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REVIEW PAPER

Ecosystem Impacts of Geoengineering: A Review for Developing a Science Plan

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Abstract Geoengineering methods are intended to reduce climate change, which is already having demonstrable effects on ecosystem structure and functioning in some regions. Two types of geoengineering activities that have been proposed are: carbon dioxide (CO_2) removal (CDR), which removes CO_2 from the atmosphere, and solar radiation management (SRM, or sunlight reflection methods), which reflects a small percentage of sunlight back into space to offset warming from greenhouse gases (GHGs). Current research suggests that SRM or CDR might diminish the impacts of climate change on ecosystems by reducing changes in temperature and precipitation. However, sudden cessation of SRM would exacerbate the climate effects on ecosystems, and some CDR might interfere with oceanic and terrestrial ecosystem processes. The many risks and uncertainties associated with these new kinds of purposeful perturbations to the Earth system are not well understood and require cautious and comprehensive research.

Keywords Geoengineering · Ecosystems · Climate change · Carbon dioxide removal · Solar radiation management

INTRODUCTION

As anthropogenic emissions of GHG rise and their concentrations in the atmosphere continue to increase, there is growing discussion about the need to evaluate "geoengineering" methods to reduce the greenhouse effects on the climate and environment (Shepherd et al. 2009). Geoengineering can be defined as the deliberate manipulation of features of the Earth system to reduce the magnitude and rate of changes in the physical climate system that are attributed to this accumulation of greenhouse gases (GHGs; IPCC 2007a). While there has now been much general discussion of the different means by which geoengineering may be accomplished and some speculation about the research strategies by which their effectiveness could be determined (Shepherd et al. 2009), there has been relatively little discussion of research needed to understand their potential for affecting ecosystems. Yet many geoengineering activities could significantly impact both natural and managed ecosystems and their functions. This is important because ecosystems, including those within forests, oceans, grasslands, and wetlands, provide both innate value and our life support systems, including numerous essential goods and services (MEA 2005). This study focuses on research needs related to identifying and quantifying potential ecosystem consequences of proposed geoengineering methods. Ecosystem impacts form a subset of a much broader range of pertinent social and physical science research questions, including issues of governance and ethics, all of which should be addressed before any proposed geoengineering method could be considered as a viable policy option.

In this report, we follow the Royal Society (Shepherd et al. 2009) in referring to two different sets of activities: carbon dioxide removal (CDR) methods, including a range of engineered and biological processes to remove carbon dioxide (CO_2) from the atmosphere, and solar radiation management (SRM or sunlight reflection) methods, typically involving reflecting a small percentage of solar light and heat back into space to offset the warming due to GHGs. CDR and SRM techniques are fundamentally different in the timescales over which the interventions would operate (Lenton and Vaughan 2009; Shepherd et al. 2009). The scale-up of a CDR deployment to the point where it would have significant climate effects would be slow (likely decades for a substantial drawdown of CO_2), but with long lasting effects. In contrast, SRM could provide rapid cooling (in months) but would require continual renewal. Of these two types of methods, only CDR would address the CO_2 concentrations responsible for both climate change as well as other CO_2-induced ecosystem effects such as ocean acidification.

The Climate System

The Earth's temperature and climate are fundamentally controlled by its energy balance, which drives and maintains the climate system. This balance consists of incoming energy from the Sun (including ultra violet, visible, and infrared) and outgoing heat (thermal infrared) radiation. These energy streams do not reach or leave Earth's surface unimpeded. On average, about one third of the incoming sunlight radiation is reflected by clouds and aerosols, ice caps, and bright surfaces. This fraction that is reflected is referred to as its "albedo". Most incoming energy passes through the atmosphere to reach Earth's surface; the part not reflected by the albedo is absorbed and so warms the surface. The absorbed energy is transferred to the atmosphere by emitted surface radiation, evaporative cooling, and direct thermal motion. Some outgoing thermal energy then emitted by Earth's surface is absorbed by GHGs in the atmosphere (mainly by water vapor and CO_2) and also by clouds, thus reducing the amount of heat radiation escaping to space and warming the atmosphere and Earth's surface. This is known as the greenhouse effect. On average, only about 60% of the radiation emitted at the surface leaves the atmosphere, after absorption and emission within the atmosphere. Increased atmospheric CO_2 is not only responsible for temperature changes, but for other consequences to the Earth system. In addition, increased CO_2 absorbed by the ocean has a measurable effect on ocean acidity, with consequent impacts on ocean biogeochemistry and biodiversity.

Carbon Dioxide Removal

CDR methods are designed to remove CO_2 from the atmosphere and transfer it to long-lived carbon reservoirs. They include:

- Land use management to protect or enhance terrestrial carbon sinks;
- Using biomass for carbon sequestration as well as (or instead of) a carbon neutral energy source;
- Accelerating natural geological processes that remove CO_2 from the atmosphere (e.g., "enhanced weathering");
- Direct engineered capture of CO_2 from ambient air (i.e., collection and removal of CO_2 from the atmosphere to storage reservoirs that are isolated from the atmosphere);
- Enhancement of oceanic uptake of CO_2 by, for example, fertilization of ocean biota with naturally scarce nutrients or increasing upwelling processes.

If implemented in addition to CO_2 mitigation, these CDR methods would reduce the proximate cause of the problem, would diminish ocean acidification, and would return the climate to something closer to the pre-industrial state. Because these CDR methods reduce the concentrations of atmospheric CO_2, other things being equal, they would be preferred to SRM methods, but they act slowly (decades) and are likely to be costly (Shepherd et al. 2009).

Solar Radiation Management

SRM methods, also called sunlight reflection methods, aim to reflect up to a few percent of the incident sunlight away from Earth. Once broadly deployed, they would take a few months to have an effect on climate, and therefore some people argue they might be useful if a rapid response is needed, for example to avoid reaching a climate threshold (Shepherd et al. 2009). Methods that have been suggested previously include:

- Increasing the surface reflectivity of the planet by brightening human structures (e.g., painting them white), planting crops with a high reflectivity, and covering deserts with reflective material;
- Enhancing marine cloud brightness (reflectivity) by increasing the number of particles acting as cloud condensation nuclei (CCN) over the oceans;
- Injecting aerosol particles (e.g., sulfates) into the lower stratosphere to mimic the effects of volcanic eruptions;
- Placing shields or deflectors in space to reduce the amount of solar energy reaching Earth.

Model simulations (and some natural analogs like volcanic eruptions that change the planetary albedo) indicate that SRM methods would act quickly (within months) (Rasch et al. 2008; Kravitz et al. 2009). In addition, some initial estimates suggest they would likely be relatively cheap (i.e., billions rather than trillions of dollars per year) (Shepherd et al. 2009). Nonetheless, SRM methods would only create an artificial, approximate, and potentially delicate temperature balance between two opposing anthropogenic forcings. They would also require ongoing maintenance for the duration that excess GHGs remain in the atmosphere (perhaps centuries) unless CDR techniques were employed. In the event ongoing SRM were halted while CO_2 concentrations remained high, Earth would warm within months. Besides having this "termination problem" (see below) (Shepherd et al. 2009), SRM methods do nothing to remediate ocean acidification (the "other CO_2 problem"). Furthermore, because the Earth system is far more complex than current climate models, there would likely be unanticipated consequences of large scale deployments of SRM methods.

Ecosystems

The world's terrestrial and aquatic ecosystems are critically important for humanity's well-being and economic prosperity (MEA 2005). They drive the production of food and energy, regulate water supplies and climate, provide resilience to disease, and recycle waste products. We also value them for recreational, inspirational, spiritual, and cultural purposes, both at the local level and more broadly. Many ecosystem functions that support these services are also dependent on biodiversity—the rich variety of species representing the full breadth of life on Earth, including specific evolutionary adaptations that lead to distinctive local biota. Ecosystems are dynamic complexes of plant, animal, and micro-organism communities interacting as a functional unit with their non-living environment (MEA 2005). Changes to the physical and biological components of ecosystems will affect the nature, interactions, and rates of ecosystem processes and therefore ecosystem services (namely resources and processes supplied by natural ecosystems) on which people depend. It is already widely recognized that climate change will have a dramatic range of consequences on ecosystems and their capacity to provide goods and services to society (MEA 2005; Mooney et al. 2009).[1]

While the objective of this work is to identify the research needed to assess the ecosystem impacts of CDR and SRM methods,[2] we acknowledge that geoengineering involves risks and uncertainties associated with novel perturbations to the imperfectly understood Earth system (as well as numerous ethical and governance questions). In particular, the interconnectedness of many ecosystem processes across a wide range of spatial and temporal scales leads to systems of such complexity, that outcomes are difficult to predict as the systems move outside any previously observed states.

Ecosystems play a variety of pivotal roles for Earth, but some specific aspects are being clearly altered by the changing climate (Mooney et al. 2009). Effects include altered ocean productivity and food web dynamics, reduced abundance of habitat-forming species, shifting species distributions, and a possible greater incidence of some diseases (Hoegh-Guldberg and Bruno 2010), as well as some decreases in biodiversity (Pereira et al. 2010). Since ecosystems are being affected, ecosystem services are also altered. For example, natural and managed ecosystems are important components of the global carbon budget; one key ecosystem service that is affected by these climate effects is the $\sim$100 Pg (turnover) of biologically produced carbon each year (Field et al. 1998, 2007). Other vital services sustain human nutrition and air quality and provide fuel, clean water, climate regulation, and spiritual and esthetic fulfillment (MEA 2005). Ecosystems also maintain the world's biodiversity.

While both CDR and SRM methods have been proposed to reduce climate change, scientists are still actively debating the strategies under which these methods might be used effectively. For example, some researchers have focused primarily on addressing global temperature and its associated impacts on precipitation (Crutzen 2006; Keith et al. 2006; Trenberth and Dai 2007). Others have focused on targeted geoengineering methods to address specific climate impacts of increased CO_2, like hurricane intensity and landfalls, persistence of summer sea ice, and precipitation regimes (MacCracken 2009). And still others have focused on addressing the impacts of ocean acidification.[3]

[1] By 2100, climate change is likely to have altered most ecosystems in their structure, function and biodiversity, and most of these alterations could compromise the services those ecosystems provide to society (IPCC 2007a). Terrestrial ecosystems currently are highly important in carbon sequestration, but the terrestrial biosphere can also act as a net source of carbon to the atmosphere. There is an increasingly high risk of plant and animal species extinctions across terrestrial, fresh water, and marine biota as global mean temperatures exceed a warming of 2–3 °C above pre-industrial levels. These impacts on biodiversity are in many cases practically irreversible. The structure and functioning of terrestrial ecosystems are likely to change; some of these impacts may be positive and others negative. The structure and functioning of marine ecosystems also are likely to be impacted regionally by climate change with models projecting elevated productivity at high latitudes and reduced productivity at low latitudes (Doney 1996). The most vulnerable ecosystems and species are thought to be coral reefs, the sea ice biome, other high-latitude ecosystems, mountain ecosystems, and Mediterranean-climate ecosystems.

[2] There is a fundamental problem in estimating the ecosystem (and other) effects of geoengineering, namely the choice of alternative (reference) scenario against which they are assessed. Throughout this document we compare with a reasonably likely scenario as our "control," i.e., one in the mid-range of SRES scenarios (IPCC 2007a), midway between the extremes of Business-as-Usual and very rapid reduction of emissions. This assumes some "moderate" rate of fossil carbon and other greenhouse gases (GHG) into the atmosphere from energy use and land use changes. The expected responses of ecosystems to the atmospheric and climatic changes resulting from increasing GHG concentrations were reviewed and summarized (IPCC 2007b). We assume that this would correspond to a leveling off of CO_2 concentrations and temperatures at approximately doubled CO_2 (560 ppm).

[3] See http://www.oxfordgeoengineering.org/about.php. Accessed 7 June 2011.

Yet one important open question remains: How would CDR and SRM methods influence the many roles of ecosystems on the Earth system? It is widely recognized that climate change, and mankind more generally, already have demonstrable effects on ecosystem structure and functions. Thus, it is very likely that climate change (and ocean acidification) will have increasing consequences in a world with continuing unabated CO_2 emissions, or even in a world with the levels of emissions reduction currently under negotiation by governments. Consequently, there is a second important open question: Would the impacts of CDR and SRM methods be less or more acceptable than the likely ecosystem impacts from climate change under politically reasonable scenarios of emissions reduction or unabated emissions? Because we know very little about how each of the CDR and SRM methods might modify ecosystems and their services, it would not be meaningful to compare their combined consequences (Boyd 2009) to the alternative, a future where emissions of GHGs are largely unmitigated. In addition, it is worth noting that some methods probably will involve additional risks and uncertainties associated with new kinds of perturbations to the imperfectly understood Earth system.

Geoengineering methods have several important characteristics from the standpoint of understanding their ecological consequences as well as their potential physical effects on the Earth system. Depending on the objective of the geoengineering, they might need to operate on very large spatial scales and might require long-term commitments. This could result in purposeful alteration of biological processes, such as productivity and carbon sequestration, or the transfer of the Sun's energy, on scales that have never before been observed, let alone attempted deliberately.

Governance of CDR and SRM Research

Although there are a growing number of publications on geoengineering methods (Shepherd et al. 2009 and references therein), to date there has been little discussion of formal governance arrangements for either research or potential implementation by international governing bodies. The UK Royal Society report outlines the need to build governance structures if research into a wide range of geoengineering methods is to take place (Shepherd et al. 2009). In 2010, the UN Convention on Biological Diversity issued two statements on climate engineering techniques. Recently the Environmental Defense Fund, the United Kingdom Royal Society, and the Third World Academy of Sciences have initiated a series of meetings aimed at discussing governance needs for SRM research (www.srmgi.org).[4] These efforts provide suggestions to governments, but do not identify mechanisms other than individual national governance to carry out recommendations. In contrast, the London Convention/London Protocol (LC/LP)[5] has assumed responsibility for establishing a governance framework for all planned research into ocean fertilization as a climate modification method. Following consultation with the research community, the Scientific Group of the LC/LP has completed an assessment framework for research on ocean fertilization. This framework if approved by the Legal Group of the LC/LP would be considered for adoption. This would be the first international governance mechanism for any climate engineering technology.

A group of researchers from Oxford University proposed a set of five principles of governance[6] that were later elaborated at the large Asilomar International Conference on principles for governance[7]. The principles emphasize the need for research to promote the collective benefit of humankind and the environment and the need to establish responsibility and liability, open and cooperative research, iterative evaluation and assessment, and public involvement and consent. Most members of the research community have articulated the belief that governance is necessary for potentially risky CDR and SRM field tests.[8]

PART 1: POSSIBLE IMPACTS OF GEOENGINEERING ON ECOSYSTEMS

The rates and impacts of the various proposed CDR and SRM methods on climate, ocean acidification, ecosystems, and human activities will vary (Boyd 2008). To compare the direct and indirect effects of these CDR and SRM methods on ecosystems, we consider two scenarios for each proposed method, one with geoengineering and the other without geoengineering. In each case, both scenarios have the same level of reduction of CO_2 emissions (although CO_2 concentrations will be lower for CDR methods). Compared to the scenarios without geoengineering, by definition, each of the geoengineered scenarios will have a lower global mean temperature. However, because this temperature reduction varies in quantity and speed (e.g., CDR techniques would have a much slower temperature response than SRM), as well as impacts on

[4] See http://www.srmgi.org/.

[5] A description of the London Convention (or London Protocol) is available at http://www.imo.org/OurWork/Environment/SpecialProgramsAndInitiatives/Pages/London-Convention-and-Protocol.aspx.

[6] The proposed five principles are available at http://www.sbs.ox.ac.uk/centres/insis/news/Pages/regulation-geoengineering.aspx.

[7] Articles on this topic are available in the special issue of *Stanford Journal of Law, Science and Policy* at http://www.stanford.edu/group/sjlsp/cgi-bin/articles/index.php?CatID=1013.

[8] See Footnote 7.

other climate characteristics (such as precipitation), ecosystem impacts of different SRM and CDR methods will be different in magnitude and regional extent and should be considered individually.

As there have been only a few limited field tests of some CDR methods (e.g., afforestation) and essentially no field tests of any SRM methods, there is little observational evidence to characterize the beneficial and detrimental effects of these methods on ecosystems. There has been some exploration of both the purposeful and inadvertent impacts of different CDR and SRM methods (Boyd 2008; Shepherd et al. 2009) that exploits information from analogs in the natural world (e.g., volcanic eruptions, Hamme et al. 2010) or from other research on the ocean's role in modulating climate (de Baar et al. 2005). Together they reveal that the impacts of both CDR and SRM methods can have both beneficial and detrimental effects. For example, the purposeful enhancement of net primary production by ocean fertilization can potentially add more carbon to the base of food webs (de Baar et al. 2005), which could be considered a positive outcome or an unwanted ecosystem disturbance. Inadvertent effects of this method could include the stimulation of populations in tropical, subarctic, and Southern Ocean waters of phytoplankton species capable of releasing toxins (Trick et al. 2010; Silver et al. 2010). Based on prior inter-comparisons of the different CDR and SRM methods (Boyd 2008; Lenton and Vaughan 2009), it is possible to put forward preliminary criteria that could be used to rank which method will be least detrimental to ecosystems. For example, a method that would best retain ecosystem health would be one that offsets the effects of climate change without directly targeting and perturbing the land, the oceans, or their biota (and also have virtually no ecological side effects). In contrast, a method that does not reduce CO_2 and for which both the purposeful and inadvertent side effects on ecosystems outweighed any benefit of mitigating climate change would be considered most detrimental.

Presently it is not possible to make a general assessment of all of the types of impacts on ecosystems that might result from all of the CDR and SRM methods. The difficulty in generalizing to all geoengineering methods is partly because of the preliminary state of research, but mostly due to the disparate nature of the dozens of individual geoengineering methods and their vastly different impacts on the Earth system. Therefore, we limited this report to a few case studies, followed by a discussion of the research necessary to extend an assessment beyond these examples. We have considered separately CDR and SRM techniques, as well as land-based and ocean-based techniques. The case studies are not intended to be comprehensive but rather to illustrate the expected range of effects, both positive and negative, on ecosystems.

Each case study was analyzed in two parts. First, we identified the physical and chemical perturbations that the CDR or SRM method is meant to induce (Table 1). Second, we identified how each individual perturbation and the collective impacts might affect ecosystems and the services that they provide for humanity (Tables 2, 3). We applied this two-part assessment framework to the methods noted above (SRM-ocean, SRM-land, CDR-ocean, CDR-land), including one example for each and a fifth example for CDR with storage underground. We assumed that each method would work approximately as designed in terms of its climate impact, its temporal and spatial scales of deployment, and its potential side effects (e.g., CDR-mediated reductions in CO_2 and decreased fertilization of terrestrial crops or enhanced photosynthesis in plant canopies by SRM-elevated diffuse light). We also took into account the likelihood that the methods will not work as envisioned, although this assessment is extremely uncertain due to the very limited amount of available information.

"Control" Scenario (Without CDR or SRM)

Since there was no need to implement CDR or SRM in pre-industrial conditions, choosing whether or not to implement CDR or SRM needs to be evaluated by comparison to a likely future that differs from the geoengineered future only in its lack of geoengineering. Current and expected climate changes have had and will have significant impacts on ecosystems and their services (IPCC 2007a, b; MEA 2005), whether or not CDR or SRM is implemented, and these changes must be considered in our assessment of the risks and benefits of CDR and SRM. We assume a mid-range mitigation scenario as our "control" scenario, which implies an approximate doubling of pre-industrial atmospheric CO_2 concentration (560 ppm).[9] Given a mid-range climate sensitivity this would equate to an increase above pre-industrial global temperatures of 3 °C (IPCC 2007a). It is likely that these changes will increase the magnitude of currently observed impacts on ecosystem and ecosystem service (IPCC 2007b).

Carbon Dioxide Removal

Removing CO_2 from the atmosphere requires identifying a means for storing the captured carbon as a stable chemical, in a location that will provide long-term storage. While several possible solutions exist, there is concern that many may not provide permanent sequestration (Table 4).

[9] See Footnote 2.

Table 1 Impacts of Control, SRM, and CDR scenarios on the physical climate system

	Control	CDR examples			SRM examples	
	Doubled atmospheric CO_2	Afforestation (land)	Engineered carbon capture and storage (underground)	Ocean fertilization (ocean)	Stratospheric aerosol injection (land/ocean)	Cloud albedo enhancement (ocean)
Mechanism for offsetting CO_2-based warming	N/A	CDR provides a nearly direct offset of CO_2 emissions by removing the CO_2. Other climate impacts from CDR are indirect: surface albedo may be changed through changes in vegetation required for some CDR strategies (e.g., afforestation); soil moisture, river runoff, nutrient cycles, etc.,may be changed to support some kinds of CDR (e.g., biochar)			SRM techniques increase planetary albedo to offset the warming associated with CO_2 increases. These albedo changes may not be uniform in space or time	
Spatial distribution	Man-made CO_2 emissions (e.g., fossil fuel burning) occur primarily over land. CO_2 is a long-lived greenhouse gas, making it well mixed in the atmosphere and insensitive to the spatial distribution of its sources and sinks. This long lifetime produces warming which is nearly uniform globally and other indirect consequences regionally	Increased vegetation on land (likely targeting temperate or tropical regions), but the CO_2 response will be global	Minimal expected changes to land or ocean regions as this method could remove CO_2 quickly, countering a lot of CO_2 emissions, with relatively little impact on local resources	Imposed biogeochemical changes in ocean regions by fertilizing with nutrients. In the Southern Ocean, direct iron addition capitalizes on large inventories of unused plant nutrients such as nitrogen and phosphate (Sarmiento et al. 2010). In low-latitude waters, indirect ocean fertilization by pumping up nutrients in ocean pipes (Karl and Letelier 2008)	Most studies to date have considered sulfate aerosols. Their long lifetime in the stratosphere means that they will spread extensively (at least hemispherically), producing relatively small albedo change locally	Marine stratocumulus clouds seem optimal for albedo change (Latham et al. 2008). These clouds exist in the eastern side of subtropical ocean basins
Atmospheric CO_2 reduction per year	N/A	0.4–0.8 Pg C/year removal of CO_2 (Shepherd et al. 2009)	1.7–1700 Pg C/year, removal of CO_2, with the expected value limited by technology and cost (Dooley and Calvin 2011)	10–30 Tg C after 100 years (Gnanadesikan et al. 2003) or 32 Pg C over 100 years (Zeebe and Archer 2005); 3.4 Pg C air–sea flux over 10 years (Jin et al. 2008)	~0 Tg C/year, except for a small enhancement from increased light into plant canopy, possible small reduction in atmospheric CO_2 due to lower temperature	~0 Tg C/year, with possible effect on atmospheric CO_2 concentration through ocean cooling providing a marginal enhancement of solubility pump
Major physical attributes of CDR or SRM method	N/A	Significant changes to albedo and latent and sensible heat fluxes over land (Pielke et al. 2002) and possible increases in cooling from biogenic aerosol	No expected effects other than reduced atmospheric and oceanic CO_2	Projected changes in ocean heat budgets with potential for episodic and extreme meteorological effects in low latitude ocean (Gnanadesikan et al. 2010)	Relatively uniform albedo change, expected reduction in stratospheric ozone, small diurnal cycle suppression, and possible seasonal suppression (Robock et al. 2008)	Significant albedo change in marine stratocumulus regions, potential small effects on local ocean salinity of the surface layer

Table 1 continued

	Control	CDR examples			SRM examples	
	Doubled atmospheric CO_2	Afforestation (land)	Engineered carbon capture and storage (underground)	Ocean fertilization (ocean)	Stratospheric aerosol injection (land/ocean)	Cloud albedo enhancement (ocean)
Climatological feature changes associated with CO_2 increases that may be ameliorated by CDR or SRM methods	Surface temperatures increase, polar amplification of temperature increase, sea level increase, sea ice decrease, poleward shift of storm tracks, increase of strength of hydrological cycle (IPCC 2007a); changes in ocean circulation (Cunningham et al. 2007) and stratification (Doney 2006); projected increase in permafrost thawing and methane release	All changes for the "Control" case would be mitigated to some extent if the CO_2 decrease is large enough. Combinations of CDR might be required; afforestation by itself would not be enough to mitigate loss of sea ice or sea level (Moore et al. 2010)			Modeling studies suggest that many large scale climate changes produced in the "Control" case could be mitigated by SRM. However, it will be difficult to simultaneously compensate for temperature changes and hydrologic cycle changes (Ricke et al. 2010). For example, if SRM were applied to the level that makes global temperature similar to present day, then tropics may be somewhat cooler than present, polar regions somewhat warmer, and the global hydrologic cycle somewhat weaker. Many other subtle changes are possible (too numerous to list here)	
Unique features of particular geoengineering strategies	N/A	Signicant demands on water and land use; possible impacts on nitrogen cycle	There are likely to be minor impacts on land use but the impacts on water use are less certain	Biologically-mediated heating effects in vicinity of fertilized surface waters (Manizza et al. 2009)	Aerosol scattering decreases the ratio of direct-to-diffuse light, with a small reduction in net phototrophic light reaching the surface; changes in ozone and additional aerosols may impact surface UVB light (Rasch et al. 2008); potential global reduction in precipitation, possible shifts in precipitation and temperature; impacts on summer monsoon	Reduction in sunlight of up to 50 W m^{-2} at surface in stratocumulus regions, surface temperature cooling larger over ocean than land; other changes similar to stratospheric aerosol injection. Local cloud albedo increases, resulting in possible changes in circulation, sea surface temperature gradients, nutrient upwelling, and El Niño patterns

Table 2 Impacts of Control, SRM, and CDR scenarios on ecosystem cycling and chemical environment

	Control	CDR examples			SRM examples	
	Doubled atmospheric CO_2	Afforestation (land)	Engineered carbon capture and storage (underground)	Ocean fertilization (ocean)	Stratospheric aerosol injection (land/ocean)	Cloud albedo enhancement (ocean)
Effects on nutrient cycling (including nutrient supply to ecosystems)	Elevated CO_2: accelerated development of nutrient limitation (Norby et al. 2010); warming: accelerated nutrient cycling, transfer of nutrients from soil to vegetation, accelerated nutrient loss (Melillo et al. 2002); increased nitrogen deposition with fossil fuel use; projected increase in ocean stratification will reduce vertical nutrient supply (Doney 2006)	Increased demand for fertilizer.	Slow reversal of baseline conditions, but no effect on nitrogen deposition	Possible nutrient robbing (Gnanadesikan and Marinov 2008); substantial macronutrient depletion, possibly limited by silicate availability (Boyd et al. 2004); O_2 loss in midwater and deep ocean resulting in possible increased hypoxia; reduced surface-ocean and increased deep ocean acidification (Cao and Caldeira 2010)	Changes caused by warming for the "Control" case would be mitigated to some extent; changes caused by elevated CO_2 would not be affected	
Chemical environment for ecosystems	Potential enhancement of anoxia on continental shelves (Chan et al. 2008)	Increased N_2O emissions	Changes for the "Control" case would be mitigated to some extent	O_2 loss in deep oceans, acidification in deep oceans (Cao and Caldeira 2010), N_2O production (Law 2008)	Some deposition of dilute sulfuric acid but small relative to natural and anthropogenic sources (Kravitz et al. 2009)	Possible increased transport and deposition of sea spray to land

Afforestation

Afforestation of "abandoned" land is suggested as a CDR geoengineering strategy that would remove carbon from the atmosphere and store it either in the vegetation itself or as organic matter (decayed vegetation) in soils.[10] In order to notably impact atmospheric CO_2 concentration, afforestation would have to be conducted on a very large scale and over a long term (e.g., Lenton 2010; Jackson and Salzman 2010). Tropical forests would likely accumulate carbon the fastest given their long growing seasons (Sabine et al. 2004). Impacts to ecosystem and ecosystem services will depend on the plant species involved, the degree to which monocultures are used, the amount of fertilizer and water needed to accelerate carbon capture, the storage necessary to meet targets, the previous use of the afforested land, and the latitude of the plantation (e.g., surface albedo impacts of boreal forests, Betts 2000). Afforestation is likely to cause changes in local and regional energy balance and hydrology, soil chemistry and acidity, along with impacts on soil carbon storage (e.g., Jackson et al. 2005; Rotenberg and Yakir 2010). New forests will also emit volatile organic compounds (VOCs), which increase CCN concentrations and affect cloud formation (Spracklen et al. 2008). The combined effects of afforestation on the hydrological balance, the surface albedo, and cloud properties can influence regional precipitation patterns and climatology, an area for which considerable new research is needed. Furthermore, nominally "abandoned" land may already be providing some services, such as esthetic contributions; so afforestation could result in the demand that these services be displaced to other land, resulting in unintended effects to that land. These socio-economic dimensions of the demands and diversity of ecosystem services could be important and should be taken into account. Finally, the permanence of carbon removal by afforestation is dependent on continued management of afforested land to maintain the sequestration. Without a commitment to continued management, afforestation is effective as CDR only for a limited duration (~100 years).

Engineered Carbon Capture and Storage

An engineered method for carbon capture with subsequent geological storage could involve using chemical sorbent materials to capture CO_2 from the atmosphere (Lackner

[10] We consider afforestation here as a CDR method, even though in some circumstances it is also considered a mitigation method, e.g., avoided deforestation.

Table 3 Impacts of Control, SRM, and CDR scenarios on ecosystem components

	Control	CDR examples			SRM examples	
	Doubled atmospheric CO_2	Afforestation (land)	Engineered carbon capture and storage (underground)	Ocean fertilization (ocean)	Stratospheric aerosol injection (land/ocean)	Cloud albedo enhancement (ocean)
Community structure and taxonomic diversity	Changes in biome distributions in land (tundra, Amazon, boreal, desertification) and ocean (Boyd and Doney 2002; Boyd and Ellwood 2010; Boyd et al. 2010) ecosystems; increased weediness; reduced biodiversity; reduced sea ice causing polar bear extinction (Durner 2009); ocean acidification; large effects on community structure in coral reefs; uncertain effects on calcifying plankton; effects will be different for different species (Fabry et al. 2008)	Reduced changes in biome distribution, more forests retained; reallocation of land use (e.g., from grassland to forest)	Changes for the "Control" case would be mitigated to some extent: reduced changes in biomes, extinctions	Purposeful redistribution of phytoplankton species (Boyd et al. 2007). Short-term (multi-week) changes in phytoplankton, heterotrophic bacteria and higher trophic levels during bloom (permanent changes are possible, with increased toxic diatoms in some regions) (Trick et al. 2010; Silver et al. 2010)	Changes for the "Control" case would be mitigated to some extent: reduced changes in biomes, extinctions. Change in seasonality will impact phenology, especially for near-freezing ecosystems	Changes for the "Control" case would be mitigated to some extent: more biodiversity than base case; unknown effects on surface-ocean species distributions (e.g., reduced light could favor phytoplankton that are adapted to lower light), but likely smaller than the "Control" case
Biomass and productivity	Benefits from warming: increased biological productivity because of CO_2 fertilization and water efficiency, including increases in oceanic net primary productivity (Saba et al. 2010); losses from warming: sensitivity to drought, possible transition of Amazon to tundra, decreased productivity from coastal changes in hydrology, increased vulnerability to wild fires	Increased forest biomass and productivity	Changes for the "Control" case would be mitigated to some extent, but localized changes in land use are likely in deserts	Purposeful increase in net primary productivity and phytoplankton biomass in surface waters (Boyd et al. 2004; Boyd et al. 2007); increases could be either sustained or transient, depending on region and amount of unused nutrients; changes on land for "Control" case would be mitigated	Biomass and productivity will be stimulated by increased diffuse radiation and synergy with high CO_2 (reduction in PAR will limit this effect); in some places, productivity could be reduced by different or exacerbated regional drought	May be more biomass than base case if global temperature is reduced, but intense cooling over small ocean regions could change ocean productivity and circulation (e.g., El Nino and monsoon cycles), which could have detrimental effects on land; changes in stratification, nutrient supply, sunlight

Table 3 continued

	Control	CDR examples			SRM examples	
	Doubled atmospheric CO_2	Afforestation (land)	Engineered carbon capture and storage (underground)	Ocean fertilization (ocean)	Stratospheric aerosol injection (land/ocean)	Cloud albedo enhancement (ocean)
Biogeochemical cycling	Increased nitrogen deposition from continued fossil fuel combustion (e.g., in Arctic); changing nutrient loads in coastal and to some extent open oceans due to eutrophication and atmospheric deposition (Duce et al. 2008); overall decreased particulate export flux in open ocean (Bopp et al. 2002)	Increased nitrogen deposition	Changes for the “Control” case would be mitigated to some extent, including possible restoration of nutrient imbalances	Increased biogeochemical cycling in surface layers (including CO_2 uptake and trace gases, DMS, N_2O); unknown extent of CO_2 drawdown; expected acceleration and enhanced re-mineralization of sinking particles (Boyd et al. 2004)	Cooler soil temperatures could reduce nutrient turnover in soils; reduced carbon loss; small change in sulfur deposition in rain; changes in atmospheric circulation and precipitation could have large scale impacts on terrestrial biogeochemical cycling	Potentially high regional changes in ocean cycling; changes in atmospheric circulation and precipitation could have large scale impacts on terrestrial biogeochemical cycling; possible localized changes in ocean chemical cycling

2003) or reacting CO_2 with strong bases (Keith et al. 2006). The captured CO_2 must be recovered, transported, and placed in a site for underground geological storage (Elliott et al. 2001; Lackner 2003; Keith et al. 2006). Geological storage is envisaged to be similar to that used for Carbon Capture and Storage (CCS) (IPCC 2005). The process has substantial energy and water requirements that vary with technique and exact design specifications (Socolow et al. 2011). In general, direct impacts of this method on ecosystem resources (e.g., water) appear relatively small and are likely to be highly localized to the site of the capture facility and the underground site of the storage facility, unless there was a major requirement for minerals, water, or materials.

Ocean Fertilization

Two proposed CDR methods for stimulating ocean biological removal of CO_2 by fertilization have received the most attention. One relies on iron fertilization to alleviate the iron limitation of phytoplankton growth. In this approach, large inventories of unused nutrients in those ocean regions that have High Nutrients but paradoxically Low Chlorophyll (termed HNLC, Martin et al. 1990) are used to stimulate phytoplankton growth, which will take up CO_2. The second approach involves nutrients like nitrate or phosphate, which have a limited supply in surface waters. The underlying principle is to increase biological productivity as a means of increasing carbon export to deeper waters.

Regions where these methods could be deployed are large (basin scale) HNLC regions limited by iron availability, such as the Southern Ocean, and oligotrophic areas that are limited by nitrate or phosphate availability (Boyd et al. 2007). Adding nutrients could be accomplished by surface enhancement (Matear and Elliott 2004) or upwelling of deeper, more nutrient rich waters over large swathes of the remaining (Low Nutrient Low Chlorophyll) ocean (Karl and Letelier 2008; Shepherd et al. 2009). By altering both the biomass of phytoplankton and the species which will thrive, these interventions will necessarily alter food web structure and hence many other ecosystem functions (Boyd et al. 2007).

Solar Radiation Management

As SRM methods do not address increased atmospheric CO_2 concentrations, they will not reduce ocean acidification or the effects of high CO_2 concentrations on terrestrial ecosystems (e.g., favoring woody over grassy plants). However, their potentially rapid reduction of warming may provide sufficient benefits in and of themselves to merit consideration under some conceivable circumstances. Two

Table 4 Impacts of Control, SRM and CDR scenarios on ecosystem services

	Control	CDR examples			SRM examples	
	Doubled atmospheric CO_2	Afforestation (land)	Engineered carbon capture and storage (underground)	Ocean fertilization (ocean)	Stratospheric aerosol injection (land/ocean)	Cloud albedo enhancement (ocean)
Supporting (net primary productivity, soil, nutrient cycling)	Mixed effects on ocean and land net primary productivity; indirect effects on soils; positive effects from high CO_2; mixed effects from increased temperature; negative effects from drought; reduced ocean nutrient supply but could be offset in some regions by enhanced atmospheric nitrogen deposition (Duce et al. 2008)	Increased forest causes higher net primary productivity	Depends on materials needed for specific carbon capture technology	Ocean nutrient robbing—localized increases in primary production but potential decreases far afield (Gnanadesikan and Marinov 2008)	Changes for the "Control" case would be same for CO_2, and productivity would be enhanced by increased diffuse radiation	Changes similar to the "Control" case are expected for land net primary productivity; enhanced upwelling and nutrient supply may increase ocean net primary productivity
Provisioning (fuel, fiber, food)	Food supply is reduced by temperature increase and drought, but partially offset by high CO_2; ocean impacts are unclear but probably negative for fisheries and shellfish (e.g., altered distribution of 'fish food' zooplankton in Atlantic,Richardson and Schoeman 2004)	Competition with food for arable land	Energy cost for capturing and storing CO_2	Possible enhancement of some fisheries due to increased phytoplankton, but such carbon cycling through food web would reduce carbon sequestration	Energy will be required for aerosol delivery; otherwise fuel and fiber likely improved relative to "Control" case	Energy is required; potential changes to fishery production in some regions (e.g., Peruvian tuna fishery); possible increased productivity for upwelling-based fisheries
Regulating (climate regulation, water quality)	Diminished capacity for carbon sequestration; terrestrial biosphere is likely to become net carbon source; tundra source of methane; change in water vapor distribution; freshwater supply redistributed; higher O_3 exposure of plants; warming reduces ocean biological (Bopp et al. 2002) and solubility pumps	Increased water use and changes to water availability; trace gas emissions reduced	Water will be required for capturing and storing CO_2	Possible albedo increases from enhanced DMS emissions; enhanced ocean capacity of CO_2; potential production of N_2O during re-mineralization (Law 2008); altered water quality (less nutrients, less O_2 and more acid) in mid and deep water as well as column	Cooler temperatures may increase water availability due to lower temperature and less drought; increased ozone hole formation from aerosol heterogeneous chemistry, causing increased UV radiation damage to land-based biota	May be better climate regulation than base case if global temperature is reduced, but intense cooling over small ocean regions could change circulation (e.g., El Nino and monsoon cycles), which could impede climate regulation; enhanced ocean upwelling could increase outgassing of CO_2
Cultural (esthetics, educational, spiritual)	Changes in biome distributions; loss of biodiversity and ecosystems, especially at high altitudes and latitudes; negative impacts on coral and other ecosystem-related tourism	Reduced visual diversity	Factories will be visually unappealing but likely to impact small, unpopulated areas	Impacts on coastal fishing communities; possible H_2S production due to increased anoxic zones; increased acidification of deep ocean biota (Cao and Caldeira 2010)	No blue sky; impeded astronomical observations	Increased man-made structures in ocean regions; possible reduced visibility at sea; similar to arguments against offshore wind turbines

SRM methods, commonly thought to be among the more feasible, are considered here, stratospheric aerosol injection and cloud albedo enhancement.

Stratospheric Aerosol Injection

Injecting sulfate (or other) aerosols into the lower stratosphere would induce a cooling, similar to that observed in response to the eruption of Mt. Pinatubo in June 1991 (Stenchikov et al. 1998; Soden et al. 2002; Crutzen 2006; Rasch et al. 2008). This cooling is a result of the aerosols' reflecting sunlight away from the planet. However, particles from volcanic eruptions do not represent an exact analog for the particles proposed for use in geoengineering, particularly because the latter will have different sizes, concentrations, and lifetimes and because their continued use will result in a larger widespread change in the stratosphere that is unlikely to scale linearly from the isolated perturbations of volcanoes. But maintaining the concentrations necessary to continuously reduce temperatures would require regular aerosol or precursor gas injections.

Sulfate aerosol geoengineering could lead to unwanted side effects such as changes in precipitation and ozone depletion in heterogeneous chemical reactions (Trenberth and Dai 2007; Robock et al. 2008; Rasch et al. 2008, Tilmes et al. 2008). The increased acidification from sulfate additions appears to be a small contribution to acid rain, with the quantities of sulfur likely less than 10% of global deposition (Kravitz et al. 2009). A large increase in total stratospheric sulfate can lead to significant ozone depletion (Tilmes et al. 2008). The impact of this ozone depletion on the amount of UVB light reaching the surface (with a consequent effect on ecosystem function) is as yet unknown because stratospheric aerosols also attenuate light in this part of the energy spectrum (Rasch et al. 2008).

The efficiency of carbon fixation by the forest canopy is increased when the light is distributed more uniformly throughout the canopy, as occurs with diffuse light. Diffuse light penetrates the upper canopy more effectively than direct-beam radiation, because direct light saturates upper sunlit leaves but shades lower leaves. The primary effect of injecting of sulfate aerosols into the stratosphere is to scatter light, and this will increase the fraction of light reaching Earth's surface that is diffuse. Hence, it has been suggested that the (small) reduction in total photosynthetically active radiation (PAR) would reduce terrestrial productivity less than the increase due to increased efficiency resulting from the increase in diffuse radiation. Such may have been the case following the Mt. Pinatubo eruption (Gu et al. 2003) and during the "global dimming period" (1950–1980) (Mercado et al. 2009). A sensitivity analysis carried out for the broadleaf forest shows that simulated gross primary productivity reaches a maximum at a diffuse fraction of 0.4, after which it decreases due to a reduction in the total PAR. In the absence of deliberate aerosol injection associated with SRM, a decline in aerosols before atmospheric CO_2 is stabilized will mean the effect of diffuse radiation on photosynthesis will decline to near zero by the end of the 21st century (Mercado et al. 2009).

Analyses of the effects of SRM on oceanic photosynthesis by phytoplankton have not been made, but oceanic photosynthesis depends on downward directed or "downwelling" PAR. In many marine ecosystems, there is a deep chlorophyll maximum where upwelling nutrients rise high enough so that there is sufficient light to drive net photosynthesis. A reduction in PAR and a shift from direct to diffuse radiation may shift this deep chlorophyll maximum with as yet unknown consequences for marine ecosystems.

Cloud Albedo Enhancement

The principle behind this geoengineering intervention is to increase the reflectivity of low-level maritime clouds by generating CCN (Latham 1990; Latham 2002). As an example, sea salt could be sprayed into the marine boundary layer using specifically designed vessels (Salter et al. 2008). Three remote marine areas are identified as having suitable atmospheric conditions for such enhancement: North East Pacific, South East Pacific, and South East Atlantic Oceans (Latham et al. 2008). Currently, little to no research has been done on the potential impact of this surface cooling and light reduction on marine ecosystems. To achieve a sufficient reduction in global annual mean temperature, this strategy requires significant localized cooling in these regions. This strong regional cooling has been shown in some modeling studies to perturb mesoscale atmospheric-oceanic systems, such as the West African Monsoon and the El Niño Southern Oscillation, although the results are inconsistent across the different studies (Latham et al. 2008; Jones et al. 2009; Rasch et al. 2009). Biological effects have not yet been estimated but could presumably be significant. These atmospheric and oceanic perturbations may in turn have significant terrestrial ecosystem impacts, especially through changes to regional precipitation regimes. Uncertainties related to changes in 'downwelling' PAR apply to this type of SRM as well.

Additional Considerations

SRM Novel Environment

Given the evidence now available from climate modeling simulations, implementing SRM methods would produce smaller temperature and precipitation changes from today's Earth than if greenhouse gas emissions continued unchecked (Shepherd et al. 2009). If these simulations are accurate (Ricke et al. 2010) and if SRM is undertaken and sustained for decades at a level chosen to roughly offset growing greenhouse gas forcing, the ecosystem impacts of SRM might be more modest than the impacts arising from climate change without SRM. However, these simulations are uncertain, especially because the combinations of changes in an SRM-altered world—more diffuse light, altered precipitation patterns, very high CO_2 concentrations—are unlike any historically known combination that today's species and ecosystems have ever faced and to which they have become adapted. Presently, we have low confidence in our ability to predict the ecological consequences to such an unknown combination of climatic variables and in our ability to predict surprises arising from the deployment of SRM, especially given the rather short transition times that may be involved with both initiation and termination.

SRM Termination Problem

SRM will provide cooling only as long as it is continually renewed. If SRM is undertaken for many decades with its forcing increasing to offset rising greenhouse gas levels, then cessation of SRM will result in very rapid warming (Wigley 2006; Matthews and Caldeira 2007), and large and rapid changes in circulatory patterns and precipitation would likely occur. Such rapid changes would almost certainly have very large harmful impacts on ecosystems.

Ecosystem responses to such rapid warming would be expected to be much more severe than the response of the biota to the more gradual warming that has already resulted—and will result in the future—from the ongoing gradual increase in greenhouse gas concentrations. With no time for species and communities to adapt, many microbial organisms, plants, animals, and their interactions could be affected, altering community structure, biogeochemical cycles, carbon and nutrient losses from soil, and fire risk. Very rapid warming could also cause accelerated thawing of permafrost. As an example of an even more sudden warming (over the time scale of days rather than the months for SRM termination), Europe experienced an extraordinarily hot summer in 2003, resulting in 40 000 extra deaths in the region during that period. July's temperature was 6 °C above the long-term average, and annual precipitation was 50% below average. The resulting drought-induced reduction of gross primary productivity by 30% produced a strong anomalous net source of CO_2 to the atmosphere, reversing 4 years of ecosystem-driven net carbon sequestration (Ciais et al. 2005). Note also that significant crop failures occurred; much larger anomalies could result from a sudden cessation of SRM.[11]

Ocean Acidification

Ongoing ocean acidification is a result of rising atmospheric levels of carbon dioxide (Shepherd et al. 2009) and would realize very different effects from any large scale adoption of either CDR or SRM or strategies. If the world, or some major emitting states, were to adopt SRM as the primary strategy for addressing climate change, rising atmospheric levels of CO_2 could be more likely to continue unchecked. In this event, ongoing ocean acidification, and the large impacts likely on ocean ecosystems (Fabry et al. 2008), would also go unchecked. In contrast, any CDR strategy that slows or reverses the rise in atmospheric CO_2 levels would help to slow or even reverse the process of ocean acidification.

Until a few years ago, the ecological consequences of ocean acidification had received very little research attention (Doney et al. 2009). Possible impacts of ocean acidification may include both reduced calcification and enhanced dissolution of the shelled organisms that constitute significant links in ocean foodwebs (Raven et al. 2005). Should significant levels of SRM be undertaken without being accompanied by a comparably major effort to limit ocean acidification, substantial impacts on the ocean would result.

While it is not the focus of this study, in principle it would be possible to engage in a form of geoengineering designed to regulate the pH of the oceans (e.g., alkalinity addition methods by oceanic "enhanced weathering" or "liming the oceans")[12] (Rau and Caldeira 2002; Rau 2011). The amount (mass) of minerals that would have to be moved to do this makes it expensive and therefore unlikely to be attractive as a global strategy in the near future. But some local "preservation" of unique or valuable ecosystems, such as specific coral reefs or aquaculture sites, might be feasible as a last resort.

PART 2: UNCERTAINTIES IN DETECTION AND ATTRIBUTION

Climate variability and anthropogenic climate change are already altering both ocean and terrestrial ecosystem dynamics on a global scale (Boyd and Doney 2002;

[11] CDR methods do not have this so-called "termination problem" (unless storage proves unstable), since any reduction of GHG concentrations is necessarily gradual and essentially permanent, and this can be regarded as a major advantage of this class of methods.

[12] See note 3.

Parmesan and Yohe 2003). But detecting and attributing the relative contributions of natural climate variability and climate change to altering ecosystem dynamics is challenging (Doney 2010). Likewise, detecting and quantifying the impact of individual (or multiple) geoengineering activities on ecology would be difficult, whether these are research experiments or potential future deployments of CDR and SRM (Boyd 2009). Scholars and international groups are already beginning to discuss questions of governance (e.g., Blackstock and Long 2010) and liability potential associated with loss of ecosystem services or alterations to ecosystem structure after an experiment or future deployment. Such questions would also require distinguishing the relative role of natural (climate variability) and anthropogenic (climate change, CDR, SRM) alterations to ecosystem structure (Boyd 2009; Blackstock and Long 2010). Research into such detection and attribution will need to play a central role in any overall research strategy to understand the ecological impacts of geoengineering.

PART 3: PRELIMINARY RESEARCH PLAN

Given the clear need to better assess the potential impacts of proposed geoengineering schemes on ecosystems, we discuss here the salient features of a research plan.

Framing the Question

To assess the ecosystem impacts of CDR and SRM, the focus needs close coordination between the design of the perturbation itself (the emulation of the CDR or SRM method) and the design of the research on its impacts on the ecosystem. It is important to carefully design the locations and durations of CDR and SRM studies to ensure that the responses of the ecosystems and their time scales of response are captured, including both the intentional perturbation as well as any associated side effects (whether anticipated or unanticipated). This is also true if natural perturbations are to be studied (such as volcanic eruptions), since the responses may occur over longer times than the observed disturbance. Particular attention needs to be paid to the large uncertainties associated with the desired effects, as well as the side effects associated with the proposed techniques. Selecting a baseline reference set of observations with which to compare the outcomes of the perturbation is also a problematic issue. In addition, many geoengineering concepts couple effects in marine, terrestrial, and atmospheric systems, thus requiring that these domains be studied together.

Scientists and funding agencies should be prepared to be cautious and judicious in designing even small-scale (i.e., on the order of 10 km in size) geoengineering field experiments, as we do not have a strong a priori basis for knowing all the potential consequences of geoengineering experiments or even for predicting whether they will yield results that can be easily interpreted. The potential for unanticipated environmental or ecological responses (e.g., toxic phytoplankton blooms, Trick et al. 2010) from such experiments, in addition to the risk of failure of the CDR or SRM method, must be acknowledged.

Observational Records and Process Studies

Many CDR and SRM methods are intrinsically very large scale or global in their application and impacts and so cannot be studied without a clear baseline observational record before beginning intervention (Law 2008). Baselines and coordinated process studies are also critical to be able to explicitly attribute the changes detected to specific causes. However, given the longevity (decades) or spatial extent (ocean basin scale or large part of the stratosphere) of some CDR and SRM methods, defining a baseline is difficult, as ideally it would include a long-term, spatially resolved record of Earth's ecosystems (Keller et al. 2008).

Numerical Models and Experiments

Ecologists need to define the key processes, space and time scales, and state variables required to study the impacts of CDR and SRM methods. Specifically, distinguishing sensitivity and adaptability to rates and to types of environmental change will increase the utility of analyses (Dawson et al. 2011). Specifically, the types of ecological models that need to be used must be clearly defined, as well as the models and model experiments (e.g., simulated CDR and SRM impacts) used in the design of observing systems and experiments. It is likely that data assimilation approaches will also be required (Raupach et al. 2005; Watson et al. 2008). Coupled feedbacks between ecosystems and climate could also be important, particularly over time scales of decades, and should be investigated using advanced Earth system models (Arneth et al. 2010; Carslaw et al. 2010).

Experiments: Analog and Field

Analog exercises (e.g., laboratory-scale experiments that capture key features of proposed geoengineering approaches) can be extremely valuable, especially when key features of the system and its feedbacks and interactions can be modeled, while greatly compressing the time and spatial scales required. Such experiments (e.g., the effects of elevated CO_2 or increased temperature on plant growth), while idealized, can lead to developing hypotheses for further exploration using full-scale experiments, numerical simulations, and observations. Analog experiments can provide evidence of sensitivity to rates of change and can be used in experiments that examine *unnatural* worlds (i.e., worlds with combinations of variables that do not, or not yet, exist on Earth.

Field experiments that use either direct manipulation or take advantage of natural perturbations (such as volcanic eruptions (Hamme et al. 2010), or large scale dust deposition to the oceans) are critical for exploring the geoengineering impacts on ecosystems. Field experiments using direct manipulation should be preceded by risk assessments and numerical modeling. To fully exploit such experiments, coupled physical, chemical, optical, and biological measurements need to be made, which would be carefully designed by experts in each area working in close cooperation (Watson 2008). A large suite of skills (and possibly international funding sources) will be required to design effective CDR and SRM experiments. However, not all experiments need to be large to be useful. For example, relatively small (but sustained) field experiments could be designed to study the effects of an increase in diffuse sunlight (such as might occur with some SRM schemes) on various terrestrial ecosystems. These local environmental studies might be performed without any introduction of stratospheric aerosols or cloud seeding. For example, translucent plastic sheeting might be used to increase the amount of light that reaches a forest canopy diffusely.

Due to their inherent complexity, experiments that are intended to provide information for evaluating geoengineering proposals should be included as an integral part of the design process, to optimize their location, spatial scale, duration, and sampling strategy. During and after an experiment, comparisons should be made between models and observations for mid-course correction to forecasts (Watson et al. 2008) and to identify model errors diagnostic of unknown or uncertain processes. In addition, comparing measurements and model outputs are vital for extrapolating results in space and time.

An international approach is required to address the scale and potential policy importance of CDR and SRM field studies. Leadership by international science organizations will be needed to design experiments that can be executed at large scales, have minimal impacts, and produce results that are credible to the many nations involved. Indeed, CDR and SRM experiments may be so large and may have sufficient trans-boundary environmental impact (Boyd 2009) that international governance may be required sooner rather than later. Societal perspectives and upstream engagement of stakeholder constituencies should also be incorporated in future experimental design (Parkhill and Pidgeon 2011).

Integration

An integrated approach to experimental design and execution, observations, and modeling is needed to study the impacts of CDR and SRM methods. Experiments are needed to provide insight into how organisms and ecosystems respond to perturbations of current environmental conditions. Observations are needed to detect consequences of CDR and SRM and determine whether anticipated or unanticipated effects occur. Models are needed to integrate observations, and to explore consequences at time and space scales that cannot be addressed with experiments.

We have outlined some but likely not all of the components and strategies important for a geoengineering research agenda. Workshops dedicated to addressing important questions may be needed to elucidate specific goals, including:

(1) To design experiments that examine the ecological consequences of an engineered planet (e.g., cool, but with high CO_2);
(2) To define the baseline observations necessary for interpreting results of CDR and SRM experiments;
(3) To define the types of models necessary to address ecological impacts of CDR and SRM (in particular, ecologists need to define the key processes, scales, state variables, and sensitivities to rates of change for modeling ecological impacts); and
(4) To define the models and analyses necessary for comparing geoengineered and non-geoengineered worlds.

PART 4: CONCLUSIONS AND RECOMMENDATIONS

From our synthesis of what is currently known about proposed CDR and SRM methods and their potential impacts on ecosystems, we offer the following conclusions and recommendations.

Conclusions

Although relatively little is presently known about the effects of CDR and SRM geoengineering methods on ecosystems, it is clear that different geoengineering strategies will bring about different ecological impacts. Regardless of whether geoengineering methods were targeted at a particular ecosystem (e.g., ocean iron fertilization) or designed to affect Earth's energy balance directly (e.g., SRM), there would likely be inadvertent effects on the targeted ecosystem as well as on ecosystems not specifically targeted. And even if geoengineering strategies are designed to address local to regional impacts of climate change, global consequences might result as well.

In addition, we note that:

- Research on the possible ecological impacts of SRM and CDR will be important before large-scale (i.e., on the order of 100 km in size) implementation is evaluated, since geoengineering may produce new environments that differ from those existing in the present or that occur in a non-geoengineered future. This research could complement studies on the ecosystem impacts of climate change that are needed and those already underway, as well as contribute to other aspects of mainstream ecological research.
- The effects of CDR and SRM methods undertaken to moderate climate change are uncertain for ecosystems and their biodiversity. These effects may be smaller or less severe than the effects of unmitigated climate change in some cases but would require the initiation of targeted research to identify the most promising approaches and locations and to reduce uncertainties.
- Some CDR and SRM methods may alter key features of the climate system such as the location of the inter-tropical convergence zone or oceanic upwelling systems with consequent effects on ecosystems and biodiversity. Though these multi-link chains of coupled physical-biological impacts are highly uncertain, they can be extremely influential (Wang and Schimel 2003).
- If SRM was undertaken without concomitant attention to increases in atmospheric CO_2, ocean acidification (and effects of CO_2 on terrestrial ecosystems) would remain a concern. If SRM was pursued, then ended abruptly, all ecosystems would sustain large and rapid changes in temperature and other climate variables, creating impacts that are likely to be more severe than current (slower) warming scenarios.
- Ecological research may produce results indicating that some or all proposed geoengineering approaches would have large and unacceptable ecosystem consequences. Therefore, support for a research program should not be interpreted as support for development of specific geoengineering technologies. Rather, support for a research program is based on the assumption that good policy decisions depend on good science.

Recommendations (for Research)

Given the current large uncertainties, research on ecosystem impacts is needed to provide the knowledge on which to base informed decisions on CDR and SRM. Current knowledge of existing biodiversity and ecosystem structure and function is inadequate and must be improved by undertaking major coordinated programs of laboratory, field, and modeling research in conditions representative of the changing climate, both with and without CDR and SRM, if they are to provide an improved baseline and basis for evaluating possible future impacts. International cooperation in the design and execution of CDR and SRM research programs would be highly desirable.

In addition, we recommend specifically that

1. Research into the impacts of CDR and SRM on ecosystems and ecosystem services, would benefit from multi- and inter-disciplinary research incorporating physical, biological and social disciplines to ensure detailed study of all relevant aspects of each CDR or SRM technique and its ecological impacts.
2. Geoengineering-related ecological research should
    a. be integrated with mainstream and climate change related research programs wherever possible and
    b. include efforts to study novel environments that may be created as a result of possible geoengineering interventions, which may include careful perturbation experiments.
3. Careful thought needs to be given to research, especially to field experiments. Although caution needs to be exercised for geoengineering-related research, a broad moratorium on experiments that are small relative to the scale of ongoing human activities is not recommended as it could impede the discovery of solutions to climate change related problems through the advancement of knowledge of the Earth system. A system of governance is needed for experiments that could have substantial or trans-boundary ecological or other impacts that would be likely to have impacts exceeding those of ongoing commercial and agricultural activities. Any such regulatory system needs to take into account the appropriate expert guidance necessary for relevant experiments.[13]

Societal decisions related to geoengineering will require input from a broad range of social and physical sciences, and include considerations of an even broader range of social, ethical, and political factors. One of the factors that should affect these decisions is a careful evaluation of ecosystem impacts, including an assessment of uncertainties and the likelihood of unanticipated outcomes. With well-designed research efforts, ecosystems scientists can help provide this much-needed information.

[13] The efforts already being made through the Solar Radiation Management Governance Initiative (of the Royal Society, the Third World Academy of Science, and the Environmental Defense Fund) and through the London Convention for ocean fertilization will contribute to the development of necessary systems and norms.

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