics of research in relation to biofuels for energy (Gove et al. 2010; Fletcher et al. 2011; Wiens et al. 2011). Overall, the effects of biomass production were 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 SRM 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 (Williams et al. 2007; Tilmes et al. 2013). Temperature and CO_2 control fundamental ecological processes and the relative influence of the two parameters is highly complex

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(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 (Long et al. 2004; Wiens et al. 2011; Donohue et al. 2013), 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 (Higgins & Scheiter 2012; De Frenne et al. 2013). 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 available 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 (The Royal Society 2009; Russell et al. 2012). This significant topic of ongoing research should occur in parallel with attempts to project biodiversity and ecosystem effects of climate

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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.

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. CGM 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.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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Appendix S1: Report of a literature review of the potential biodiversity and ecosystem effects of climate engineering (or 'climate engineering').

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Scope of this review

Within this report, the two major types of climate engineering techniques are considered and form the two main sections of the report; 1) Carbon dioxide removal (CDR) techniques, and 2) Solar radiation management (SRM) techniques. Within each category, a number of proposed climate engineering techniques are considered. For each technique, a description of the intended mechanism by which it would counteract climate change is given, followed by an outline of how the technique may be implemented. Where possible, an idea of the scale at which the technique would be used is given, and the domain or location is defined.

The potential impacts of the techniques are then outlined. First, the direct chemical, physical (or in some cases, biological) environmental change caused by implementation of the climate engineering technique is defined, and below this, likely biodiversity and ecosystem effects of this change are indicated. These are laid out as follows:

1. **Direct biological chemical or physical environmental change**

a) Biodiversity and ecosystem impact 1

b) Biodiversity and ecosystem impact 2

c) etc.

Climate engineering techniques included

The range of climate engineering techniques included within this report is based on those most commonly included in recent considerations of climate engineering (The Royal Society, 2009; Vaughan & Lenton, 2011; Secretariat of the Convention on Biological Diversity, 2012; Russell *et al*., 2012; Rickels *et al*., 2011).

Afforestation and reforestation, and biofuel production have been subject to detailed reviews elsewhere (IPCC, 2000; The Royal Society, 2001; IPCC, 2007b; UNEP, 2009) so their effects are explored only in limited detail here. Similarly, enhancement of soil carbon (often combined with afforestation and reforestation) is not considered here as it remains poorly defined as a method of climate engineering (e.g. Secretariat of the Convention on Biological Diversity, 2012)

Defining the effects

The effects of climate engineering on biodiversity and ecosystems are numerous and complex. If effective, all techniques will counteract projected climate change to a greater or lesser degree. By ameliorating temperature rises and other climate change impacts, climate engineering will have indirect effects on biodiversity and ecosystems. These are likely to be beneficial relative to the impacts of projected climate change in the absence of climate engineering (Secretariat of the Convention on Biological Diversity, 2012). However, in addition to their influence on global climate, climate engineering will also cause a range of changes to environmental factors that strongly influence biodiversity and ecosystems, such as light intensity, regional precipitation and biogeochemical cycling (see Figure 1 below), and many could affect ecosystems and biodiversity *directly*, for example, through land-use change. It is these 'side-effects' of climate engineering – separate from their climate change effect – that we focus on in this report.

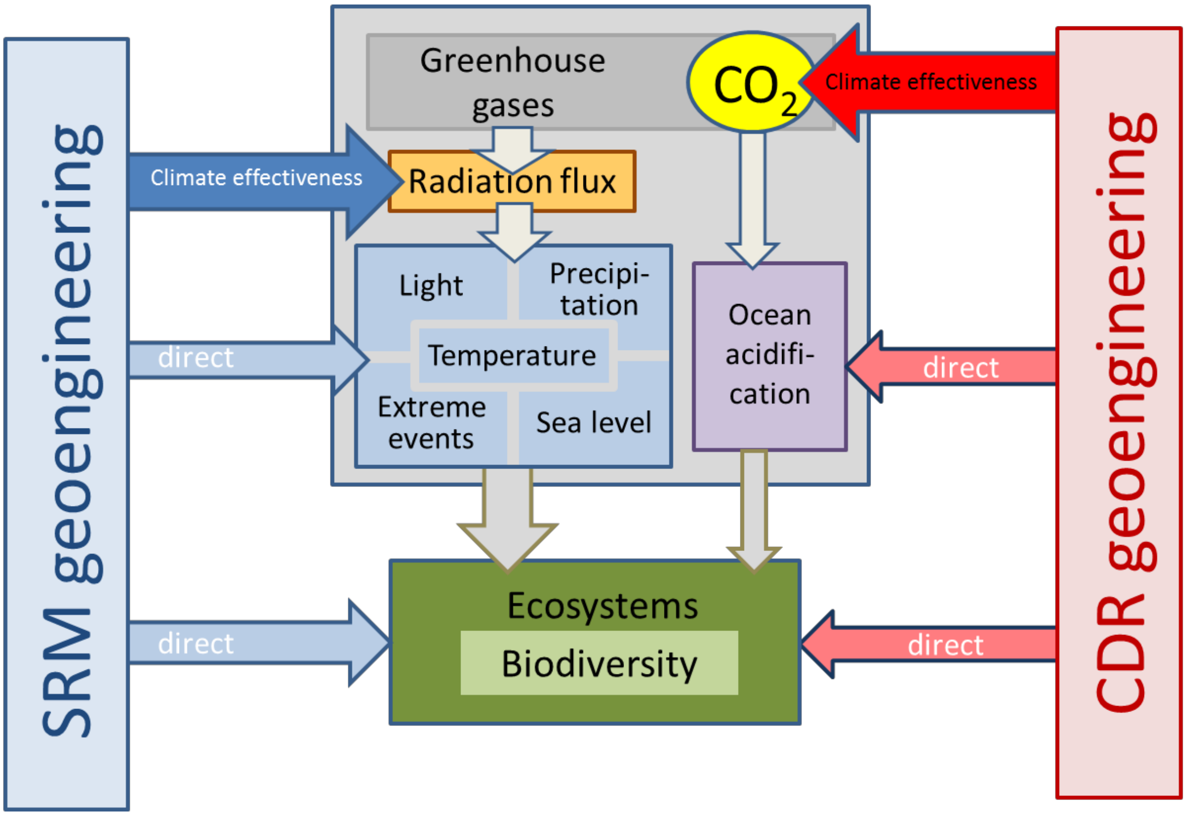

Figure 1. Schematic of climate engineering impacts; direct and climate effectiveness. Diagram adapted from Secretariat of the Convention on Biological Diversity (2012)

As an example, increased biofuel use with Carbon Capture and Storage (BECCS) could be anticipated to reduce CO_2 emissions. This would contribute to reducing climate change, thereby reducing consequential impacts on biodiversity and ecosystems. This type of indirect effect is not covered here, but potential biodiversity and ecosystem impacts of biofuel feedstock production and CO_2 storage associated with this technique are explored.

This review considers climate engineering only in terms of its effects on biodiversity and ecosystems. Factors such as the relative effectiveness, technical feasibility, time-scales (implementation and termination), cost, reversibility (technical and political), safety and public acceptability, as well as governance of techniques, are not covered. These are assessed elsewhere, for example in the recent reviews by the Secretariat of the Convention on Biological Diversity (2012) and the Royal Society (2009; Boyd, 2008; Robock, 2008; Vaughan & Lenton, 2011; Rickels *et al*. 2012; Pidgeon *et al*. 2013).

Nature of effects and scientific evidence

The biodiversity and ecosystem effects of climate engineering may be beneficial or detrimental. Within this report, effects are not explicitly categorized either way; some may have both beneficial and detrimental consequences, and for some, the consequences are unknown or poorly understood. Where potential effects are global-scale, for example changes in precipitation or ocean circulation, effects on biodiversity and ecosystems will be wide-ranging, regionally variable and often highly uncertain. These are therefore covered only broadly in this report as it is beyond the scope of the current study to represent all regional-scale effects of these global-scale alterations.

Where possible, studies providing evidence for effects are cited. Please note that a full and exhaustive literature review is beyond the scope of this study. We therefore emphasize that there may be additional evidence beyond that included within this report.

Section 1: Carbon Dioxide Removal (CDR) Climate engineering Techniques

Carbon Dioxide Removal (CDR) techniques are intended to remove carbon dioxide (CO_2) from the atmosphere, isolating it in a long-term store. By reducing the atmospheric concentration of the principle greenhouse gas, it is anticipated that the rate of earth and atmosphere warming would be reduced. These methods would also counteract direct effects of high atmospheric CO_2 concentrations, including ocean acidification (The Royal Society, 2009).

Proposed CDR techniques include measures to enhance natural biological carbon sequestration, accelerate or stimulate natural chemical and physical CO_2 uptake, and large-scale engineering methods to directly capture CO_2 from ambient air.

1 Direct ocean fertilization

Limiting nutrients – iron, nitrates or phosphates – are added directly to the surface ocean. Iron would be added to High Nutrient Low Chlorophyll regions. Nitrates and phosphates would be added to Low Nutrient Low Chlorophyll regions.

Intended climate effect: Ocean fertilization is intended to enhance ocean primary productivity in regions where it is currently limited by low nutrient availability. The abundance and growth of phytoplankton, which absorb CO_2 during photosynthesis, would be enhanced resulting in an increased 'drawdown' of CO_2 from the atmosphere. Carbon is stored within the phytoplankton, and, after they die or are eaten, a small proportion sinks into the deep sea in fecal matter and other detritus where it is removed from the atmosphere for decades to centuries.

Implementation:

Iron fertilization has received the most attention as it is anticipated to be the most effective in many (but not all) ocean regions (Williamson *et al*., 2012). Iron (in a soluble form such as ferrous sulfate) would be added to High Nutrient Low Chlorophyll regions of the ocean which cover approximately 20% of the ocean surface (Edwards *et al*., 2004). In these regions, although other macronutrients are available, low iron concentrations limit productivity. This technique would be primarily focused on the Southern Ocean, where it is anticipated to be most effective (Williamson *et al*., 2012), although the equatorial Pacific and northern Pacific would also be suitable (The Royal Society, 2009). Continual injections of iron would be required. However, the quantities of iron required would be several orders of magnitude smaller than the quantities of the (macro)nutrients phosphorus and nitrogen required for ocean fertilization (Lampitt *et al*., 2008). The maximum conceivable fertilization - to sequester ~1.5Gt C/yr - would require around 2% of annual iron production. For more realistic fertilization scales, at most ~0.2% of annual iron production would be required[1].

To date, there have been 12 mesoscale iron-addition experiments - using ferrous sulfate, iron-chelate, iron sulfide and hematite in powdered form - with varying impacts on primary productivity and carbon exportation to the deep ocean (Williamson *et al*., 2012). It has been suggested following one of the experiments, that for two billion tons of carbon to be sequestered (25% of current annual emissions), an area ten times larger than the Southern Ocean would need to be fertilized with iron (Buesseler & Boyd, 2003).

Phosphorus and nitrogen are also suggested for direct ocean fertilization as they are limiting across a significant proportion of the ocean. They would be added in soluble or finely powdered forms (such as anhydrous monosodium phosphate or phosphoric acid for phosphorus, and urea, ammonia or nitrates for nitrogen; Williamson *et al*., 2012) to Low Nutrient Low Chlorophyll regions of the ocean, which cover approximately 40% of the ocean surface, including tropical and sub-tropical gyres (The Royal Society, 2009; Secretariat of the Convention on Biological Diversity, 2009; Vaughan & Lenton, 2011). It has been suggested that macronutrients should only be applied to surface waters over the deep ocean, not shallow bays or coastal waters where they would lead to significant eutrophication.

[1] Annual iron production was 2.9 Gt in 2011 (Jorgensen, 2013). A conservative figure of 25% iron content for the ores is assumed (i.e. 0.7 Gt Fe). The efficiency of biogenic carbon export into deeper water layers (C:Fe) is taken as a conservative figure of 1,000 (de Baar *et al*., 2008) . The maximum suggested feasible iron fertilisation is 1.5 Gt C sequestered per year. Given the assumed efficiency of export figure, that would require 1.5 Mt iron, i.e. 0.2% of global production. More realistic fertilisation levels is 0.15 Gt C per year, which would therefore require c.0.02% of global iron production, meaning the resulting increase in production would be very small (C.Vivian, *pers. Comm*.)

Estimates suggest that many billions of tons of nitrogen and phosphorus fertilizer would be required every year to achieve discernible climatic effects (Secretariat of the Convention on Biological Diversity, 2012). The process would also be slow to impact the climate; if the whole global ocean deficit of nitrogen could be addressed, it would take 600 years to achieve the additional deep-ocean storage of carbon required to counteract current CO_2 emission rates (Lenton & Vaughan, 2009). It is considered that phosphorus addition could be more effective in the long-term than nitrogen fertilization as it would better promote nitrogen fixation (The Royal Society, 2009).

Nutrients would be in soluble or fine powdered form, and suggestions for distribution include the use of submarine pipes, transporting nutrients to an area of ocean beyond the continental shelf, or releasing nutrients from large ships. Continual injections of nutrients would be required (Lampitt *et al*., 2008).

1.1 Environmental changes and biodiversity and ecosystem effects:

Outlined below are the primary physical, chemical and biological environmental changes caused by the implementation of this technique. Where possible, the potential biodiversity and ecosystem effects of each environmental change are indicated.

NOTE: **Direct Ocean Fertilization – regardless of the nutrient used – will have a range of common effects. Where effects vary depending on the nutrient used, the differences are indicated.**

1. **Increased mining of fertilizing minerals**

   Iron: It is unlikely that the mining requirements for fertilization with iron would make a significant difference to existing mining impacts (as indicated on the previous page).

   Phosphorus: Significant increase in mining relative to current levels due to large volumes of phosphates required.

a) Habitat loss, fragmentation or degradation due to excavation of land, disposal of mining waste materials (Goff & Lackner, 1998; The Royal Society, 2009; Secretariat of the Convention on Biological Diversity, 2012) and transportation of mined nutrients to addition sites.

b) Noise pollution disturbance to wildlife with effects on foraging, predator avoidance, communication, reproductive success, population density, community structure and survival (Lengagne, 2008; Barber *et al*., 2010).

c) Biodiversity and ecosystem impacts of localized air pollution and dust (IPCC, 2005).

d) Pollution of freshwater bodies from dust and acid run-off; potential toxicity to *aquatic* organisms leading to decline in health and abundance of affected species (e.g. inhibited spawning and development of fish eggs, smothering of benthic macroinvertebrates) and shifts in community structure and composition (Committee on Hardrock Mining on Federal Lands, 1999).

e) Sedimentation of rivers and lakes leading to reduction in photosynthetic activity of aquatic plants with decreased light (Committee on Hardrock Mining on Federal Lands, 1999).

f) Pollution of soil and vegetation from dust and acid run-off; potential toxicity to *terrestrial* organisms leading to decline in health and abundance of affected species and shifts in community structure and composition.

g) Reduced photosynthesis due to ‘smothering’ by dust deposition (Vardaka *et al*., 1995).

h) Increased erosion (IPCC, 2005) causing direct loss of terrestrial habitat and reduced soil nutrients.

i) Reduced ‘biologically available water’ in adjacent habitats due to increased abstraction for mining processes (The Royal Society, 2009) causing decline in species health and abundance, increased competition for water, community shift towards drought-tolerant species and toxicity of concentrated pollutants.

2. Increased production (manufacture and processing) of nitrate fertilizers for use in ocean (Secretariat of the Convention on Biological Diversity, 2009) with associated effects on the environment.

a) Significant increase in energy and methane consumption with associated resource use, habitat destruction, pollution etc.

3. **Increased primary productivity and phytoplankton biomass in the upper ocean with impacts on ecological community structure and functioning (Glibert *et al.*, 2008; Secretariat of the Convention on Biological Diversity, 2009).**

   Iron: in High Nutrient Low Chlorophyll Regions of the ocean, 12 different mesoscale iron-ocean-fertilization experiments showed increased phytoplankton biomass (Boyd *et al*., 2007).

   Nitrogen/phosphorus: in Low Nutrient Low Chlorophyll Regions of the ocean.

   a) Changes in structure and composition of phytoplankton communities with possible loss of biodiversity and changes to ecosystem functions (Glibert *et al*., 2008; Secretariat of the Convention on Biological Diversity, 2009).

      Iron: A shift from small phytoplankton to larger diatoms and to grazing species (Hoffmann *et al*., 2006). This shift was observed in seven of 12 mesoscale iron-fertilization experiments (Boyd *et al*., 2007).

      Nitrogen: A shift to more cyanobacteria, picoeukaryotes and dinoflagellates rather than diatoms (Cloern, 2001; Heil *et al*., 2007; Secretariat of the Convention on Biological Diversity, 2009).

      Phosphorus: (*Shift in communities occurs due to the availability of the next limiting nutrient; Secretariat of the Convention on Biological Diversity, 2009).*

   b) Change in copepod populations, such as an increase in copepod egg abundance with impacts on fish populations (Thingstad *et al*., 2005; Secretariat of the Convention on Biological Diversity, 2009).

      Changes in food-web dynamics as a result of changes in phytoplankton communities; consequences are not well understood due to the complexity of marine food webs (Boyd *et al*., 2007; The Royal Society, 2009).

Iron: Likely to favor larger diatoms and copepods over small microzooplankton with implications for higher trophic levels (Lucas *et al*., 2007; Denman, 2008; Tsuda *et al*., 2009).

Nitrogen: Cyanobacteria, picoeukaryotes and dinoflagellates (predicted to increase with nitrogen fertilization) are poor quality food for zooplankton grazers with implications for higher trophic levels (Azam *et al*., 1983).

Phosphorus: *Two small-scale field studies found rapid increases in bacterial production and zooplankton biomass after fertilization (Wallace et al. 2010).*

c) Possible increase in harmful algal blooms (Boyd *et al*., 2007; Secretariat of the Convention on Biological Diversity, 2009). Should they occur, toxic blooms could kill organisms in higher trophic levels due to bioaccumulation of toxins (Underdal *et al*., 1989; Hallegraeff, 1993; Bajarias *et al*., 2006; Silver, 2010; Trick *et al*., 2010).

Iron: Blooms of toxic dinoflagellates (Trick *et al*., 2010).

Nitrogen: Blooms of cyanobacteria, picoeukaryotes and dinoflagellates (Glibert *et al*., 2008).

Phosphorus: *no further detail found*.

d) Increased abundance of fish and invertebrates. May favor the proliferation of opportunistic species such as jellyfish (Takeda & Tsuda, 2005; Powell, 2008).

e) Changes in composition of bacterial communities, such as an increase in biomass and bacterial production (Hall & Safi, 2001; Thingstad *et al*., 2005)

f) Unquantified impacts on marine viruses (Suttle, 2005).

4. Localized warming of ocean surface as phytoplankton biomass absorbs solar radiation (Frouin & Iacobellis, 2002). Could result in changes in global ocean circulation (The Royal Society, 2009).

a) Increased primary productivity (O'Connor *et al*., 2009).

b) Increased plankton biodiversity (previously observed in response to ocean warming; Beaugrand *et al*., 2010).

c) Changes in food web dynamics, such as an increased dominance of zooplankton (O'Connor *et al*., 2000; Kletou & Hall-Spencer, 2012).

5. **Reduced rate of ocean acidification in surface waters with increased photosynthetic uptake of dissolved CO_2.**

a) Impact on calcification rates of calcifying organisms and other biological structures (e.g. O'Donnell *et al*. 2013). Either decreased (Riebesell *et al*., 2007) or increased rates (Iglesias-Rodriquez *et al*., 2008; Wood *et al*., 2008).

b) Impacts on rate and extent of coral bleaching (Anthony *et al*., 2008).

6. **Increased cloud formation over ocean areas due to release of isoprene from phytoplankton which creates cloud condensation nuclei (Meskhidze & Nenes, 2006; Arneth *et al.*, 2007; Arneth *et al.*, 2008; Rayfuse *et al.*, 2008).**

a) Reduced light penetration in the ocean due to localized reduction in incoming solar radiation and shift to greater fraction of diffuse light compared to direct light with increased cloud cover. Leads to decrease in productivity in the euphotic zone (Raymont, 1980; Secretariat of the Convention on Biological Diversity, 2012), including impact on deeper corals and kelp (The Royal Society, 2008).

b) Cooling of atmosphere and ocean surface due to cloud formation by sulfate aerosols (Zepp *et al*., 2007). See Section 8.4 Enhanced marine cloud albedo for effects.

7. **Increased release of dimethylsulphonopropionate and dimethyl sulfide (DMS) at ocean surface from increased numbers of phytoplankton leading to potential increase in marine cloud formation (Wingenter *et al.*, 2007; Secretariat of the Convention on Biological Diversity, 2009).**

a) Potential toxicity of DMS to marine life.

b) Reduced light penetration in the ocean due to localized reduction in incoming solar radiation and shift to greater fraction of diffuse light compared to direct light with increased cloud cover. Leads to decrease in productivity in the euphotic zone (Raymont, 1980; Secretariat of the Convention on Biological Diversity, 2012), including impact on deeper corals and kelp (The Royal Society, 2008).

c) Cooling of atmosphere and ocean surface due to cloud formation by sulfate aerosols (Zepp *et al*., 2007). See Section 8.4 Enhanced marine cloud albedo for effects.

8. **Increased release of halocarbons at ocean surface from increased numbers of phytoplankton (Roy, 2010; Vaughan & Lenton, 2011).**

   a) Potential impacts of increased halocarbon concentrations on marine life (which are currently poorly known, e.g. Christian *et al*. 2010).

9. **Increased release of nitrous oxide at ocean surface from increased numbers of phytoplankton (Fuhrman & Capone, 1991; Law, 2008).**

   a) Potential impacts of nitrous oxide on marine life including changes to phytoplankton growth rates (Zhengbin *et al*., 2003).

10. **Increased release of methane at ocean surface from increased numbers of phytoplankton (Fuhrman & Capone, 1991).**

    a) Potential impacts of methane on marine life.

11. **Reduced light penetration in ocean due to large algal blooms at surface (Secretariat of the Convention on Biological Diversity, 2009).**

    a) Decrease in productivity in the euphotic zone (Raymont, 1980), including impacts on deeper corals and kelp among others (The Royal Society, 2008).

12. **Increased flux of organic matter and particulate organic carbon sinking to the deep ocean and sea floor (Wolff *et al.*, 2011).**

a) Enhanced biomass and abundance of benthic species (Levin *et al*., 2001; Glover *et al*., 2002).

b) Changes in benthic species composition and possible increase *or* decrease in biodiversity (Lampitt *et al*., 2008).

c) Risk of low oxygen conditions in bottom waters in continental margins due to increased rates of decomposition, with associated impacts on marine organisms (Lampitt *et al*., 2008).

13. Increase in anoxic or hypoxic regions in mid and deep oceans due to increased respiration during decomposition of additional organic matter (The Royal Society, 2009).

a) Biodiversity loss; responses of marine organisms to low oxygen are almost all negative (Lampitt *et al*., 2008).

b) Fish mortality with hypoxia and anoxia (Joyce, 2000; Glibert *et al*., 2008).

c) Shifts in microbial communities (Fuhrman & Capone, 1991).

d) Changes in food-web dynamics (Diaz, 2001).

e) Damage to sensitive habitats such as coral reef even with small-scale fertilization (UNESCO/IOC, 2008).

14. Increased acidification in the deep ocean due to increased CO_2 (re-mineralized from sinking organic matter; Cao & Caldeira, 2010).

a) Impacts on deep-sea organisms (e.g. squid), which can be highly sensitive to small changes in pH (Seibel & Walsh, 2001; Barry *et al*., 2004; Vetter & Smith, 2005; Cao & Caldeira, 2010).

b) Decline in fish populations due to reduced hatching and survival (Ishimatsu *et al*., 2004).

c) Change in fish communities as some taxa (e.g. teleosts) less sensitive to increased CO_2 (Ishimatsu *et al*., 2004; Pörtner *et al*., 2004).

d) Impact on calcification rates of calcifying organisms. Either decreased (Riebesell *et al*., 2007) or increased rates (Iglesias-Rodriquez *et al*., 2008; Wood *et al*., 2008).

e) Decrease in food chain length and change in composition resulting in reduced food availability for higher trophic levels (IPCC, 2005).

NOTE – The following effects are specific to particular nutrients used in fertilization.

15. Iron: Localized depletion of macronutrients including silicic acid in sea-surface waters 'downstream' of stimulated algal blooms (Chisholm *et al.*, 2001; Secretariat of the Convention on Biological Diversity, 2009) potentially leading to redistribution of nutrients on a global scale (Sarmiento & Orr, 1991; Lampitt *et al.*, 2008; Secretariat of the Convention on Biological Diversity, 2009).

a) 'Downstream' reduction of macronutrients and therefore productivity for thousands of kilometers (Jin *et al*., 2008).

b) Changes in composition of phytoplankton communities as nutrients successively become critically limiting (Egge & Aksnes, 1992; Chisholm *et al*., 2001).

c) Long-term reduction in primary production and biological export of carbon to depth (Gnanadesikan *et al*., 2003; Aumont & Bopp, 2006; Zahariev *et al*., 2008).

d) Reduced fish populations due to reduced primary productivity (Lampitt *et al*., 2008).

e) Reduced diatom production due to limiting silicic acid limits, despite availability of other macronutrients and iron (Secretariat of the Convention on Biological Diversity, 2009).

f) Changes to food web structures and dynamics (Egge & Aksnes, 1992).

16. Nitrogen: Increased eutrophication in coastal areas due to enhancement of existing nitrogen loading from terrestrial run-off if the fertilization were to take place close to

coastal waters (Secretariat of the Convention on Biological Diversity, 2009). (NOTE: It is unlikely that eutrophication could occur in the open ocean due to differing circulation patterns, nutrient supply mechanisms and biological communities compared with coastal seas; Lampitt *et al.*, 2008).

a) Increased phytoplankton productivity and biomass leading to blooms.

b) Shift in phytoplankton community composition (Lampitt *et al*., 2008).

c) Increase in harmful algal blooms at the coast, such as red tides, brown tides and *Pfiesteria*. Toxic blooms can kill fish, and accumulation of toxins in fish and shellfish can kill humans (Underdal *et al*., 1989; Hallegraeff, 1993).

d) Loss of biodiversity and fisheries as algal blooms deplete oxygen levels, causing hypoxia and anoxia – 'dead zones' (Glibert *et al*., 2008).

e) Community shifts in coral reef areas leading to algal overgrowth of corals and ecosystem disruption (Lapointe, 1999; McCook *et al*., 2001).

17. Nitrogen: Increased formation of ammonium and ammonia at the ocean surface due to degradation of added urea (Secretariat of the Convention on Biological Diversity, 2009).

a) Potential toxicity to marine life, although it is unlikely that toxic ammonium concentrations would be reached (Secretariat of the Convention on Biological Diversity, 2009).

18. Nitrogen: Volatilization of ammonia to atmosphere due to degradation of added urea (Secretariat of the Convention on Biological Diversity, 2009).

2 Enhanced ocean upwelling and downwelling

The natural process of upwelling – in which deep ocean waters are brought to the surface by ocean circulation – would be enhanced using manmade pipes and pumps. The 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 downwelling would be enhanced by cooling CO_2-rich ocean surface waters, causing them to sink to the deep ocean.

Intended climate effect: Enhanced upwelling methods would bring nutrient-rich waters from the deep ocean to the surface. The abundance and growth of phytoplankton, which absorb CO_2 during photosynthesis, would be enhanced resulting in an increased 'drawdown' of CO_2 from the atmosphere. Carbon is stored within the phytoplankton, and, after they die or are eaten, a small proportion sinks into the deep sea in fecal matter and other detritus where it is removed from the atmosphere for decades to centuries. Downwelling methods aim to increase the rate at which CO_2-rich surface waters sink to the deep ocean where the CO_2 is retained over long timescales (Secretariat of the Convention on Biological Diversity, 2012).

Implementation: It has been suggested that upwelling could be enhanced using free-floating or tethered vertical pipes to transfer water from a deep waters to the surface (Lovelock & Rapley, 2007). Pipes would be 100-200 m long and 10 m in diameter, with a one-way valve at the lower end for pumping stimulated by wave movement. It is estimated that 134 million pipes would be required to sequester one-third of the CO_2 produced by humans annually (Kithil, 2006; White *et al*., 2010; Atmocean Inc, 2012). The pipes would be focused in low-nutrient and low-productivity regions in the middle ocean (Maruyama *et al*., 2011).

Enhanced downwelling would involve the enhancement of the natural circulation of the ocean– such as the cycle of North Atlantic Deep Water (NADW) production - by reducing the temperature of surface waters, causing them to sink. Suggested methods include cooling sub-polar surface waters by 1°C using large floating pumps that form and thicken sea ice (Lenton & Vaughan, 2009; Zhou & Flynn, 2005). Cooling efforts would be focused in sub-polar regions (The Royal Society, 2009). Alternatively, floating pipes similar to those used for upwelling can be used, but with valves operating in the opposite direction (Salter, 2009).

2.1 Environmental changes and biodiversity and ecosystem effects:

Outlined below are the primary physical, chemical and biological environmental changes caused by the implementation of this technique. Where possible, the potential biodiversity and ecosystem effects of each environmental change are indicated.

1. **Increased primary productivity and phytoplankton biomass in surface ocean (Lovelock & Rapley, 2007).** There was a consistent increase in phytoplankton biomass and primary production in five ship-based experiments (McAndrew *et al*., 2007).

For effects of increased primary productivity and phytoplankton biomass (blooms), see Section 1. Direct Ocean Fertilization, point 3 - 15. The effects of enhanced upwelling would be similar, although at a different scale and location.

2. **Increased acidification of the surface ocean, as water brought up from the deep ocean contains high concentrations of CO_2 (Secretariat of the Convention on Biological Diversity, 2012), leading to ocean acidification into areas not yet impacted (Secretariat of the Convention on Biological Diversity, 2009)**.

a) Impacts on rate of calcification by calcifying organisms (IPCC, 2005). Over a dozen studies of corals and coralline algae have indicated reductions in calcification rates (IPCC, 2005), although longterm trends are still uncertain (Beare *et al*., 2013). Leads to a possible community shift to higher ratios of non-calcifiers over calcifiers (Pörtner *et al*., 2004).

b) Loss of calcifying species from the bottom or middle of the food web (Cooley & Doney, 2009) with impacts for higher trophic levels.

c) Changes in communities, such as domination by species less sensitive to CO_2 and increased abundance of larger species (IPCC, 2005; Finkel *et al*., 2010).

d) Damage to ecological communities sensitive to acidification – e.g. coral reefs – in areas not previously affected.

e) Increase in nitrogen and carbon dioxide fixation by the cyanobacteria Trichodesmium, which supports a large proportion of primary productivity in low-nutrient areas of oceans. This would result in significant changes in marine nitrogen and carbon cycles, potentially driving some oceanic systems towards phosphate limitation (Secretariat of the Convention on Biological Diversity, 2009).

3. Localized cooling of sea surface with upwelling of cool water from the deep ocean (Secretariat of the Convention on Biological Diversity, 2009). Potentially leading to changes in ocean circulation (Shepherd, 2011).

a) Reduced primary productivity in surface waters leading to decline in phytoplankton communities.

b) Changes to community composition and food-web dynamics.

c) Preservation of coral reefs by counteracting increased surface temperatures (Secretariat of the Convention on Biological Diversity, 2009).

d) Impacts on pelagic communities of changes in circulation including changes in community structure and composition.

4. Reducing stratification of seawater and enhancing mixing as a result of artificially enhanced upwelling (Shepherd, 2011).

a) Changes to community composition and food-web dynamics.

b) Loss of characteristic ecological communities associated with different ocean layers.

5. Increased downwelling of cooled surface waters to the deep ocean (Secretariat of the Convention on Biological Diversity, 2012).

a) Alteration of deep-sea ecological communities including changes in structure, composition and diversity. Effects will be long-lasting as many species are long-lived (Secretariat of the Convention on Biological Diversity, 2012)

b) Unknown impacts on deep-sea microbes (Secretariat of the Convention on Biological Diversity, 2012)

c) Creation of low-nutrient zones where downwelling occurs leading to reduced productivity in surface waters.

6. Increased prevalence of manmade structures in the ocean providing hard substrates in open ocean environments and acting as artificial reefs (Langhamer 2012).

a) Mechanism for spread of non-native and invasive species as large numbers of structures distributed at regular intervals across the open ocean will act as artificial reefs and enhance the settlement of larvae of benthic species, thereby potentially serving as ‘stepping stones’ to extend species distributions. Offshore energy platforms are known to accumulate otherwise coastal populations of native and invasive species (Langhamer 2013).

b) Increasing the number of structures in open ocean waters may interfere with normal migratory patterns and behaviors of highly-migratory species. Structures are likely to act like Fish Aggregating Devices (FADs) which influence the behavior and movements of species such as tuna, causing them to gather around the structures. This clustering can increase vulnerability to fishing gear, including purse seine fishing methods (LeRoy *et al*. 2013)

3 Enhanced weathering

Enhanced weathering would increase the rate at which CO_2 is naturally removed from the atmosphere by the weathering (dissolution) of carbonate and silicate rocks, which react with CO_2 to form bicarbonates.

Intended climate impact: Enhanced weathering climate engineering would increase the rate of weathering (dissolution) of basic rocks which naturally react with CO_2 from the atmosphere, converting it to bicarbonate and silicate minerals (‘carbonation’). Proposed approaches involve various methods of increasing the surface area of rock exposed to CO_2.

3.1 Enhanced weathering - spreading basic or alkaline materials on land

Basic or alkaline rocks – such as olivine or serpentine – would be quarried and ground into fine particles. These materials would then be spread on agricultural and forest soils and river catchments where they would undergo accelerated weathering, reacting with atmospheric CO_2 and converting it to mineral compounds.

Implementation: One suggested method of enhanced weathering would involve quarrying of basic or alkaline materials such as olivine (magnesium iron silicate) or serpentine (magnesium iron phyllosilicate), grinding them to form to fine particles, and spreading the materials on agricultural and forest soils and river catchments to increase the surface area exposed to weathering (Secretariat of the Convention on Biological Diversity, 2012).

It is suggested that the technique would be most effective in the humid tropics (Schuiling & Tickell, 2010; Secretariat of the Convention on Biological Diversity, 2012). It is estimated that 0.6 GtC/yr of carbon could be sequestered if the Amazon and Congo basins were both fully treated with olivine at an application rate of approximately 300 $g/m^2/yr$ (Köhler *et al*., 2010). Large quantities of suitable rocks would need to be quarried from natural silicate formations close to the surface, for example in Lake District and Cornwall in the UK (Renforth, 2012). It has been estimated that to remove as much CO_2 as we are currently emitting, approximately 7 km^3/yr (approximately twice the current rate of coal mining) of ground silicate materials would be required (The Royal Society, 2009).

3.1.1 Environmental changes and biodiversity and ecosystem effects:

Outlined below are the primary physical, chemical and biological environmental changes caused by the implementation of this technique. Where possible, the potential biodiversity and ecosystem effects of each environmental change are indicated.

1. **Large scale quarrying and transportation of basic or alkaline materials (Goff & Lackner, 1998; Secretariat of the Convention on Biological Diversity, 2012).** Approximately 7 km^3 of ground basic or alkaline materials per year would need to be quarried. This is approximately twice the current rate of coal mining (The Royal Society, 2009).

For impacts of mining, please refer to Section 1 Direct Ocean Fertilization, point 1.

2. **Changes in soil properties including structure, density, aggregation and water retention with addition of powdered alkaline rock.**
   a) Potential increase in productivity due to facilitated oxygen and water infiltration and storage (Bronick & Lal, 2005).

3. **Increased availability of soil nutrients (e.g. phosphorus, molybdenum) with addition of mined materials on land (Secretariat of the Convention on Biological Diversity, 2012)**
   a) Increased plant productivity (Shackley & Sohi, 2010); liming of soils (a variation on this technique) often results in increased crop yields (Haynes & Naidu, 1998).

   b) Changes in plant community structure and diversity with expansion of rapid-growing nutrient-exploiting species.

   c) Changes to food web structure and dynamics.

   a) Reduced requirement for fertilizer applications and therefore eutrophication and the associated biodiversity impacts.

   b) Increase in microbial activity (Shackley & Sohi, 2010).

4. **Increase in soil pH – i.e. increased alkalinity (Secretariat of the Convention on Biological Diversity, 2012)**
   a) Change in ecological community composition and structure with an increase in species favored by alkaline conditions.
   b) Increase in microbial activity up to pH 7. Initial increase in fungi but decline at higher pH (Lehmann *et al*., 2011)
   c) Increase in plant productivity and growth (Haynes & Naidu, 1998).
   d) Change in nutrient availability with pH change leading to change in plant-community structure and composition based on differing nutrient use of species.

e) Altered pH of aquatic ecosystems due to run-off with effects on ecological communities (e.g. decline in organism health, change in community composition with shift to species less vulnerable to pH change (Secretariat of the Convention on Biological Diversity, 2012).

f) Reduction in manganese and aluminum toxicity for organisms in acidic soils i.e. pH < 5.5 (Adams & Wear, 1956).

5. **Increased soil albedo leading to reduced soil temperatures (Secretariat of the Convention on Biological Diversity, 2012).**

a) Reduced rate of biological processes including nutrient cycling.

6. **Disturbance to habitats in the humid tropics to spread basic materials for maximum effectiveness (Secretariat of the Convention on Biological Diversity, 2012).**

a) Destruction and fragmentation of tropical habitats to allow access to distribute materials onto soil.

b) Addition of alkaline materials over large areas of tropical soils.

7. **Leaching of bicarbonate ions and cations into freshwater bodies and the sea, leading to increased alkalinity (Secretariat of the Convention on Biological Diversity, 2012).**

a) Reduced acidity of freshwater bodies, with possible beneficial impacts in areas affected by acidification (Secretariat of the Convention on Biological Diversity, 2012).

b) Initial spike in pH may cause decline in aquatic species which are intolerant to alkali conditions resulting in change in community structure, shortened food chains and decline in biodiversity (Secretariat of the Convention on Biological Diversity, 2012). Particular impacts in continental shelf waters where compounds are at higher concentrations (Secretariat of the Convention on Biological Diversity, 2012).

c) Reduced impact of acidification on affected marine ecosystems and organisms (Kleypas *et al*., 1999; Riebesell *et al*., 2000; Secretariat of the Convention on Biological Diversity, 2012).

d) Change in relative growth and reproduction of some marine plankton (Shepherd, 2011).

8. **Leaching of biologically-available silicon into freshwater bodies and the sea** (Secretariat of the Convention on Biological Diversity, 2012).

   a) Regional increase in abundance of diatoms in the ocean (Secretariat of the Convention on Biological Diversity, 2012).

3.2 Enhanced weathering - *in situ*

CO_2 would be dissolved in liquid and injected into basic rocks in the Earth's crust where it would react with basic or alkaline minerals such as olivine to form mineral compounds.

Implementation: Proposals for enhanced weathering *in situ* aim to enhance carbonation of peridotite rock formations (formations containing a high proportion of the mineral olivine) in the Earth's upper mantle, by injecting CO_2-rich fluids into the geology (Kelemen & Matter, 2008; Kelemen *et al*., 2011). The olivine reacts with CO_2 to form solid carbonate minerals.

It is estimated that there is the potential to sequester more than 1 GtC/yr of carbon in Oman alone by this method (Kelemen & Matter, 2008). Researchers at Columbia University and the U.S. Geological Survey have identified large suitable rock formations (6000 square miles) at or near the surface in the United States that could also be used to absorb CO_2 (Krevor *et al*., 2009). Other suitable reserves occur on spreading mid-ocean ridges in the Mid-Atlantic and Indian Ocean, the large igneous Bushveld intrusion in South Africa and the Stillwater formation in Montana (Kelemen *et al*., 2011).

Consuming 1 billion tons of CO_2 per year would require 1 million drill holes, equivalent to the current number of producing oil and gas wells in the US (Kelemen *et al*., 2011). For context, annual global CO_2 emissions were 34 billion tons in 2011 (Olivier *et al*., 2012).

3.2.1 Environmental changes and biodiversity and ecosystem effects:

Outlined below are the primary physical, chemical and biological environmental changes caused by the implementation of this technique. Where possible, the potential biodiversity and ecosystem effects of each environmental change are indicated.

1. **Excavation of soil and overlying geology to expose alkaline rock formations such as peridotite formations rich in olivine minerals. Disposal of associated waste materials** (Goff & Lackner, 1998; The Royal Society, 2009).

For impacts of excavation, please refer to *Section 1 Direct Ocean Fertilization, point 1* *but* ***note*** *that excavation and drilling for* 'Enhanced weathering – *in situ' would have a significantly smaller spatial footprint as it involves drilling holes (and could utilize directional drilling to minimize the footprint further) rather than large scale mining or quarrying.*

2. **Impacts of injecting CO_2 into deep geology.**

   For impacts of injecting CO_2 into deep geology, please refer to Section 6.1. Geological CO_2 storage.

3.3 Enhanced weathering – adding basic or alkaline materials to ocean

Ocean alkalinity is increased by adding mined and processed carbonate or silicate materials to the surface ocean. The basic/alkaline materials react with CO_2 dissolved in the water, converting it to bicarbonate ions. The CO_2 content of the ocean is reduced allowing more CO_2 to be absorbed from the atmosphere.

Intended climate effect: Ocean alkalinity methods involve spreading basic or alkaline materials – such as powdered rocks containing olivine minerals, powdered limestone or liquid calcium hydroxide – across the surface ocean (Lenton & Vaughan, 2009; Secretariat of the Convention on Biological Diversity, 2012). The minerals would react with dissolved CO_2 to form carbonates and silicates (Kohler *et al*., 2013). The concentration of CO_2 in the ocean would be reduced, leading to increased uptake of atmospheric CO_2. Some dissolution products (e.g. silicic acid) would also fertilize phytoplankton, increasing the biological pump.

Implementation: Minerals would be dispersed from ships in the mid-ocean (Secretariat of the Convention on Biological Diversity, 2012). Alternative suggestions include releasing CO_2-rich solutions into the ocean (The Royal Society, 2009; Kelemen *et al*., 2011), either directly through a pipeline into the sea or indirectly by discharging solutions into rivers (Secretariat of the Convention on Biological Diversity, 2012).

Alkaline materials would be added to the open ocean, perhaps focused in upwelling regions where CO_2-rich waters are brought to the surface (Harvey, 2008). Alternatively, materials may be added to the ocean indirectly through river channels, so would be focused in coastal zones (Secretariat of the Convention on Biological Diversity, 2012). A further proposal is the possibility of adding materials directly to intertidal and shallow sea zones (Schuiling & de Boer, 2010; 2011)

It is estimated that addition of 3Pg (petagrams[2]) per year of olivine over the entire open ocean would compensate approximately 9% of current anthropogenic CO_2 emissions. Approximately 300 large ships operating throughout the year would be needed to distribute this volume of olivine, and it would entail a significant increase in global olivine mining (Kohler *et al*., 2013). *In this report, we focus on the addition of powdered rock materials*.

3.3.1 Environmental changes and biodiversity and ecosystem effects:

Outlined below are the primary physical, chemical and biological environmental changes caused by the implementation of this technique. Where possible, the potential biodiversity and ecosystem effects of each environmental change are indicated.

1. **Large-scale mining and transportation of alkaline minerals** (Secretariat of the Convention on Biological Diversity, 2012): approximately 7 km^3 of ground alkaline materials per year would need to be mined. This is approximately twice the current rate of coal mining (The Royal Society, 2009).

[2] Petagram = 1,000,000,000 tonnes

For impacts of mining refer to *<u>Section 1 Direct Ocean Fertilization, point 1</u>.*

2. **Increased alkalinity of surface-ocean due to addition of alkaline minerals.** In the order of an increase of pH of 0.007 after 10 years of olivine addition (Kohler *et al*., 2013).

   a) Initial spike in pH may cause decline in marine species which are intolerant to alkali conditions resulting in change in community structure, shortened food chains and decline in biodiversity (Secretariat of the Convention on Biological Diversity, 2012). This can be MI minimized by appropriate selection of materials and particle size and through rapid dilution from vessels (Secretariat of the Convention on Biological Diversity, 2012)

   b) Reduced impact of acidification on affected ecosystems and organisms (Kleypas *et al*., 1999; Riebesell *et al*., 2000; Secretariat of the Convention on Biological Diversity, 2012).

   c) Change in relative growth and reproduction of some plankton (Shepherd, 2011).

3. **Increased calcium ions in the surface ocean due to added materials (Secretariat of the Convention on Biological Diversity, 2012).**

   a) Potential for increased calcium bicarbonate to promote coral growth (as observed in studies; Marubini & Thake, 1999).

   b) Impacts on biodiversity are not well understood (Secretariat of the Convention on Biological Diversity, 2012).

4. **Increased concentration of silicic acid in the ocean, produced during the dissolution of silicate minerals (Kohler *et al.*, 2013).**

   a) Increased phytoplankton productivity in areas where silicic acid is currently a limiting nutrient (Kohler *et al*., 2013).

   b) Shift in composition of phytoplankton populations towards diatoms (Kohler *et al*., 2013)

5. **Reduced water transparency due to an increase in suspended particulate matter leading to reduced light penetration in the ocean (Kohler *et al.*, 2013).**

a) Reduced productivity in the upper ocean compared to present-day values (Secretariat of the Convention on Biological Diversity, 2012). However, impacts on marine ecosystems are not fully understood due to the complex balance of upwelling nutrients and the light availability for oceanic photosynthesis (Russell *et al*., 2012).

6. 'Settling out' of added materials onto seabed (most likely in shallower waters e.g. continental seas)

a) Smothering of benthic organisms leading to strong local-scale productivity changes and alteration of the water column dynamics

4 Biomass for carbon sequestration

Plants take up CO_2 from the atmosphere and it is retained in the ecosystem as biomass, litter or soil carbon until returned to the atmosphere by respiration, decomposition or fire. Carbon can therefore be stored as standing biomass e.g. in trees (see Section 7 Afforestation and reforestation) or the biomass can be harvested and stored on land (buried in anaerobic stores, or as biochar) or in the ocean.

Intended climate effect: Plants absorb atmospheric CO_2 during photosynthesis, converting it to organic matter. Normally this organic matter releases this CO_2 back into the atmosphere when the organic matter decays. Climate engineering techniques propose to 'lock' this CO_2 in long-term stores, removing it from the atmosphere for decades to centuries. **Note: Most biomass-based techniques require harvesting of biomass and for high rates of sequestration would require increased production of biomass feedstocks**. ***The impacts of biomass production – listed below in section 4.1 - are therefore relevant to all of the biomass techniques.***

4.1 Biomass production (relevant to all biomass techniques)

All biomass climate engineering techniques involve the production of dedicated biomass feedstocks. The current amount of 'waste' biomass (e.g. forest and crop residues) is limited, since these products have other uses or ecosystem benefits, so biomass production at scale for climate

engineering purposes would need purpose-planted crops or trees. There are a wide range of feedstocks that could be used including: coppiced trees,* Miscanthus *(for lignocellulose); oilseed rape, canola, sunflower, palm, soy (for biodiesel); and wheat grain, barley, sugar beet (for bioethanol). Production would either require more intensive production on existing land, or new plantations, the extent of which would either replace semi-natural ecosystems, or displace food crops into semi-natural ecosystems.

4.1.1 Environmental changes and biodiversity and ecosystem effects:

Outlined below are the primary physical, chemical and biological environmental changes caused by the implementation of this technique. Where possible, the potential biodiversity and ecosystem effects of each environmental change are indicated.

1. Conversion of land for large-scale production of biomass feedstocks.

a) Loss, degradation and fragmentation of natural and semi-natural habitats (Secretariat of the Convention on Biological Diversity, 2012) particularly if plantations are established (see b) below). For example one study estimated that 0.4–114 million hectares of natural land could be lost due to biodiesel production alone, depending upon the feedstock and whether current agricultural land is used (Koh, 2007). Even if marginal land, e.g. European set-aside arable land, is replaced by biomass crops, effects on overall biodiversity are likely to be negative (Anderson & Fergusson, 2006).

b) Conversion of habitats to monoculture plantations supporting low species diversity (Koh, 2007; Biofuels watch, 2009).

2. Biodiversity and ecosystem impacts of species used for biomass or biofuel feedstocks

a) Use of fast-growing tree varieties, altering habitat composition and causing a loss of biodiversity (International Declaration Opposed to Biochar: www.rainforest-rescue.org/news/1150/declaration-biochar-a-new-big-threat-to-people-land-and-ecosystems, accessed 2012).

b) Potential for introduction of invasive species. For example, grasses used for biofuel, such as sweet sorghum (*Sorghum bicolor*), giant reed (*Arundo donax*) and reed canary grass (*Phalaris canariensis*) are invasive in particular habitats in the U.S. (Raghu *et al*., 2006). Biofuel crops may also carry invasive pathogen and pest species (The Royal Society, 2008b).

c) Use of short-rotation harvesting systems which increases the frequency with which habitats are disturbed.

d) Use of a narrow range of tree varieties specifically selected for this purpose (either using traditional breeding or genetic modification) will alter habitat composition and structure for a range of other species.

e) Potential for feedstock plantations to be beneficial to local biodiversity if replacing low diversity (e.g. intensively managed) or degraded landscapes and if they are well managed. For example, compared to conventional crops, mixed grasses or large-scale short-rotation coppice willow, can benefit birds, butterflies and flowering plants (Cunningham *et al*., 2004b; Semere & Slater, 2005; Sage *et al*., 2006).

3. **Repeated biomass harvesting and removal from site – either of existing biomass, or of dedicated biomass feedstocks.**

a) Removal of nutrients from the system resulting in reduced soil fertility and a reduction in productivity in the long term (Hartemink, 2005; Zeng, 2008; Biofuels watch, 2009). For example in tropical rainforests, a large fraction of nutrients are locked in live and dead trees rather than in the soil and so if material is removed, productivity could be severely limited over time (Zeng, 2008).

b) Harvesting and removal of crop residues linked to high rates of soil erosion, resulting in nutrient depletion and greater sensitivity to desiccation (Biofuels watch, 2009; Blanco-Canqui & Lal, 2009), and reducing soil quality and productivity (Lal, 2010).

c) Sedimentation of water bodies receiving the eroded soil, leading to 'smothering' and reduced photosynthesis due to reduced light penetration (Martinelli & Filoso, 2008).

d) Fragmentation of habitats and introduction of alien species by the road networks needed for biomass harvesting.

e) Mortality and disruption of life-cycles due to the frequent physical disturbance, traffic and noise of harvesting operations.

4. **Increased use of fertilizers and pesticides for feedstock production (The Royal Society, 2008b) as nutrient availability in plantations declines over time (Hartemink, 2005).**

   a) Eutrophication of water bodies from nitrogen and phosphorus runoff with resulting impacts on biodiversity (Smith *et al*., 1999).

   b) Loss of biodiversity as plants adapted to high-nutrient conditions dominate, with knock-on effects for habitats, food webs and species dependent on original conditions.

5. **Increased water use for feedstock production.** For example *Miscanthus* and short-rotation coppice, which are potential crops for biofuels, are predicted to have higher water demands than arable crops (Rowe *et al*., 2007). This is a near-inescapable consequence of high growth rates.

   a) Reduced biologically available water in adjacent ecosystems.

6. **Increased cloud formation in regions with biomass production due to release of isoprene (depending on feedstock type - particularly coniferous forestry), which creates cloud condensation nuclei (Meskhidze & Nenes, 2006; Arneth *et al.*, 2007; Arneth *et al.*, 2008; Rayfuse *et al.*, 2008).**

   a) Reduced air quality due to emissions of volatile organic carbon, such as isoprene, from plants. The VOC reacts with oxides of nitrogen to form tropospheric ozone, which is harmful to plants and animals at high concentrations (The Royal Society, 2008b).

   b) Potential increase in primary productivity with more uniform light distribution in diffuse-light conditions. For example, in forests, diffuse light penetrates the canopy better than direct light (Kanniah *et al*., 2012; Russell *et al*., 2012).

c) Reduction in intensity of sunflecks – bursts of strong light which penetrate vegetation canopies and contribute 10 – 90% of light to understory vegetation – with implications for growth of ground-level plants (Leakey *et al*., 2005; Montagnini & Jordan, 2005; Secretariat of the Convention on Biological Diversity, 2012).

4.2 Biomass storage on land

Biomass is harvested and stored in anaerobic conditions on land – either by burial in deep trenches, or in air-tight stores - to reduce the rate of decomposition.

Implementation: Biomass would be stored in anaerobic conditions on land. One suggestion is that vegetation could be harvested and buried in trenches below the organic horizon and rooting zone and below the water table or some other barrier to oxygen diffusion. Another proposal is that vegetation could be stored in anaerobic above-ground shelters (Zeng, 2008). The lack of oxygen in these stores would limit decomposition of the biomass and the carbon would remain stored.

4.2.1 Environmental changes and biodiversity and ecosystem effects:

Outlined below are the primary physical, chemical and biological environmental changes caused by the implementation of this technique. Where possible, the potential biodiversity and ecosystem effects of each environmental change are indicated.

These impacts are in addition to those listed under <u>'Biomass production' (Section 4.1)</u>.

1. **Removal of existing semi-natural biomass sources (i.e. standing forests, shrubland) to be stored in anaerobic stores. This is different from the use of purpose-grown feedstocks.**

a) Loss of semi-natural forest and/or shrubland habitats leading to loss of forest biodiversity (Zeng, 2008)

b) Loss of dead wood habitats, with resulting impacts on biodiversity including saprophytic species important in nutrient cycling (Read & Perez-Moreno, 2003).

c) Reduction in forest fire regimes if dead wood is collected and buried rather than being left to accumulate (Zeng, 2008) leading to change in community structure.

2. **Clearance of land to create trenches for storage of biomass in anaerobic conditions (Zeng, 2008).**
    a) Habitat loss, degradation and fragmentation.
    b) Biodiversity and ecosystem impacts of disposal of spoil; for instance covering of other habitats and erosion into rivers.

4.3 Biomass storage in the ocean

Biomass is harvested, baled and deposited onto the sea floor at depths below 1000-1500m where conditions (low temperature, low oxygen, limited mixing) limit decomposition.

Implementation: Proposals include 'Crop Residue Oceanic Permanent Sequestration' (Metzger & G., 2001; Strand & Benford, 2009). This would involve baling crop residues and placing them on ocean sediments at depths over 1000-1500 m (Strand & Benford, 2009). At such depths there is limited mixing between the deep and upper oceanic layers and terrestrially derived organic matter is relatively stable due to the cold, limited oxygen availability and the apparent lack of a marine mechanism for the breakdown of lignocellulose (Strand & Benford, 2009). Effects could also be minimized by placing bales in areas of high sedimentation (Strand & Benford, 2009). The type of packaging would be a significant factor when assessing potential impacts as its permeability to water and gases would influence the flux of substances into near-seabed water. Additionally, if the bales were buried within the sediment, such impacts are likely to be significantly reduced (Secretariat of the Convention on Biological Diversity, 2012).

Authors of the CROPS proposal suggest that an annual layer of biomass 4m deep across 1000km^2 of sea bed could sequester 0.6Gt C per year (Strand & Benford, 2009).

4.3.1 Environmental changes and biodiversity and ecosystem effects:

Outlined below are the primary physical, chemical and biological environmental changes caused by the implementation of this technique. Where possible, the potential biodiversity and ecosystem effects of each environmental change are indicated.

These impacts are in addition to those listed under <u>'Biomass production' (Section 4.1)</u>.

1. **Significant, but relatively local/regional-scale, physical impact on deep ocean seabed due to coverage with harvested terrestrial biomass, e.g. by ballasted bales** (Secretariat of the Convention on Biological Diversity, 2012).

    a) Habitat loss for seabed organisms.

    b) Altered composition and structure of biological communities of deep-ocean sediment (Strand & Benford, 2009).

    c) Change in nutrient cycling processes involving ocean and seabed interactions.

2. **Increased nutrient availability in the deep ocean and on sea floors due to introduction of harvested terrestrial biomass.**

    a) Increase in biomass of benthic organisms (Secretariat of the Convention on Biological Diversity, 2012).

    b) Change in benthic community structure and composition e.g. increased scavenger species (Shepherd, 2009)

3. **Reduced oxygen in the deep ocean due to decomposition of introduced organic matter i.e. the harvested terrestrial biomass (The Royal Society, 2009). However, this would be influenced by location and packaging (see 'Implementation' above).**

    a) Loss of biodiversity; responses of marine organisms to low oxygen are almost all negative (Lampitt *et al*., 2008).

b) Fish mortalities (Glibert *et al*., 2008).

c) Alteration of food-web dynamics (Diaz, 2001).

4. **Increased release of hydrogen sulfide in the deep ocean during decomposition of organic matter (Secretariat of the Convention on Biological Diversity, 2012). However, this would be influenced by location and packaging (see 'Implementation' above).**

   a) Reduced local oxygen levels effecting respiration and performance of higher marine organisms (IPCC, 2005).

5. **Increased release of methane and nitrous oxide during decomposition of organic matter** (Secretariat of the Convention on Biological Diversity, 2012). **However, this would be influenced by location and packaging (see 'Implementation' above).**

   a) Potential toxicity to marine organisms.

   b) Change in composition and structure of biological communities to favor species enhanced by these gases.

6. **Eventual return of carbon and nutrients (released during decomposition) to upper ocean (The Royal Society, 2009). Over century to millennial timescales.**

4.4 Biochar

Biomass is burned in low oxygen conditions ('pyrolysis') to form a solid product similar to charcoal called biochar. This is then dug or ploughed into soils where it acts as a carbon reservoir.

Implementation: Biochar is a charcoal-like product produced by the decomposition of biomass in low or zero-oxygen conditions using pyrolysis or gasification (Secretariat of the Convention on Biological Diversity, 2012). The flammable gases driven off in the process are available as an energy source. Potential sources of biochar include dedicated biomass feedstocks, as well as agricultural, forestry and food wastes, other organic waste including manure and sewage, or 'slash and char' shifting agriculture (Sohi *et al*., 2009; Vaughan & Lenton, 2011).

Once biomass has been converted to biochar, it would be dug or ploughed into soils on tillable land where it would act as a carbon reservoir, potentially for thousands of years (Shackley & Sohi, 2010; Secretariat of the Convention on Biological Diversity, 2012). This process is likely to be repeated rather than once-off. The effectiveness of carbon storage depends on the type of soil, as one ten-year study found that mixing biochar with leaf litter increased rather than decreased carbon release because of increased activity by micro-organisms (Wardle *et al*., 2008). Biochar is also suggested to enhance the nutrient content of soils (Vaughan & Lenton, 2011), though this is inconsistent with claims of its low decomposition rate.

The scale at which biochar would need to be implemented and the global upper limit for biochar application are, as yet, poorly defined (The Royal Society, 2008; Vaughan & Lenton, 2011). It is estimated that up to 1 billion hectares of new tree plantations would be required to produce a climatically significant volume of biochar (Read, 2008), and that the biochar storage capacity of all global croplands and grasslands amounts to ~400Pg C in total (Vaughan & Lenton, 2011). Biochar can only be incorporated into tillable land, such as croplands.

Up to 0.21Pg C per year might be offset if all slash-and-burn agriculture was replaced with 'slash-and-char' methods. A further 0.16Pg C per year could be stored by converting agricultural and forestry wastes to biochar (Vaughan & Lenton, 2011). This could be increased to approximately 5-9 GtC/yr if all renewable fuel use in 2100 was met with pyrolysis and conversion to biochar, rather than traditional combustion (Lehmann *et al*., 2006).

4.4.1 Environmental changes and biodiversity and ecosystem effects:

Outlined below are the primary physical, chemical and biological environmental changes caused by the implementation of this technique. Where possible, the potential biodiversity and ecosystem effects of each environmental change are indicated.

These impacts are in addition to those listed under <u>'Biomass production' (Section 4.1)</u>.

1. ***Addition of biochar can have effects on soil microbial communities through the many physical and chemical changes to soils (e.g. through changes in soil structure, aggregation, water***

retention etc.). The following effects could be caused by any of the environmental changes below:

a) Change in diversity of soil bacteria, archaea and fungi. Potentially a decrease (Jin, 2010; Taketani & Tsai, 2010; Khodadad *et al*., 2011), leading to Changes in microbial community composition and structure (Jin, 2010; Lehmann *et al*., 2011).

b) Temporary increase in soil microbial activity (Steiner *et al*., 2003; Steiner *et al*., 2008; Shackley & Sohi, 2010).

c) Increase in activity of mycorrhizal fungi and thus plant growth (Yamato *et al*., 2006; Rondon *et al*., 2007; Warnock *et al*., 2007).

d) Changes to biomass and activity of meso-faunal species e.g. earthworms. Increase or decrease (Shackley & Sohi, 2010; Van Zwieten *et al*., 2010; Gomez-Eyles *et al*., 2011).

2. **Change in soil bulk density and aggregation with ploughing in of biochar with impacts on water retention and aeration (Shackley & Sohi, 2010).** Biochar has a lower bulk density than that of mineral soils and is therefore likely to reduce overall bulk density of soil, although increases are also possible (Verheijen *et al*., 2010).

   a) Increase in productivity as improved soil structure facilitates oxygen as well as water infiltration and storage (Bronick & Lal, 2005).

   b) Change in soil microorganism activity.

   c) Soil compaction through use of machinery to spread biochar (Verheijen *et al*., 2010).

3. **Increased soil fertility due to increased retention of nutrients with addition of biochar (e.g. phosphorus, potassium and zinc).**

   a) Initial increase in plant productivity including enhanced root growth (Matsubara *et al*., 2002; Noguera *et al*., 2010). However, often only achieved with additional use of nitrogen fertilizer (Gathorne-Hardy *et al*., 2009; Shackley & Sohi, 2010).

b) Longer-term decline in productivity as nutrients contained in biochar rapidly depleted (Steiner *et al*., 2007).

c) Change in plant community composition with change in abundance of certain species (Mikan & Abrams, 1995; 1996; Lehmann *et al*., 2011).

d) Change in incidence of plant disease. Studies have shown both reduced incidence of crop infection with applications of biochar (Matsubara *et al*., 2002; Nerome *et al*., 2005; Elad *et al*., 2010), and increased incidence (Bais *et al*., 2005).

e) Reduced eutrophication of aquatic systems due to potentially reduced nutrient leaching i.e. increased retention (Lehmann *et al*., 2006; Shackley & Sohi, 2010; Vaughan & Lenton, 2011).

4. Enhanced retention of water in soil due to increased organic matter in some soil types (Sohi *et al.*, 2009).

a) Increased plant productivity (Matsubara *et al*., 2002; Ernsting & Smolker, 2009; Noguera *et al*., 2010).

b) Reduced water stress in water-limited regions (Secretariat of the Convention on Biological Diversity, 2012).

c) Enhanced plant root growth and increased mycorrhizal activity (Matsubara *et al*., 2002; Yamato *et al*., 2006; Rondon *et al*., 2007; Warnock *et al*., 2007; Noguera *et al*., 2010).

d) Changes in community composition and structure to species favored by high soil-water conditions.

e) Reduced water delivery to downstream channels and water bodies with impacts for freshwater biodiversity.

f) Reduced run-off and thus soil erosion and leaching of agricultural nutrients that result in water pollution (Ernsting & Smolker, 2009)

g) Cooling of soil with implications for biological communities (Alfy Gathorne-Hardy pers. comm.).

5. **Change in soil pH (Shackley & Sohi, 2010) - increase or decrease depending on feedstock and processing (Lehmann *et al.*, 2011). Verheijen *et al.* (2010) suggest that most biochars have neutral to basic pH and many studies show an increase in soil pH after biochar application when the initial pH was low (i.e. acidic soils).**

    a) Increase in microbial activity with increase in pH (Shackley & Sohi, 2010) e.g. bacterial increase with increasing pH up to 7.

    b) Increase in fungal growth with increasing pH (Lehmann *et al*., 2011).

    c) Changes in microbial community composition and structure (Jin, 2010; Lehmann *et al*., 2011). For example, reductions in the diversity of bacteria, archaea and fungi have been found with biochar applications (Jin, 2010; Taketani & Tsai, 2010; Khodadad *et al*., 2011).

    d) Increase in plant productivity with increased pH (Shackley & Sohi, 2010).

    e) Reduced negative impacts of salts/metal cations with increased pH - biochar could help restore degraded or inundated land (Wingate *et al*., 2009).

    f) Change in meso-faunal activity with change in pH, e.g. reduced earthworm survival rates (Chan *et al*., 2008; Weyers *et al*., 2009).

6. **Reduced soil albedo (Briggs *et al.*, 2005; Oguntunde *et al.*, 2008) leading to potential increased in soil temperatures (Verheijen *et al.*, 2010).** The reduction in albedo will depend on factors such as the: original color of the soil, color of the biochar, amount added, degree of mixing, surface roughness, change in water retention, vegetation cover, time of year and aspect (Verheijen *et al*., 2010).

    a) Increased soil temperature with impact on metabolic rate and activity of soil organisms, impacting nutrient cycling rates etc.

7. **Change to rate of decomposition of soil organic matter; increase *or* decrease (Wardle *et al.*, 2008; Shackley & Sohi, 2010).**

    a) Change in productivity rate.

    b) Potential decrease in soil aggregation and water retention with increase in decomposition.

8. **Biochar may sorb polar compounds including toxic substances which otherwise inhibit biological processes (Zimmerman *et al.*, 2004; Cornelissen *et al.*, 2005; Yu *et al.*, 2006; Rhodes *et al.*, 2008).**

    a) Increase in biological productivity and processes (e.g. nitrogen fixation) due to reduced effective concentrations of toxic polar compounds in soils (Zimmerman *et al*., 2004; Cornelissen *et al*., 2005; Yu *et al*., 2006; Rhodes *et al*., 2008; Lehmann *et al*., 2011).

    b) Reduced availability and effectiveness of herbicides and pesticides leading to reduced productivity and possible compensatory increase in application (Jordan & Smith, 1971; Yang *et al*., 2006).

    c) Increased abundance of soil microbes (Lehmann *et al*., 2011).

9. **Biological decomposition of biochar (Hamer *et al.*, 2004) – resulting in oxidation leading to formation of carboxyl groups (Lehmann *et al.*, 2005) – and leaching from soils by percolating water or wind erosion (Nguyen *et al.*, 2008; Major *et al.*, 2010).**

    a) Possible toxicity to organisms.

    b) Increase in microbial activity.

    c) Changes in microbial communities.

    d) Impacts of direct contact or ingestion of biochar on soil megafauna are poorly understood (Verheijen *et al*., 2010).

10. **Increase in polycyclic aromatic hydrocarbons (formed during pyrolysis) in soils due to decomposition and leaching of biochar (Shackley & Sohi, 2010).**

    a) Soil and water pollution with toxic, mutagenic and/or carcinogenic impacts on organisms (Samanta *et al*., 2002).

    b) Accumulation in marine sediments and organisms with toxic, mutagenic and/or carcinogenic impacts on organisms (Nikolaou *et al*., 2009).

11. **Increase in heavy metals (contained in biochar formed from municipal solid waste, sewage sludge, treated wood etc.) in soils and water bodies (Shackley & Sohi, 2010).**

    a) Direct toxicity to soil micro-organisms and plants.

    b) Change in the composition and structure of soil microbial communities. Studies have shown potential decrease in community size and activity with increased metal contamination (Brookes & McGrath, 1984; Chander & Brookes, 1991; Konopka *et al*., 1999).

    c) Change in plant production and communities, with potential reduction in plant growth and reproduction. For example, a study of metals in soil found that plant growth decreased with increased metal concentration and reproduction was delayed (Ryser & Sauder, 2006).

    d) Bioaccumulation in higher trophic levels, including marine organisms, with potentially toxic effects (Boran & Altinok, 2010).

12. **Disruption of the soil and vegetation where tillage to incorporate biochar takes place in semi-natural or infrequently-tilled ecosystems such as grasslands.**

    a) Loss of plant and soil biodiversity as a result of tillage.

    b) Invasion of alien or weedy species.

4.5 Bioenergy and carbon storage (BECCS)

Biomass is harvested, processed and burned as a fuel ('biofuels'). Feedstocks could be purpose-grown (e.g. sugar beet for bioethanol, sunflower for biodiesel) or organic waste (food waste, crop

residue etc.). CO_2 emissions produced during the fermentation process and combustion of these biofuels is captured and transferred to long-term stores. Storage can be in geological or deep ocean stores (**Section 6.1 **and** Section 6.2**). Alternatively, CO_2 can be used in industrial processes (not covered by this report).

Implementation: Biomass can be burned as biofuel to provide energy. There are a wide range of feedstocks that could be used for the three main types of biofuel:

- Lignocelluloses fuel: forestry residues, wood, straw, coppice pellets/chips, *Miscanthus*
- Biodiesel: oilseed rape, canola, sunflower, palm oil, soy oil, algae
- Bioethanol: wheat grain, barley, sugar beet, sugar cane, sweet sorghum, fruits.

The CO_2 emissions released from the combustion of these fuels can be captured using either post-combustion or pre-combustion systems, or alternatively, using oxyfuel combustion. The captured CO_2 would then be transported via pipelines (for distances up to around 1,000 km) or using ships (for smaller amounts or for transportation overseas; IPCC, 2005).

Options for storage of the CO_2 are geological storage (e.g. oil and gas fields, coal beds, deep saline formations etc.), ocean storage (direct release into the ocean water column or onto the deep seafloor to form a 'lake') and industrial fixation of CO_2 into inorganic carbonates (IPCC, 2005). *The latter is not covered in this report*.

4.5.1 Environmental changes and biodiversity and ecosystem effects:

Outlined below are the primary physical, chemical and biological environmental changes caused by the implementation of this technique. Where possible, the potential biodiversity and ecosystem effects of each environmental change are indicated.

These impacts are in addition to those listed under 'Biomass production' (Section 4.1) and impacts of geological CO_2 storage (Section 6.1) or ocean CO_2 storage (Section 6.2).

1. **Environmental impacts associated with processing and transportation of biofuels.**

   a) Dust pollution from processing and transport of fuels (Toft *et al*., 1995; European Environment Agency, 2011) leading to 'smothering' of terrestrial and aquatic habitats, and reduced photosynthesis (Vardaka *et al*., 1995).

   b) Noise pollution from processing, transportation and storage (Toft *et al*., 1995) leading to disturbance to wildlife; impacts on foraging, predator avoidance, communication, reproductive success, population density, community structure and survival (Lengagne, 2008; Barber *et al*., 2010).

   c) Increased water abstraction for use in processing leading to a reduction in biologically available water in adjacent ecosystems.

2. **Fermentation waste from processing streams (The Royal Society, 2008).**

   a) Water pollution with resulting impacts on freshwater organisms.

   b) Soil pollution with resulting biodiversity impacts.

3. **Increased acidity of precipitation caused by emissions of nitrous oxide, ammonia and sulfur dioxide from biofuel processing (Timperley *et al.*, 1985; European Environment Agency, 2011).**

   a) Impacts of acid rain on terrestrial and freshwater biodiversity.

   b) Impacts of acid rain on marine biodiversity.

5 Direct air capture and storage (DAC)

Direct Air Capture involves the use of free-standing engineered structures covered in a sorbent material which selectively traps CO_2 from ambient air. This stream of pure CO_2 is then transferred to long-term storage sites. DAC structures, sometimes called 'artificial trees', can be as small as $12m^2$, and can be constructed in any area with good air flow.

The CO_2 captured using DAC can be stored in geological or deep ocean stores (Section 6.1 ***and*** Section 6.2***).***

Implementation: Direct Air Capture involves the capture and isolation of CO_2 from ambient air. Large, free-standing structures would be constructed with surfaces covered in CO_2-sorbing materials, such as solid ion-exchange resins, amines on silica, or strongly alkaline solutions such as sodium hydroxide (The Royal Society, 2009). These 'artificial trees' would be constructed on open areas of land with good air flow (Socolow *et al*., 2011). The isolated stream of pure CO_2 would then transferred to long-term stores in geological formations (see: Section 6.1, Geological CO_2 storage) or in the deep ocean (see Section 6.2, Ocean CO_2 storage).

5.1 Environmental changes and biodiversity and ecosystem effects:

Outlined below are the primary physical, chemical and biological environmental changes caused by the implementation of this technique. Where possible, the potential biodiversity and ecosystem effects of each environmental change are indicated.

These impacts are in addition the impacts of geological storage (section 6.1***) or ocean storage (*** section 6.2***) of the CO_2 captured through this method.***

1. **Construction of large air-capturing structures on open areas of land.**

    a) Habitat fragmentation or loss due to land-use conversion. However, the footprint is anticipated to be relatively small, particularly compared to the land-use per carbon unit required for biomass-based approaches (Secretariat of the Convention on Biological Diversity, 2012).

    b) Pollution of air and water from large-scale production of chemical sorbents with possible toxicity impacts on organisms.

2. **Localized reduction in CO_2 content of ambient air 'downstream' of DAC.**

    a) Reduced vegetation growth down-flow of air capture sites (Socolow *et al*., 2011).

3. **Contamination of air 'downstream' of DAC if reactive sorption chemicals used in process evaporate (Socolow *et al.*, 2011).**

    a) Toxicity to organisms leading to decline in health and size of population, change in community structure and potential loss of biodiversity.

4. **Depletion of surface and groundwater due to large water requirements for some capture methods (The Royal Society, 2009).**

    a) Reduced 'biologically available water' in adjacent habitats (The Royal Society, 2009).

    b) Decline in population size and health for water-dependent species.

    c) Change in ecological communities to favor drought-resistant species.

    d) Degradation (e.g. increased concentration of pollutants) or destruction of aquatic habitats with loss of inhabitant species.

6 Storage of CO_2

An isolated stream of pure CO_2 – captured during biofuel burning (BECCS), or by Direct Air Capture (DAC) – is transferred to a long-term store.

6.1 Geological storage of CO_2

Geological storage can be used for CO_2 streams from Biofuels (section 4.5) and Direct Air Capture (section 5).

Implementation: An isolated stream of pure CO_2 – captured via BECCS or DAC – would be injected into geological reservoirs for long-term storage. Reservoirs may be pre-existing features such as depleted oil and gas stores, unmineable coal seams or deep saline-water-saturated rock formations. Alternatively, wells may be drilled. CO_2 would be transferred via subterranean pipelines (IPCC, 2005).

6.1.1 Environmental changes and biodiversity and ecosystem effects:

Outlined below are the primary physical, chemical and biological environmental changes caused by the implementation of this technique. Where possible, the potential biodiversity and ecosystem effects of each environmental change are indicated.

1. **Drilling of geological wells with associated impacts to the environment (destruction of habitats, noise and dust pollution etc.). Also disposal of large amounts of waste from well drilling – although there is specific legislation to minimize this (European Environment Agency, 2011).**

   For potential impacts, please refer to Section 1 Direct Ocean Fertilization, point 1*, effects of mining) but please* ***note*** *that the scale of the effects for '*Geological storage of CO_2*' would have a significantly smaller spatial footprint as it involves drilling holes (and could utilize directional drilling to minimize the footprint further) rather than large scale mining or quarrying*.

2. **Infiltration of brine into groundwater with small possibility of impact on overlying soils (IPCC, 2005).**

   a) Habitat degradation with increased salinity (IPCC, 2005).

   b) Potential change in structure and composition of soil biological communities and plant communities with shift to saline-adapted species.

3. **Displacement and leakage of methane due to injection of CO_2 into deep geological reservoirs (Baines & Worden, 2004). Although, economic value of methane gas and existence of capturing technologies makes uncontrolled leaks unlikely.**

   a) Ecological impacts of high local concentrations of methane gas.

4. **Ground movement - subsidence or uplift of the earth - as a consequence of pressure changes induced by CO_2 injection (Damen *et al.*, 2006). Fracturing and movement along geological faults could produce seismic activity (Wyss & Molnar, 1972; Raleigh *et al.*, 1976; Ahmad & Smith, 1988; Sminchak *et al.*, 2002; Streit *et al.*, 2005).**

a) Fragmentation or loss of habitat.

b) Altered soil erosion and water flow regimes.

5. **Injection of CO_2 into deep geology at storage site leading to significant increase in geological CO_2 levels.**

    a) Potential change in microbe communities in deep geology. Effect of CO_2 on subsurface microbial populations is not well understood, however, some species may be favored by low pH, high CO_2 conditions (IPCC, 2005).

    b) Impacts of CO_2 on organisms dwelling in deep geologic formations. Very little is known about these communities (Benson *et al*., 2002).

6. **Potential leakage of CO_2 from geological stores into surrounding geology and overlying soils (IPCC, 2005; Damen *et al.*, 2006). However, there is no evidence of terrestrial impacts from current CO_2 storage projects (IPCC, 2005).**

    a) Plant mortality through 'root anoxia' with decrease in oxygen concentration has been shown in several studies (Leone *et al*., 1977; Flower *et al*., 1981; Farrar *et al*., 1999). Furthermore, tree kills associated with soil gas concentrations of CO_2 over 20% (from volcanic activity) have been observed in the U.S. (Benson *et al*., 2002).

    b) Leaks to soil and soil water may increase acidity leading to increased leaching of soil minerals resulting in long-term effects on soil quality (European Environment Agency, 2011); for example, manganese and aluminum availability may increase resulting in toxicity.

7. **Potential leakage of CO_2 gas through geology and soils and into air. However, the chance of these occurring would be very low as engineered storage sites will be chosen to minimize the chance of leakage. They would also be on a significantly smaller scale than the very rare natural eruptions which are sometimes used as analogies (e.g. the overturning of Lake Nyos; IPCC, 2005).**

a) Wildlife mortality by suffocation from accumulation of lethal levels of CO_2, for example in valleys (Benson *et al*., 2002; Damen *et al*., 2006).

8. **Increased concentration of CO_2 in groundwater leading to acidification (International Energy Agency, 2011b). Risk would be minimized by appropriate site selection. Effect only applicable to terrestrial storage, not to sub-seabed storage.**

a) Potentially increased release of contaminants such as (toxic) metals, sulfate or chlorine, with risk of toxicity to organisms (IPCC, 2005).

b) Increase in biologically-available heavy metals (Ryser & Sauder, 2006) leading to changes in soil and plant communities. For example, a study of metals in soil found that plant growth decreased with increased metal concentration and that reproduction was delayed and reduced, which could have a significant impact at population, community and ecosystem level (Ryser & Sauder, 2006). Other studies have shown decreased microbial community size and activity with metal contamination (Brookes & McGrath, 1984; Chander & Brookes, 1991; Konopka *et al*., 1999).

9. **Infiltration of CO_2-rich water into soils, resulting in acidification (International Energy Agency, 2011b) with potential toxicity to soil organisms, plants and species at higher trophic levels (for terrestrial CO_2 storage sites only)**

a) Greater mobilization of biologically-available metals in groundwater and soils leading to reduced plant health and productivity and changes in community structure and composition (Ryser & Sauder, 2006).

b) Changes in structure, composition and activity of soil microbial communities with potential decrease in community size and activity with metal contamination (Brookes & McGrath, 1984; Chander & Brookes, 1991; Konopka *et al*., 1999).

c) Increased leaching of minerals from soils causing long-term change in quality (European Environment Agency, 2011); for example, manganese and aluminum availability may increase resulting in toxicity.

d) Change in structure and composition of soil communities with shift to favor species adapted to high CO_2, low pH environments.

e) Change in activity of soil organisms.

f) Change in composition of overlying plant communities with implications for habitat structure and other organisms.

10. **Contamination of CO_2 stores (and leakages) with hydrogen sulfide, nitrous oxide, sulfur dioxide and other trace gases.** Hydrogen sulfide is more toxic than CO_2 and dissolution of sulfur dioxide in groundwater creates a much stronger acid than CO_2 (IPCC, 2005). However, expected levels of H_2S and NOx, and SOx in injected CO_2 are negligible (up to 100 ppm for the former two and up to 70 ppm for the latter; International Energy Agency, 2011c).

a) Potential toxic impacts on biodiversity; worse than CO_2 (IPCC, 2005).

b) Dissolution of sulfur dioxide in groundwater creates a strong acid which may alter structure and composition of groundwater communities, as well as other organisms when groundwater reaches soils and water bodies (IPCC, 2005).

6.2 Ocean storage of CO_2

Ocean storage can be used for CO_2 streams from Biofuels (section 4.5) and Direct Air Capture (section 5).

Implementation: There are a number of proposed methods for ocean storage of CO_2. In this report, two main options are considered:

(1) Dissolution of CO_2 within the water column in the mid-depths of the ocean (typically below 1000m) using fixed pipelines from the shore or from a moving ship.

(2) Deposition of liquid-form CO_2 onto the seafloor via a vessel at depths below 3,000m where CO_2 is denser than water and is expected to form a 'lake' (IPCC, 2005).

CO_2 would be stored for century-to-millennial timescales but would eventually be returned to the upper ocean and atmosphere. Using the first option – mid-depth dissolution - would lead to immediate dissolution of CO_2 into the ocean water column, whereas the second option – sea-floor deposition in the deep ocean - would cause relatively slow dissolution of CO_2 from the lake surface due the surface area exposed compared to the volume of CO_2 and the formation of hydrates at the water-CO_2 interface inhibiting dissolution (IPCC, 2005).

Currently, neither of these options is permitted under Annex 1 of the 1996 London Protocol (although the position under the London Convention is uncertain). A third option of storing CO_2 in sub-seabed geological formations is permitted under the 2006 amendment to the 1996 London Protocol[3] (International Maritime Organization, 2006; International Energy Agency, 2011). This option entails storing CO_2 in geological formations beneath the continental shelf, and could possibly extend to the limits of the continental margin i.e. depths of approximately <3,200 m. Sub-seabed storage beneath continental margins could have similar effects to seabed deposition if the stores were to leak but the likelihood of this with suitably selected sites is very low and there would be a much slower rate of release of CO_2 into the water column.

It has also been suggested to inject liquid CO_2 a few hundred meters into deep-sea sediments at greater than 3,000 m depth where the density of CO_2 and the formation of hydrates will stabilize the CO_2 (House at al. 2006). The risks of leakage from this option are likely to be greater than that for sub-seabed storage beneath continental margins but less than from lakes of liquid CO_2 on the seafloor. This option might be considered to fall within the 2006 amendment to the 1996 London Protocol. However, at the time the amendment was passed it was not conceived to include storage of CO_2 beneath unconsolidated deep-sea sediments.

[3] Annex 6 Resolution LP.1(1) On the Amendment to Include CO_2 Sequestration in Sub-Seabed Geological Formations in Annex 1 to the London Protocol
http://www.imo.org/blast/blastDataHelper.asp?data_id=17614&filename=01.pdf

Each of the environmental changes below could result from any of the two methods listed above. However, the intensity and location of the effects would vary. For method 1, dissolution of CO_2 in ocean waters would be immediate, and would occur in the mid-depths of the ocean. For method 2 there would be a much slower release of CO_2 into the water column, and this would occur in the deep ocean close to the sea floor. For sub-seabed geological storage, which is currently permitted in international policy, the effects would be similar to method 2 if there was a leak, but the likelihood of this occurring and the rate at which CO_2 would be released are both low.

6.2.1 Environmental changes and biodiversity and ecosystem effects:

Outlined below are the primary physical, chemical and biological environmental changes caused by the implementation of this technique. Where possible, the potential biodiversity and ecosystem effects of each environmental change are indicated.

1. **Rapid localized increase in dissolved CO_2 levels in mid ocean due to direct dissolution, or more gradual increase in levels in deep-ocean waters near the seabed due to gradual dissolution from seabed lake stores (Hall-Spencer *et al*., 2008).**

    a) Immediate mortality of marine organisms close to injection points and CO_2 lakes in mid-deep ocean (Tamburri *et al*., 2000; IPCC, 2005), including benthic communities (Williamson *et al*., 2012).

    b) Significant changes in structure and composition of deep-ocean communities as most species are adapted to stable physicochemical conditions and low CO_2 levels, and therefore are highly sensitive to changes (IPCC, 2005).

    c) Changes in the structure and function of communities of sediment-mixing organisms with significant impacts on sediment nutrient flux (Widdicombe & Needham, 2007).

    d) Changes in structure and composition of zooplankton communities as species less sensitive to CO_2 could start to dominate (IPCC, 2005).

    e) Impacts to the metabolism and growth of zooplankton species (Crocker & Cech, 1996).

f) Decrease in copepod egg production and hatching rates (Kurihara *et al*., 2004) and increased mortality (IPCC, 2005).

g) Impacts on metabolism, growth and reproduction of marine invertebrates such as crustaceans, scallops, mussels and echinoderms/gastropods (Crocker & Cech, 1996; Kurihara *et al*., 2004).

h) Decline in fish populations due to reduced hatching and survival of fish larvae (Ishimatsu *et al*., 2004), and altered metabolism and growth (Crocker & Cech, 1996).

i) Decrease in food chain length and composition resulting in reduced food availability for high trophic levels (IPCC, 2005).

2. Increased acidity of the mid or deep ocean due to increased concentration of CO_2.

a) Impacts on rates of calcification by calcifying organisms (Gattuso *et al*., 1999; Reynaud *et al*., 2003; Feely *et al*., 2004; IPCC, 2005; Friedrich *et al*., 2012); likely to be a decrease. Resulting change in structure and composition of biological communities (Pörtner *et al*., 2004).

b) Significant changes in structure and composition of deep ocean communities as most species are adapted to stable physiochemical conditions, and therefore are highly sensitive to changes e.g. squid. Long-term impacts due to long life-spans (Tamburri *et al*., 2000; Seibel & Walsh, 2001; Barry *et al*., 2004; Ishimatsu *et al*., 2004; Kurihara *et al*., 2004; Vetter & Smith, 2005; Cao & Caldeira, 2010).

c) Changes in productivity and growth of species of algae and heterotrophic bacteria (IPCC, 2005) leading to changes in species composition such as increase in abundance of larger species (Finkel *et al*., 2010).

d) Impacts on metabolism and growth of zooplankton, fish and benthic species (IPCC, 2005).

e) Change in availability of nutrients including phosphate, silicate and ammonia (IPCC, 2005).

f) Increase in biologically-available metals (e.g. copper, cadmium and lead) in the mid-deep ocean (Salomons & Forstner, 1984; Sadiq, 1992) with potential toxicity for ocean organisms (Casas & Crecelius, 1994; Rainbow, 2002; Millero *et al*., 2009).

3. **Increased levels of hydrogen sulfide in mid or deep-ocean due to contaminated CO_2 streams (IPCC, 2005).** However, expected levels of H_2S in injected CO_2 are negligible (up to 100 ppm; International Energy Agency, 2011c).

a) Potential toxicity of hydrogen sulfide to marine biodiversity.

b) Change in structure and composition of micro-organism communities with a shift to species favored by hydrogen sulfide.

4. **Increase in anoxic and hypoxic regions in the mid or deep ocean due to increased hydrogen sulfide levels.** However, expected levels of H_2S in injected CO_2 are negligible (up to 100 ppm; International Energy Agency, 2011c).

a) Loss of biodiversity; responses of marine organisms to low oxygen are almost all negative (Lampitt *et al*., 2008).

b) Impact on respiration and performance of higher marine organisms (IPCC, 2005).

c) Decline in fish populations with hypoxia and anoxia (Glibert *et al*., 2008).

d) Alteration of food webs dynamics (Diaz, 2001).

5. **Eventual increase in CO_2 levels and reduction in pH in the upper ocean as CO_2 is re-circulated. Timescale estimated to be century-to-millennia, although it may be shorter, particularly for mid-ocean dissolution (Hall-Spencer *et al.*, 2008).**

a) Impacts on rates of calcification by calcifying organisms (Gattuso *et al*., 1999; Reynaud *et al*., 2003; Feely *et al*., 2004; Friedrich *et al*., 2012); likely to be a decrease. Resulting change in structure and composition of biological communities (Pörtner *et al*., 2004).

b) Increased ‘bleaching’ of coral reefs (IPCC, 2005).

c) Changes in structure and composition of phytoplankton communities (IPCC, 2005).

7 Afforestation and reforestation

Afforestation and reforestation is the conversion of land from non-forested to forested resulting in increased uptake of CO_2 from the atmosphere and storage in vegetation and soils. ‘Afforestation’ is in areas where land was without trees for over 50 years and ‘reforestation’ where trees had been removed during the last 50 years (IPCC, 2007b).

Afforestation and reforestation are not always considered as climate engineering activities, and are only considered in broad detail here as they, and avoidance of deforestation, have been subject to detailed reviews elsewhere (IPCC, 2000; The Royal Society, 2001; IPCC, 2007b; UNEP, 2009). However they have been included, as to be effective as a climate engineering technique, they would have to be undertaken on an unprecedented scale, which qualifies them for attention here.

Implementation: Afforestation and reforestation involves the establishment of forest on land that is not currently forested. It is intended that the established trees will absorb and store a greater amount of CO_2 than the existing land cover.

The greatest impact of afforestation and deforestation is direct land-use change. This could result in the loss of diverse ecosystems if monocultures replace more diverse systems, and may lead to the introduction of invasive non-native species (Ramanamanjato & Ganzhorn, 2001). However, there is also significant potential for benefits to biodiversity if forests are established on degraded or mono-cropped land and are well managed. Other potential impacts include increased water uptake (Jackson *et al*., 2005), changes in nutrient cycling and significant alteration of local soils (Jackson *et al*., 2005; Russell *et al*., 2012; Secretariat of the Convention on Biological Diversity, 2012). Plantations can also increase water quality and reduce soil erosion (Walker *et al*., 2002; Pattanayak *et al*., 2005; Secretariat of the Convention on Biological Diversity, 2012), but do not automatically do so. Combined effects of changes in the hydrological cycle, surface albedo and cloud cover - which can influence regional precipitation patterns - are not well understood (Russell *et al*., 2012; Secretariat of the Convention on

Biological Diversity, 2012). In terms of temperature, in the tropics, afforestation tends to cause net cooling, in temperate regions, marginal cooling, and at high altitudes (with seasonal snow), afforestation can cause increased temperatures (Bala *et al*., 2007).

If afforestation was carried out on all land that could support forests and is not currently used for agriculture (approximately 3900MHa) – i.e. its maximum physical potential - it could sequester up to 67% of CO_2 emissions by 2100. If afforestation occurred only on abandoned agricultural land (approximately 800 – 1000MHa), it is estimated that it could sequester up to 7% of CO_2 emissions by 2100 (Van Minnen *et al*., 2008).

7.1 Environmental changes and biodiversity and ecosystem effects:

Outlined below are the primary physical, chemical and biological environmental changes caused by the implementation of this technique. Where possible, the potential biodiversity and ecosystem effects of each environmental change are indicated.

1. **Large-scale establishment of forest on currently non-forested areas causing direct change in habitat type**

    a) Increased area of forest habitat. The habitat quality depends on management regime.
    b) Conversion of existing habitats, many of which are of equal or greater biodiversity – e.g. grassland, heath, unmanaged forest – to managed forest.
    c) Buffering of neighboring habitats against environmental perturbation (George *et al*., 1999; Plantinga & Wu, 2003).

2. **Impacts of tree species and plantation management used in afforestation and reforestation**

    a) Establishment of monoculture plantations which support low habitat and species diversity (Ramanamanjato & Ganzhorn, 2001).

    b) Introduction of non-native trees and/or associated species (Ramanamanjato & Ganzhorn, 2001; Secretariat of the Convention on Biological Diversity, 2012).

c) Use of fast-growing tree species leading to change in habitat structure and composition.

d) Use of nitrogen-fixing species resulting in increased soil acidity.

e) Impacts of changed practices to manage plantations for this purpose, such as rotation length, thinning, pruning (Pawson *et al*. 2013).

3. **Reduced surface albedo and changes in local temperatures; net cooling in the tropics, warming in the subtropics, marginal net cooling in temperate regions and no cooling, or net warming, at high latitudes (e.g. Bala *et al*., 2007).**

a) Changes in respiration rates (Russell *et al*., 2012; Secretariat of the Convention on Biological Diversity, 2012).

b) Changes in nutrient cycling rate leading to changes in plant growth rates and ecological community composition.

4. **Changes to soil structure and composition with establishment of forests on currently non-forested land.**

a) Changes to nutrient cycling and availability leading to changes in plant growth rates and community composition (Jackson *et al*., 2005; Russell *et al*., 2012; Secretariat of the Convention on Biological Diversity, 2012).

b) Changes in local and regional soil chemistry (Jackson *et al*., 2005; Russell *et al*., 2012; Secretariat of the Convention on Biological Diversity, 2012).

c) Reduced soil erosion due to establishment of a canopy cover and binding by tree roots on exposed soils; however, increased erosion due to forestry roads and planting and harvesting activities where forests replace well-established grasslands.

d) Increased soil carbon content leading to increased plant productivity.

5. **Alteration of local water regimes with establishment of forest on non-forested land.**

   a) Increased water uptake with increased tree cover leading to reduction in 'biologically available water' in soils and river systems draining from the afforested land (Jackson *et al*., 2005).

   b) Increased soil water retention potentially resulting in increased 'biologically available water' or in anoxic conditions (Walker *et al*., 2002; Pattanayak *et al*., 2005; Secretariat of the Convention on Biological Diversity, 2012).

   c) Improved water quality in nearby water bodies (e.g. due to reduced soil erosion and leaching; Walker *et al*., 2002; Pattanayak *et al*., 2005; Secretariat of the Convention on Biological Diversity, 2012), or alternatively, reduced water quality due to increased erosion.

   d) Reduced flooding impact on neighboring ecosystems (George *et al*., 1999; Plantinga & Wu, 2003).

   e) Increased evapotranspiration leading to potential increase in precipitation rates with associated biodiversity impacts (Russell *et al*., 2012; Secretariat of the Convention on Biological Diversity, 2012).

6. **Regional increases in cloud cover due to higher rates of evapotranspiration and provision of biological cloud condensation nuclei (Vaughan & Lenton, 2011).**

   a) Reduced photosynthesis due to reduced light intensity, *or;*

   b) Increased photosynthesis due to increase in diffuse light compare to direct light

Section 2: Solar Radiation Management (SRM) techniques

Solar radiation management is the use of techniques to reflect a small proportion of sunlight away from earth to offset warming caused by greenhouse gases.

Intended climate effect: The climate engineering techniques related to Solar Radiation Management aim to reduce the amount of solar radiation absorbed by the Earth, producing a cooling effect that will counteract the warming caused by anthropogenic greenhouse gas emissions. To offset the warming caused by a doubling of atmospheric CO_2, it is estimated that a solar radiation reduction of approximately 2% would be required (Lenton *et al*., 2008; Lunt *et al*., 2008; The Royal Society, 2009). Unlike CDR methods, SRM techniques would not reduce the atmospheric concentration of CO_2, and so would result in a future climate with lower temperatures than those predicted under climate change, but with high atmospheric CO_2 concentrations. The direct impacts of increased CO_2 levels – including ocean acidification – would not be addressed (Secretariat of the Convention on Biological Diversity, 2012).

SRM techniques would affect temperatures immediately after global deployment, and it could be possible to achieve detectable cooling within a few years (Matthews & Caldeira, 2007; The Royal Society, 2009). However, the reverse effect would occur if SRM climate engineering methods failed or were abruptly halted at any point, resulting in a rapid rise in global temperatures to a level determined by the atmospheric concentration of greenhouse gases at the time. This is referred to as the "termination problem" of SRM climate engineering (The Royal Society, 2009). Rates of warming could be up to five times greater than the rate of climate change with no mitigation and no SRM (Matthews & Caldeira, 2007).

There are two main types of SRM climate engineering:

1) Methods that reflect light in or above the Earth's atmosphere and

2) Methods that increase the surface albedo (reflectivity) of the Earth.

Techniques in the first category operate by 'dimming' incoming solar radiation on a global scale. Studies suggest it would be theoretically possible to fully counteract the radiative forcing[4] caused by anthropogenic greenhouse-gas emissions using these methods (Secretariat of the Convention on Biological Diversity, 2012). In contrast, surface albedo techniques can only be implemented in certain

[4] Radiative forcing refers to a change in the balance of incoming and outgoing radiation reaching the earth. A doubling of atmospheric CO_2 concentrations is anticipated to cause a global mean radiative forcing of approximately $+4W/m^2$ due to a reduction in the thermal radiation to space. It is estimated that balancing this forcing would require a reduction in incoming solar radiation of approximately 2%.

The Royal Society (2009) Climate engineering the climate - Science, governance and uncertainty. RS Policy document 10/09. The Royal Society, London.

regions, and are generally able to achieve a far smaller cooling effect (Lenton & Vaughan, 2009; The Royal Society, 2009; Secretariat of the Convention on Biological Diversity, 2012).

If effective, SRM could counteract most of the anticipated climate change. However, although global temperature could be returned to a lower value, the climate would be significantly altered. For example, modelling suggests that there will be relative warming at high latitudes and cooling in the tropics (i.e. a reduced equator-to-pole temperature gradient), and that regional precipitation and air circulation regimes will be changed (Jones *et al*., 2009; The Royal Society, 2009; Irvine *et al*., 2011; Schmidt *et al*., 2012; Secretariat of the Convention on Biological Diversity, 2012). Under the low-temperature, high-CO_2 conditions created by SRM, changes in plant productivity are also likely to alter evapotranspiration rates, with implications for the hydrological cycle in heavily vegetated regions (Bala *et al*., 2008). In the ocean, cooling at the surface could alter currents and global circulation on a global scale, and may lead to increasing acidification as cooler waters absorb more CO_2 (Matthews *et al*., 2009).

There are significant uncertainties associated with predicting the likely region-specific climate impacts of SRM (Bala *et al*., 2008; Secretariat of the Convention on Biological Diversity, 2012). Climate models are able to indicate the broad climate consequences of SRM but are unable to fully represent the complex and interacting physical and biogeochemical factors determining climate effects of SRM (IPCC, 2007). The range of modeling studies currently available presents an 'ad hoc' selection of SRM scenarios. The chosen study regions vary between studies and even where there is overlap, projections for the same location can vary significantly depending on the model, conditions and parameters used (e.g. see Latham *et al*., 2008; Jones *et al*., 2009; Secretariat of the Convention on Biological Diversity, 2012; Secretariat of the Convention on Biological Diversity, 2012). As such, presenting the full range of possible climate impacts of SRM is beyond the scope of this report, and we focus mainly on global-scale impacts of SRM and broad patterns of change suggested in the literature.

8 SRM techniques causing global dimming

A number of SRM techniques would act to reduce incoming solar radiation on a global scale leading to 'dimming'. These methods have the potential to cause significant global cooling and include:

1. Sunshades in space,
2. Stratospheric sulfate aerosols, and
3. Enhanced marine cloud albedo (NB: effects are similar but at a smaller magnitude)

These will have a number of common effects, which are outlined below. Subsequently, unique impacts associated with the individual techniques are detailed in separate sections.

8.1 Common environmental changes and biodiversity and ecosystem effects of SRM techniques causing global dimming:

Outlined below are the primary physical, chemical and biological environmental changes caused by the implementation of the SRM techniques causing global dimming (sunshades, stratospheric sulfate aerosol injections and enhanced marine cloud albedo). Where possible, the potential biodiversity and ecosystem effects of each environmental change are indicated.

1. **A small but detectable reduction in global temperature within a few years and the potential for a much larger reduction in temperatures with more intensive implementation of techniques (Matthews & Caldeira, 2007; The Royal Society, 2009).** This is compared to a baseline of climate warming which will have occurred prior to SRM deployment.

    a) Recovery of species and ecosystems adversely affected by climate change warming.

    b) Decline in species less resilient to rapid temperature changes; long-lived, slow-reproducing species and species with temperature regulated sex determination particularly vulnerable.

    c) Shift in ecological communities to species better adapted to cooler temperatures.

d) Reduced primary productivity (relative to the enhanced primary productivity predicted with increasing temperatures under climate change).

e) Slowed carbon and nutrient recycling relative to enhanced rates predicted with increasing temperatures under climate change (Secretariat of the Convention on Biological Diversity, 2012).

2. **Reduced equator-to-pole temperature gradient due to the greater reduction in incoming solar radiation at the tropics compared to higher latitudes (Matthews & Caldeira, 2007).**

3. **Reduced amplitude of the seasonal temperature range with relatively warmer winters and cooler summers compared to the current climate (The Royal Society, 2009).**

4. **Reduced diurnal (day to night) temperature range compared to the current climate due to stronger cooling from SRM during daytime (Lunt *et al.*, 2008).**

5. **Slowing of the global hydrological cycle with overall reductions in precipitation and evaporation. SRM-induced global dimming aimed at offsetting a doubling of CO_2 is predicted to cause a 2% decrease in global precipitation and evaporation. The reduction would be most pronounced over land and at the equator (Trenberth & Dai, 2007; Bala *et al.*, 2008).**

   a) Changes to soil moisture content and therefore 'biologically available water'. Increases in some regions and reductions in others, for example significant reduction in soil moisture predicted in the tropics (with sufficient dimming to offset a doubling of CO_2, compared to soil moisture conditions in pre-industrial climate conditions (Matthews & Caldeira, 2007; Bala *et al*., 2008).

   b) Change in rate of primary productivity, which is strongly influenced by soil moisture. Consequences for rate of carbon and nutrient cycling (Secretariat of the Convention on Biological Diversity, 2012).

c) Change in quantity and quality of freshwater systems (Secretariat of the Convention on Biological Diversity, 2012).

6. **Regional changes in precipitation due to changes in global atmospheric circulation patterns, resulting in some regions experiencing an increase in precipitation and others experiencing a decrease (Bala *et al.*, 2008; Lunt *et al.*, 2008; McCusker *et al.*, 2012).**

7. **Creation of a high-CO_2, low-temperature climate (compared to the current 'low-CO_2 and low-temperature' climate and the high-CO_2, high-temperature conditions under projected climate change). SRM could counteract some or all warming caused by anthropogenic greenhouse gases, but would not directly address atmospheric CO_2 concentrations. For example, CO_2 concentrations may double and SRM could theoretically maintain the global temperature at current (2012) levels (Ricke *et al.*, 2010; Secretariat of the Convention on Biological Diversity, 2012).**

   a) Enhanced plant primary productivity (relative to current levels; Govindasamy *et al*., 2003).
   b) Reduced water stress to plants with higher CO_2 concentrations (Secretariat of the Convention on Biological Diversity, 2012).
   c) Change in plant communities as plant groups differentially favored by high CO_2 conditions (Collatz *et al*., 1998), for example, the balance between savannah grasslands and forests may be altered (Bond, 2008; Bond & Midgley, 2012)
   d) Effects on ocean acidification (see point 9 below).

8. **Rapid increase in global temperatures if SRM climate engineering fails or is terminated; the 'termination effect' (The Royal Society, 2009).** If SRM climate engineering is terminated after many years of use, it is possible that very high rates of warming could occur, up to five times greater than the anticipated rate of climate warming that would have occurred without SRM (Matthews & Caldeira, 2007; Irvine *et al*., 2012).

a) Decline in species less resilient to rapid temperature changes; long-lived, slow-reproducing species and species with temperature regulated sex determination are particularly vulnerable (Quintero & Wiens, 2013).

b) Shift in ecological communities to species better adapted to warmer temperatures.

c) Increased primary productivity with increased temperatures (relative to the reduced rate under lower temperatures established when SRM was effective).

d) Reduced primary productivity due to drought (e.g. Ciais *et al*., 2005).

e) Increased rate of carbon and nutrient cycling (relative to the reduced rate under lower temperatures established when SRM was effective).

f) Thawing of permafrost (Russell *et al*., 2012).

9. Increase in dissolved inorganic carbon (DIC) content of ocean and potential increased ocean acidification due to high atmospheric CO_2 concentrations and lower ocean surface temperature (creating higher capacity for dissolved CO_2). However, this may be partially offset due to enhanced uptake of CO_2 by terrestrial biomass (Matthews *et al.*, 2009).

a) Beneficial consequences for some organisms including phytoplankton, microscopic algae and cyanobacteria (Secretariat of the Convention on Biological Diversity, 2012).

b) Physiological impacts on fish resulting in behavior changes with consequences for the wider ecological community (Secretariat of the Convention on Biological Diversity, 2012).

c) Reduced growth, metabolism and survival of marine organisms (Secretariat of the Convention on Biological Diversity, 2012).

d) Reduced calcification rates leading to a decline in calcifying organisms, including reef-building species and organisms with calcium based exoskeletons (Secretariat of the Convention on Biological Diversity, 2012).

10. **Changes in ocean circulation due to changes in climate conditions and fluxes of energy in to and out of the ocean (McCusker *et al.*, 2012).**

8.2 Sunshades in space

Sun shields or deflectors would be installed in space to reflect a proportion of sunlight away from the Earth to offset warming from greenhouse gases.

Implementation: Sunshields or deflectors would be placed between the sun and the Earth to reflect a proportion of incoming solar radiation back into space, offsetting warming caused by anthropogenic greenhouse gas emissions. Suggestions include placing millions of mirrors in a near-Earth orbit, or establishing a ring of dust particles or lightweight satellites above the equatorial region (The Royal Society, 2009). Other proposals consider placing reflectors at a point 1.5 million km from Earth towards the Sun (referred to as the Lagrange L1 point), where the surface area of shades needed would be considerably smaller (The Royal Society, 2009). Options include a superfine aluminum mesh, large reflective shield or trillions of reflective metallic discs or lenses (~50cm diameter). Shades could be launched into orbit using high-powered electromagnetic cannons (Angel, 2006), or put in place by dedicated space craft.

Overall, to provide a 2% reduction in solar radiation reaching the earth, it is estimated that the total surface area of reflectors would need to be about 3 million km^2 (The Royal Society, 2009). As an example of the associated launch capacity, one proposal estimated that to get the necessary trillions of 2ft wide reflective disks into space, 20 electromagnetic launchers would be required to fire missiles with stacks of 800,000 disks every five minutes for twenty years (Angel, 2006).

The effects of sunshade climate engineering include the effects of dimming (*see above – Section 8.1: Common Environmental changes and biodiversity and ecosystem effects of SRM techniques causing global dimming*) and the infrastructure used to launch structures.

8.2.1 Environmental changes and biodiversity and ecosystem effects

Outlined below are the primary physical, chemical and biological environmental changes caused by the implementation of this technique. Where possible, the potential biodiversity and ecosystem effects of each environmental change are indicated.

NB: These are in addition to the effects listed in <u>Section 8.1: Common Environmental changes and biodiversity and ecosystem effects of SRM techniques causing global dimming</u>.

1. **Environmental impacts of infrastructure used to deploy sun shields (Angel, 2006; Robock *et al.*, 2008).**
    a) Habitat destruction, fragmentation or degradation.
    b) Pollution impacts - particularly noise pollution from intensive launch methods.

2. **Reduction in incoming Photosynthetically Active Radiation reaching the Earth (Secretariat of the Convention on Biological Diversity, 2012). Likely to be relatively small reduction, of the order of 1% (Lunt *et al.*, 2008).**
    a) Reduced primary productivity in many ecosystems, including the ocean (Secretariat of the Convention on Biological Diversity, 2012)
    b) Increased productivity amongst shade tolerant species, particularly in arid areas where water stress will be reduced (Stanhill and Cohen 2001)
    c) Changes in relative abundance of photosynthesizing species leading to change in community composition and structure, i.e. increase in species favored by lower light intensity (Secretariat of the Convention on Biological Diversity, 2012).
    d) Significant detrimental impacts on ecosystems where light is the main growth-limiting factor (Secretariat of the Convention on Biological Diversity, 2012).

8.3 Stratospheric sulfate aerosols

Sulfur dioxide would be injected into the lower stratosphere, where it would form sulfate aerosols that scatter solar radiation back into space (as observed during large-scale volcanic eruptions).

Sulfur dioxide or hydrogen sulfide would be injected into the lower stratosphere, where they would form reflective sulfate aerosol particles. These particles scatter incoming solar radiation back into space. This method was suggested as a means to replicate the effects of large-scale volcanic eruptions during which the release of sulfate aerosols led to global cooling (Kirchner *et al*., 1999; Keith, 2000). Studies using climate modelling suggest that artificial enhancement of stratospheric sulfate aerosols could be effective in counteracting the effects of anthropogenic climate change (e.g. Caldeira & Wood, 2008; Rasch *et al*., 2008; Robock, 2008).

It is estimated that between 1.5 and 5 million tons/year of sulfur would need to be injected to cause a 2% reduction in incoming solar radiation (Vaughan & Lenton, 2011). Studies show that sulfur released during the eruption of Mount Pinatubo resulted in a reduction in global surface temperature of up to 0.5°C for approximately two years (Robock, 2002; Soden *et al*., 2002). This suggests an injection of 10 million tons of sulfur could cool the Earth by 0.5 °C for 1-2 years.

Suggested methods of delivery of sulfur gases include using custom built aircraft, rockets, balloons or missiles, depending on the delivery altitude required (Robock *et al*., 2008; The Royal Society, 2009). Injection would be most effective over the tropics from where particles would be spread throughout the global atmosphere by the stratospheric circulation. In order to generate a global loading of aerosols to balance warming due to greenhouse gases, there would need to be regular injections (at least annually, if not more frequent) of sulfate-forming gases for decades or centuries as aerosols would spread and have a lifetime in the stratosphere of roughly one year (Robock *et al*., 2008).

There has also been some suggestion of injection of aerosols into the troposphere (National Academy of Sciences, 1992), but due to serious potential environmental and human health impacts, this option has largely been ruled out of the list of potential climate engineering options (Crutzen, 2006; MacCracken, 2006; Vaughan & Lenton, 2011). ***This tropospheric sulfate aerosol technique is therefore not considered further.***

8.3.1 Environmental changes and biodiversity and ecosystem effects

Outlined below are the primary physical, chemical and biological environmental changes caused by the implementation of this technique. Where possible, the potential biodiversity and ecosystem effects of each environmental change are indicated.

NB: These are in addition to the effects listed in <u>Section 8.1: Common Environmental changes and biodiversity and ecosystem effects of SRM techniques causing global dimming</u>

1. **Environmental impacts of the methods used to inject aerosols into the stratosphere (Robock *et al.*, 2008) – planes or fixed terrestrial structures.**

2. **Global-scale reduction in incoming Photosynthetically Active Radiation reaching Earth (Secretariat of the Convention on Biological Diversity, 2012). Likely to be relatively small reduction of the order of 1% (Lunt *et al.*, 2008).**

    a) Reduced terrestrial productivity (but see Impact 2 – diffuse radiation – below)

    b) Reduced primary productivity in the ocean and some other systems (Secretariat of the Convention on Biological Diversity, 2012).

    c) Changes in relative abundance of photosynthesizing species leading to change in community composition and structure (Secretariat of the Convention on Biological Diversity, 2012).

    d) Even a small reduction in incoming radiation could be harmful for ecosystems where light is the main growth-limiting factor (Secretariat of the Convention on Biological Diversity, 2012).

3. **Increased proportion of incoming radiation reaching Earth as diffuse rather than direct radiation (Secretariat of the Convention on Biological Diversity, 2012).**

a) Increased primary productivity and carbon fixation with more uniform light distribution in diffuse light conditions. For example, in forests, diffuse light penetrates the canopy better than direct light (Kanniah *et al*., 2012; Russell *et al*., 2012), and this effect is likely to outweigh the reduction in photosynthetically active radiation (see 1 above).

b) Change in plant communities due to differential impact of diffuse light on species in different layers of the canopy. Potential overall decline in biodiversity (Secretariat of the Convention on Biological Diversity, 2012).

c) Reduction in intensity of sunflecks – bursts of strong light which penetrate vegetation canopies and contribute 10 – 90% of light to understory vegetation – with implications for growth of ground-level plants and therefore forest regeneration (Leakey *et al*., 2005; Montagnini & Jordan, 2005; Secretariat of the Convention on Biological Diversity, 2012).

d) Change in evapotranspiration rates due to changes in terrestrial productivity.

e) Reduced productivity in the upper ocean (compared to present-day values) as diffuse light penetrates less effectively than direct light (Secretariat of the Convention on Biological Diversity, 2012). However, impacts on marine ecosystems are not fully understood due to the complex balance of upwelling nutrients and the light availability for oceanic photosynthesis (Russell *et al*., 2012).

f) Bees and other insects using polarized light for navigation may be adversely affected (Secretariat of the Convention on Biological Diversity, 2012).

4. **Reduction in stratospheric ozone leading to increased UV radiation. For example, sulfates released by the eruption of Mount Pinatubo reduced stratospheric ozone by 2% (Harris *et al.*, 1997; Tilmes *et al.*, 2008). A particularly high impact is expected in polar regions in the spring (The Royal Society, 2009).**

    a) UV damage to plants with some species being impacted more severely leading to changes in ecological community composition (Secretariat of the Convention on Biological Diversity, 2012).

b) Change in ocean productivity with increased UV leading to changes in ecological community composition and function. Changes may include a reduction in phytoplankton productivity and an increase in the abundance of some diatoms e.g. *Pseudo nitzschia* (Mengelt & Prézelin, 2005).

c) Biodiversity and ecosystem implications of delayed recovery of the depleted Antarctic ozone layer (Robock *et al*., 2008; Tilmes *et al*., 2008).

d) Reduced calcification rates leading to a decline in calcifying organisms (including reef-building species and organisms with calcium-based exoskeletons; Matthews & Caldeira, 2007; The Royal Society, 2009; Secretariat of the Convention on Biological Diversity, 2012).

5. **Increased acidity of precipitation.** The size of this effect is considered small since quantities of sulfur are estimated to be 1% - 10% of current global deposition, and would be distributed over a wider area than current acid rain from sulfur emissions (Crutzen, 2006; Kravitz *et al*., 2009).
   a) Direct damage to plants.
   b) Increased acidification of freshwater bodies.
   c) Acid run-off to oceans.

6. **Environmental impacts of sulfate production**

8.4 Enhanced marine cloud albedo

Marine cloud brightness or reflectivity would be enhanced by increasing the number of particles acting as cloud condensation nuclei (e.g. by spraying seawater into clouds), to reduce the amount of sunlight absorbed and so reduce temperatures.

Implementation: The albedo of clouds in the troposphere (lower atmosphere) can be enhanced by increasing the availability of cloud condensation nuclei and therefore the concentration of water droplets within clouds (Twomey, 1977; Albrecht, 1989). Stratocumulus clouds cover approximately 25% of the oceanic surface and currently reflect between 30-70% of the sunlight that reaches them (Latham *et al*., 2008). It has been suggested that increasing the reflectivity of all stratocumulus clouds by 10% could offset the warming caused by a doubling of atmospheric CO_2 (Latham *et al*., 2008). Proposed methods include spraying seawater particles from large (300 ton) wind-powered satellite-guided ships or from conventional vessels or aircraft (Salter *et al*., 2008). It is estimated that approximately 1500 vessels would be required to offset the warming from a doubling of CO_2 levels (Latham *et al*., 2008).

This scheme would be limited to remote ocean areas with relatively 'clean' atmospheric conditions. It is anticipated to be particularly effective in the North East Pacific, South East Pacific and South East Atlantic Oceans where cloud condensation nuclei abundance is naturally low (Latham *et al*., 2008). However, it would also work to a lesser extent elsewhere (Partanen *et al*., 2012).

An advantage of this method is that it could be used flexibly in different regions at different times, and addition of cloud condensation nuclei could be stopped should any adverse impacts arise. The salt particles would rain or settle out within approximately two weeks (The Royal Society, 2009). Impacts would primarily occur over the open ocean and mid-ocean islands would be affected.

Another suggestion is that rain-making bacteria *Pseudomonas syrengae* could be used due to its ability to cause cloud condensate nucleation at -1.8 °C. The Ice Nucleation Active protein is currently being isolated and used in local weather modification and snow making (Maki *et al*., 1974; Christner, 2008). ***This method using P. syrengae is not considered further in this report***.

8.4.1 Environmental changes and biodiversity and ecosystem effects

Outlined below are the primary physical, chemical and biological environmental changes caused by the implementation of this technique. Where possible, the potential biodiversity and ecosystem effects of each environmental change are indicated.

NB: These are in addition to the effects listed in Section 8.1: Common Environmental changes and biodiversity and ecosystem effects of SRM techniques causing global dimming.

1. **Strong localized cooling of air temperature and ocean surface in the areas where cloud albedo modification is applied (and moderate cooling more widely)**

2. **Alteration of ocean circulation associated with change in fluxes of energy into and out of the atmosphere (McCusker *et al.*, 2012). It has been suggested that impacts would be local and unpredictable (The Royal Society, 2009), and are not well understood (Russell *et al.*, 2012).**

    a) Potential changes in productivity and communities.

    b) Suggested positive impact on pelagic fish populations (Shepherd, 2011).

    c) Potential for changes in seasonal succession (Shepherd, 2011).

3. **Reduced ocean stratification due to enhanced mixing between layers with localized cooling of ocean surface. Potential increased nutrient supply at ocean surface (Shepherd, 2011).**

4. **Localized reduction in incoming solar radiation in the modified ocean regions of the order of 10% (Jones *et al.*, 2009) leading to reduced light penetration in the ocean.**
    a) Decrease in productivity in the euphotic zone (Raymont, 1980; Secretariat of the Convention on Biological Diversity, 2012), including impact on deeper corals and kelp (The Royal Society, 2008).

5. **Increased proportion of incoming radiation reaching the Earth's surface as diffuse rather than as direct radiation in modified ocean regions (Secretariat of the Convention on Biological Diversity, 2012), which could reduce light penetration into the ocean (Secretariat of the Convention on Biological Diversity, 2012).**
    a) Decrease in productivity in the euphotic zone (Raymont, 1980), including impact on deeper corals and kelp (The Royal Society, 2008).

6. **Over the ocean, an increase in cloud droplet concentration and reduced evaporation will suppress rainfall (Bower *et al.*, 2006; Vaughan & Lenton, 2011). Overall, increase in proportion of global**

precipitation falling over land rather than over the ocean (The Royal Society, 2009). Anticipated to offset effects of the overall slowing of the hydrological cycle – see 1 above - for terrestrial systems.

7. **Dispersion of large volumes of sea salt into the atmosphere resulting in deposition away from the source. Amounts are probably negligible compared to natural levels (The Royal Society, 2008), for example, Partanen *et al.* (2012) estimated an increase in deposition by approximately 10% of current levels.**

   a) Salinization of terrestrial and freshwater habitats in deposition zones.

   b) Potential acidification, for example of freshwater habitats, as a result of salinization (Pryor and Sørensen 2000)

9 SRM techniques increasing the albedo of the Earth's surface

Surface albedo SRM techniques are designed to reflect a proportion of incoming solar radiation back into space by increasing the reflectivity of the Earth's surface. These techniques would have to be deployed over very large areas in order to impact climate at a globally-significant scale (Secretariat of the Convention on Biological Diversity, 2012).

9.1 Enhanced desert albedo

The albedo of desert regions – which receive a high proportion of incoming solar radiation – would be increased by covering areas in manmade reflective materials.

Implementation: The albedo of desert regions, which cover 2% of Earth's total surface area (The Royal Society, 2009), would be increased by covering large areas with reflective polyethylene-aluminum materials (Gaskill, 2012). It has been estimated that an area of 4 million square miles (approximately 43 times the land area of the UK) – across the Saharan, Arabian and Gobi deserts – would be required. The areas deemed suitable are stable, largely uninhabited, sparsely vegetated and flat (Vaughan & Lenton, 2011).

It is suggested that covering this entire area in a material that increases albedo from 0.4 to 0.8 (albedo is measured on a scale of 0 to 1, where 0 is 100% absorption of all incoming radiation and 1 is 100% reflection) could offset about three quarters of the radiative forcing caused by a doubling of CO_2 (Gaskill, 2012), although, other estimates find a much weaker effect (Vaughan & Lenton, 2011).

9.1.1 Environmental changes and biodiversity and ecosystem effects

Outlined below are the primary physical, chemical and biological environmental changes caused by the implementation of this technique. Where possible, the potential biodiversity and ecosystem effects of each environmental change are indicated.

1. **Large-scale coverage of desert habitat with manmade material and the infrastructure to service it.**
   a) Loss and fragmentation of desert habitat leading to decline in species dependent on these habitats.

2. **Substantial localized cooling (of up to 15°C) in desert regions in the vicinity of reflective covers and lesser cooling more broadly (Irvine *et al.*, 2011).**
   a) Reduced heat stress to desert organisms.
   b) Decline in species specifically adapted to hot and dry desert conditions, partly by displacement by less specialized organisms.

3. **Reduced diurnal (day to night) temperature range in modified desert regions due to stronger cooling from albedo increases during daytime (Irvine *et al.*, 2011).**

4. **Reduced amplitude of the seasonal temperature range with much greater cooling in summer particularly in the vicinity of the modified regions (The Royal Society, 2009; Irvine *et al.*, 2011).**

5. **Potentially strong reduction in continental rainfall, particularly in monsoon regions, if implemented at a large scale (Irvine *et al.*, 2011).**

6. **Reduced input of desert dust – a major source of fertilizing iron - to the oceans (Vaughan & Lenton, 2011) and to terrestrial habitats, e.g. dust from the Saharan desert is a significant source of nutrients to the Amazon rainforest (Koren *et al*., 2006).**

   a) Reduced ocean primary productivity in regions dependent on desert dust fertilization (Vaughan & Lenton, 2011).
   b) Reduced primary productivity in dust-dependent terrestrial habitats (e.g. Amazon rainforest).

7. **Physical disturbance due to installation and maintenance of the reflective structures; desert erosion by vehicles; introduction of people and alien species into previously sparsely populated and trafficked areas etc.**
   a) Increased desert erosion leading to loss of habitats (Belnap 1995; Goossens and Buck 2009; Goudie 2009)

9.2 Increasing urban albedo (brightening/whitening built structures)

The albedo of urban structures would be enhanced by covering them with bright paint or materials to reflect a proportion of incoming solar radiation back into space.

Implementation: Roofs, roads and other urban surfaces – constituting 0.05-1% of global land surface (Akbari *et al*., 2009; Lenton & Vaughan, 2009) - would be made bright, reflective white (e.g. by painting). This measure could potentially be extended to all areas of human settlement (Hamwey, 2007), and would be most effective in regions receiving high rates of solar radiation (i.e. lower latitudes).

The maximum possible change in radiative forcing with all urban surfaces becoming white has been estimated to counteract less than 5% of the radiative forcing from anthropogenic greenhouse gases (Secretariat of the Convention on Biological Diversity, 2012).

9.2.1 Environmental changes and biodiversity and ecosystem effects

Outlined below are the primary physical, chemical and biological environmental changes caused by the implementation of this technique. Where possible, the potential biodiversity and ecosystem effects of each environmental change are indicated.

1. **Air, water and soil pollution impacts from production of whitening paints/materials.**
    a) Toxicity to organisms.
2. **Localized cooling in urban areas (Taha, 2008; Oleson *et al.*, 2011; Secretariat of the Convention on Biological Diversity, 2012).**
    a) Reduced primary productivity of plants in close proximity to buildings.
    b) Reduced heat stress on plants in urban areas.
3. **Weak regional cooling and small changes in precipitation across heavily urbanized regions such as Western Europe and East coast USA (Irvine *et al.*, 2011).**

9.3 Enhanced cropland and grassland albedo

Plants selected for their high albedo would be established over large areas of cropland or grassland/shrubland to increase the proportion of incoming solar radiation reflected back into space from the Earth's surface.

Implementation: Under this proposal, plant varieties with variegated or light-colored leaves, high leaf glossiness or a greater amount of leaf hair would be established on croplands and perhaps more broadly on grassland, shrubland and savanna habitats (Hamwey, 2007; Ridgwell *et al*., 2009) to increase vegetation albedo.

It is recognized that differences in the albedo of plants exert an important influence over the regional climate (Ridgwell *et al*., 2009). There are estimates, however, that it may be possible to achieve a 25% increase in albedo across grassland habitats (Hamwey, 2007), and a 40% increase across croplands (Ridgwell *et al*., 2009), which in combination would be equal to offsetting ~20% of warming caused by doubling CO_2 (Vaughan & Lenton, 2011). However, this amount of radiative forcing entails replacement of vegetation across *all* global grasslands/shrublands or croplands respectively, which is unlikely to be feasible or socially, economically or ecologically acceptable (Vaughan & Lenton, 2011). Actual implementation would likely be on a smaller scale, although to have a climatically-significant effect, several million km^2 of cropland or grasslands would have to be replaced (Secretariat of the Convention on Biological Diversity, 2012).

9.3.1 Environmental changes and biodiversity and ecosystem effects

Outlined below are the primary physical, chemical and biological environmental changes caused by the implementation of this technique. Where possible, the potential biodiversity and ecosystem effects of each environmental change are indicated.

1. **Establishment of monocultures of high-reflectivity crops, possibly with a very narrow genetic base and probably genetically modified, over several million km^2 to replace cropland.**

   a) Reduced habitat and biological diversity.

   b) Reduced resistance of communities to pests and disease.

2. **Use of plant varieties with higher albedo than existing crop varieties (Peterson et al., 2000; Watkinson et al., 2000; Ridgwell et al., 2009; Carpenter, 2011), potentially using genetically modified varieties.**

   a) Effects on disease resistance, growth rates and drought tolerance are not yet understood (The Royal Society, 2009).

   b) Reduced water-use (lighter crops tend to have greater water use efficiency) leading to higher soil water content, benefiting species in water-limited regions (Ridgwell *et al*., 2009; Singarayer *et al*., 2009).

3. **Establishment of plantations of high-reflectivity vegetation over several million km^2 to replace natural and semi-natural grassland, shrubland and savanna habitats.**

   a) Loss of diverse grassland shrubland and savanna habitats, leading to decline in endemic species.

4. **Conversion of 'dark' (low albedo) forest habitats to establish 'lighter' (higher albedo) grassland or cropland** (Singarayer *et al*., 2009).

   a) Loss of forest habitat resulting in decline in forest species.

   b) Reduced carbon storage, water cycling, and nutrient cycling as trees replaced with agricultural crops.

5. **Weak regional cooling across agricultural/planted regions, e.g. agricultural regions of mid-west USA (Singarayer *et al*., 2009; Irvine *et al*., 2011).**

   a) Changes in plant productivity.

   b) Changes in community structure and composition with shifts to species adapted to lower temperatures at high latitude or higher temperatures at low latitudes.

6. **Reduced local evapotranspiration, cloud cover and precipitation due to reduced absorption of incoming solar radiation (Vaughan & Lenton, 2011).**

   a) Change in availability of biologically available water.

7. **Potentially reduced primary productivity as increased reflectivity reduces light absorption for photosynthesis (Vaughan & Lenton, 2011).**

   a) Changes to nutrient, carbon and water cycling due to changes in productivity.

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