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Edited by Zinta Zommers and Keith Alverson

Resilience

The Science of Adaptation to Climate Change

Elsevier
Radarweg 29, PO Box 211, 1000 AE Amsterdam, Netherlands
The Boulevard, Langford Lane, Kidlington, Oxford OX5 1GB, United Kingdom
50 Hampshire Street, 5th Floor, Cambridge, MA 02139, United States

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British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library

Library of Congress Cataloging-in-Publication Data
A catalog record for this book is available from the Library of Congress

ISBN: **978-0-12-811891-7**

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Publisher: Candice Janco
Acquisition Editor: Laura Kelleher
Editorial Project Manager: Tasha Frank
Production Project Manager: Nilesh Kumar Shah
Cover Designer: Christian Bilbow

Typeset by MPS Limited, Chennai, India

Cover Image: IrinaK/Shutterstock - Working traffic lights over streets flooded by Hurricane Harvey in Houston, Texas, September 2017

Contents

Section V
Next Steps

Chapter 24

Ecological, Agricultural, and Health Impacts of Solar Geoengineering

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Chapter Outline

Proposals to engineer the climate are not new (Budyko, 1974; Latham, 1990), but received little attention until Nobel Laureate Paul Crutzen's 2006 essay on the potential to cool the Earth by injecting sunlight-reflecting aerosols into the stratosphere (Crutzen, 2006)—breaking the taboo on geoengineering research. Since Crutzen's essay, slow and stalling progress on emissions reductions (Peters et al., 2013), increasing attribution of negative impacts in social and environmental systems to climate change (Carleton and Hsiang, 2016), and the ambitious goal in the Paris Climate Agreement to hold global warming to below 2°C (Rogelj et al., 2016) have all heightened attention on solar geoengineering as a potential tool to reduce the impacts of climate change.

The term "geoengineering" (also called "climate engineering" or "climate intervention") refers to suggestions to artificially enhance Earth's albedo, called albedo modification or solar radiation management (SRM), and to suggestions to remove carbon dioxide from the atmosphere to reduce the greenhouse effect, called carbon dioxide removal (CDR). They are quite distinct in technology, risks, costs, and benefits. Here we only address SRM. The aim of proposed SRM techniques is to increase the reflection of sunlight back to space to cool the climate. SRM is not typically considered climate change adaptation because the aim of proposed schemes is to reduce climate impacts on human and natural systems by reducing the amount of global warming rather than human and natural systems adapting to cope with higher temperatures. Thus, SRM might be used in combination with, or to buy time for, further mitigation, adaptation, and CDR efforts. For example, if climate sensitivity to carbon dioxide increasing is at the mid−high end of estimates then using some moderate and temporary amount of SRM in combination with aggressive emissions mitigation may keep global mean temperatures below 2°C and prevent climate impacts from more extreme warming (Smith and Rasch, 2013; Keith and MacMartin, 2015). The consideration of SRM technologies therefore requires the development of strong governance mechanisms and must be considered in close coordination with mitigation and adaptation efforts. Indeed, to deploy SRM in isolation would be reckless (Box 24.1).

Climate model simulations have shown that SRM techniques may be able to offset a substantial fraction of the change in temperature and precipitation from increased atmospheric greenhouse gas concentrations (Kravitz et al., 2013).

Resilience. DOI: https://doi.org/10.1016/B978-0-12-811891-7.00024-4
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BOX 24.1 Potential Responses to Global Warming

Global warming is a real threat to humanity (IPCC, 2013), and there are a number of possible societal responses:

1. **Do nothing**, and hope that the problem is not so bad, or future technology will address most of the impacts. This has been the overwhelming global response so far.
2. **Mitigation**. Reduce the anthropogenic emissions of greenhouse gases and aerosols that are causing global warming. This is the most important response, and some steps are being taken, as outlined in the 2015 Paris Agreement at the 21st Conference of the Parties of the United Nations Framework Convention on Climate Change. But additional mitigation beyond the Paris pledges will be needed to prevent dangerous anthropogenic climate change.
3. **Adaptation**. Reducing the impacts of global warming by such actions as retreating from flooding sea coasts and new farming practices for different climates are already starting, but will not be enough to prevent the worst climate impacts.
4. **Geoengineering** (also called "climate engineering" or "climate intervention"). Geoengineering is defined as "deliberate large-scale manipulation of the planetary environment to counteract anthropogenic climate change" (Shepherd et al., 2009). The term is applied to two quite distinct ideas, removing the primary cause of global warming, CO_2, directly from the air (carbon dioxide removal or CDR), and reflecting sunlight to cool Earth (solar radiation management or SRM). CDR is probably a good idea, if it could be done on a large scale and inexpensively (National Research Council, 2015a), but it would take effect slowly. SRM, so far an unproven technology, might cool Earth quickly (Fig. 24.1), but would come with many potential risks and concerns (National Research Council, 2015b; Robock, 2016; and see Box 24.2). For example, the trade-offs in SRM effects on temperature and precipitation are such that no currently feasible SRM technique is able to return both temperature and precipitation to a preindustrial state (Kravitz et al., 2013).

BOX 24.2 Solar Radiation Management Schemes, and Their Potential Benefits and Risks

Although reflecting sunlight using space-based satellites, by brightening the ocean or land surface, or by brightening clouds over the oceans has been studied, the most serious proposal for SRM is creating a cloud in the stratosphere to reflect sunlight back to space, mimicking the effects of large volcanic eruptions (National Research Council, 2015b). The benefits, risks, and concerns of such a scheme are summarized in Table 24.1. See sections of this chapter for further details.

However, simulations have also shown trade-offs in SRM effects on temperature and precipitation so that no SRM technique is able to completely reverse anthropogenic climate change and return the climate to a preindustrial state (Kravitz et al., 2013). Furthermore, the risks associated with stratospheric SRM may outweigh the potential benefits (Robock, 2008, 2016), and more research is needed so that if policy-makers are tempted to implement SRM they will be making an informed decision.

Research to date has focused almost exclusively on climate and physical environment responses to SRM such as precipitation, temperature, and sea ice extent (Irvine et al., 2017). However, any decision to deploy SRM would rest fundamentally on the technology's impacts on natural and human systems (e.g., health, agriculture and ecosystems). Thus, SRM research is at a critical juncture where evaluation of SRM from the climate impacts community is required urgently in order to advance any contribution of SRM to reducing climate risks. In this chapter, we summarize existing knowledge of SRM impacts on climate, agriculture, ecosystems, and human health, and highlight priorities for future research. We focus our summary on the two most widely discussed and, at this time, most plausible SRM techniques: stratospheric aerosol injection (SAI) and marine cloud brightening (MCB).

24.1 SOLAR RADIATION MANAGEMENT TECHNIQUES

Large tropical volcanic eruptions clearly demonstrate the potential efficacy of SAI. For example, the Mt Pinatubo eruption in 1991 injected 15−20 million tons of sulfur dioxide gas into the stratosphere, which converted to a global cloud of sulfuric acid droplets, reflecting incoming sunlight back to space and causing a reduction in mean global surface air temperature of 0.3−0.5°C for 2 years (Soden et al., 2002). However, unlike the aerosols that naturally fall out of the stratosphere in the years after a volcanic eruption, SAI involves the continued injection of either aerosol particles (e.g., calcite) or their precursors (e.g., sulfur dioxide) into the lower stratosphere to sustain global cooling (Fig. 24.1; Irvine

TABLE 24.1 Risks or Concerns and Benefits of Stratospheric Geoengineering, Adapted from Robock (2008, 2014, 2016). See Relevant Chapter Sections for Further Details

Potential Benefits	Potential Risks or Concerns
Physical and biological climate system	***Physical and biological climate system***
1. Reduce surface air temperatures, which could reduce or reverse negative impacts of global warming, including floods, droughts, stronger storms, sea ice melting, and sea level rise.	1. Drought in Africa and Asia
2. Increased primary productivity (land and oceans)	2. Decreased primary productivity
3. Increased terrestrial CO_2 sink	3. Unexpected shifts in species regional distributions
4. Reduced heat stress for coral reefs and other heat-sensitive ecosystems.	4. Ozone depletion
	5. Continued ocean acidification
	6. May not stop ice sheets melting
	7. Impacts tropospheric chemistry
	8. Rapid warming if geoengineering stopped suddenly
Human impacts	***Human impacts***
5. Beautiful red and yellow sunsets	9. Less solar electricity generation
6. Increased crop yields relative to global warming impacts	10. Decreased crop yields
7. Reduced heat-related mortality	11. More sunburn
	12. Degrade passive solar heating
	13. Effects on airplanes flying in stratosphere
	14. Effects on electrical properties of atmosphere
	15. Affect satellite remote sensing
	16. Degrade terrestrial optical astronomy
	17. White appearance of the sky
	18. Affect stargazing
Governance	***Governance***
8. Prospect of geoengineering being implemented could increase drive for mitigation efforts	19. Cannot stop geoengineering effects quickly
	20. Potential for commercial control of technology
	21. Who sets the thermostat?
	22. Societal disruption, and conflict among countries over optimal climate
	23. Conflicts with current international treaties
	24. Moral hazard – the prospect of geoengineering working could reduce effort for mitigation efforts
	Ethics
	25. Military use of geoengineering technology
	26. Moral authority – do we have the right to do this?
Unknowns	***Unknowns***
9. Unexpected or surprise benefits	27. Human error during implementation
	28. Unexpected or surprise consequences

et al., 2016). In this chapter, we focus primarily on the consequences of the most widely simulated scenario—injection of sulfur dioxide (SO_2) that reacts with water to form a layer of sulfuric acid droplets. Depending on their size, the resultant aerosol particles would have a lifetime of approximately 1–3 years. Injecting the aerosols into the equatorial stratosphere at ~20 km altitude would make the most effective use of stratospheric currents to spread the aerosol layer globally and achieve as even as possible a distribution of radiative forcing (Irvine et al., 2016). Initial estimates indicated that an injection of 3–5 million tons of SO_2 per year would be sufficient to offset warming from a doubling of preindustrial CO_2 concentration, but accounting for the growth of aerosol particles showed that emissions of 90 million tons of SO_2 per year would be required to offset business as usual greenhouse gas emissions by the end of the current century (Heckendorn et al., 2009; Niemeier and Timmreck, 2015). This would be the equivalent of 5–7 Mt Pinatubo eruptions per year. High-altitude aircraft are the most feasible option to deliver the aerosols at an estimated cost of USD 1–10 billion per million tons of material per year (Robock et al., 2009), which is a relatively inexpensive deployment, at least in terms of direct economic cost and orders of magnitude less than the estimated cost of decarbonizing the world's economy.

Placing an array of mirrors in space to block a small percentage of incoming sunlight has been proposed (Angel, 2006). Although space mirrors remain infeasible at present, simply turning down incoming solar radiation in climate

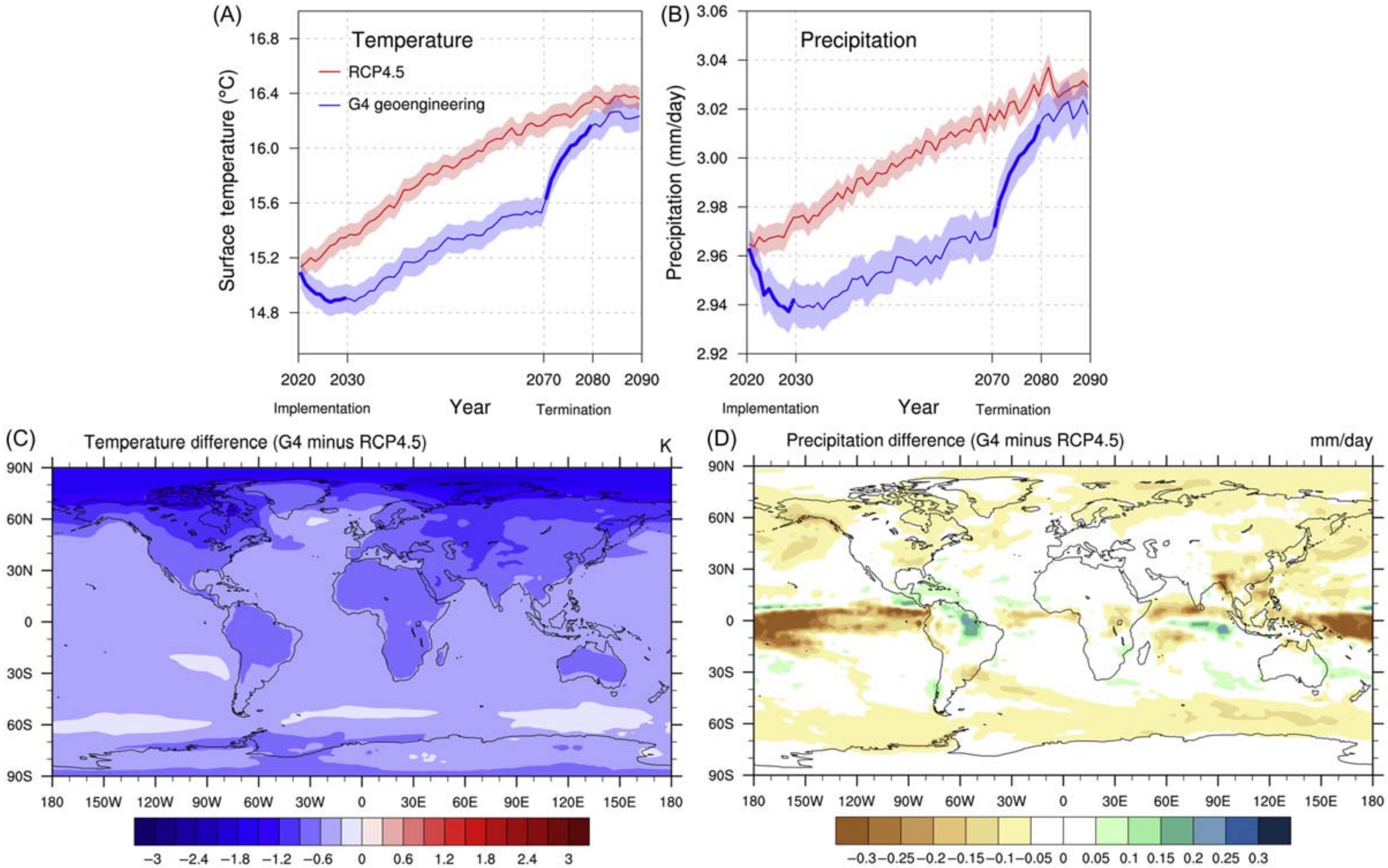

FIGURE 24.1 Comparison of global mean temperature (A) and precipitation (B) trends for RCP4.5—a scenario with moderate greenhouse gas mitigation—and G4—a scenario with greenhouse gas mitigation equal to RCP4.5, but with stratospheric sulfur dioxide injections of 5 million tons per year beginning in 2020 and ending abruptly in 2070. The increasing temperatures in G4 after 2030 result from the continuation of greenhouse gas emissions increasing radiative forcing. Absent more aggressive mitigation, maintaining lower temperatures would require increasing aerosol injections. The difference between G4 and RCP4.5 scenarios for mean temperature (C) and precipitation (D) for the period 2030−2069, showing cooling and reduced precipitation for G4. Solid lines in A and B show global means and shaded regions show one standard deviation across 12 ensemble members from four climate models (see Trisos et al., 2018). Bold lines in A, B show the first 10 years of geoengineering ("Implementation") and the 10 years after geoengineering is stopped ("Termination").

simulation models (called "sunshade geoengineering") provides a useful proxy for understanding SAI. For example, the G1 scenario of the Geoengineering Model Intercomparison Project (GeoMIP) used models that turned down insolation by up to 5% instead of simulating the more realistic but computationally intensive creation of a stratospheric aerosol layer (Kravitz et al., 2013). We discuss sunshade geoengineering model results relevant to SAI and note the significant differences in the resulting climate responses of precipitation (Niemeier et al., 2013), solar radiation partitioning (Xia et al., 2016), and atmospheric chemistry (Nowack et al., 2016; Xia et al., 2017).

In contrast to SAI, marine cloud brightening (MCB) is a more geographically-specific approach. The proposed MCB scheme would inject salt from evaporated sea water into the marine boundary layer to directly scatter light and to increase the reflectivity (albedo), and potentially increase the persistence, of low-lying maritime clouds that reflect incoming solar radiation (Latham et al., 2008). MCB has an analogue in ship tracks, highly reflective marine clouds produced by particulate matter in ship exhausts that act as effective cloud condensation nuclei, producing a cooling effect on the order of $-0.1\ \mathrm{Wm}^{-2}$ (Schreier et al., 2006). Calculations suggest an increase of approximately 0.06 in cloud-top albedo would generate cooling sufficient to offset a doubling of CO_2 concentration (Latham et al., 2008). Salter et al. (2008) proposed MCB deployment could be achieved with ships sailing perpendicular to the prevailing wind so that the injected plume of sea salt did not trail the ship. However, aligning ships at all times perpendicular to an always changing wind would require excellent weather forecasting, as well as rapid communication of forecasts to the ships to automatically adjust route in response to anticipated wind changes. Climate models that apply MCB globally or everywhere within 30° of the equator simulate additional particles in regions that will not form stable low-lying marine clouds, and have found that the increased direct reflection from those particles may be more effective than cloud brightening (Ahlm et al., 2017). Partanen et al. (2012) estimated marine boundary layer conditions to be suitable for MCB across only 3.3% of the global ocean area in three distinct regions that, to achieve a substantial global mean temperature reduction, would be exposed to very significant light limitation and local cooling: the west coast of the United States, the west coast of Africa in the Southern Hemisphere Tropics and subtropics, and the west coast of South America. These regions are also those with upwelling of nutrient-rich waters that make for rich fishing grounds, and are close to large population centers.

24.2 SOLAR RADIATION MANAGEMENT SCENARIO DEVELOPMENT FOR IMPACT ASSESSMENT

SRM poses a significant challenge to researchers assessing climate impacts on human and natural systems because of the flexibility to design SRM deployment to achieve a wide variety of specific climate outcomes; for example, either restoring Arctic sea ice cover or preindustrial precipitation (Irvine et al., 2017). This flexibility in how SRM is implemented (e.g., restricting SAI to a single hemisphere) thus presents both the climate simulation and impact assessment communities with a potentially overwhelming number of scenarios for analysis. To date, SRM research has focused on a prescribed set of idealized SRM scenarios developed primarily to understand climate responses to SRM—for example, SRM used to completely offset all warming from $4 \times CO_2$—rather than address specific climate policy goals (Keith and MacMartin, 2015). From a policy perspective the more relevant research focus is instead likely to be an engineering and design perspective that asks: What SRM strategy will achieve a particular set of climate, and more importantly, human and natural system outcomes?

One recent suggestion has been to focus impact assessment efforts on a set of more policy-relevant scenarios; for example, the temporary use of SRM to only partially offset warming and reduce climate impacts as mitigation proceeds (Keith and MacMartin, 2015; Kravitz et al., 2015). However, this smaller number of scenarios will still be insufficient to capture the variety of SRM deployment choices and thus address the wide range of questions about SRM impacts on natural and human systems. A partial solution could be to develop a smaller set of policy-relevant reference scenarios that have been assessed using complex Earth System and climate impacts models, and then use these to develop computationally efficient emulators for the climate effects of a wider range of SRM scenarios (Irvine et al., 2017). These simplified methods for climate emulation would include considerable uncertainties in climate responses to greenhouse gas concentrations and SRM that would limit the confidence in their projections. Thus, while a full scoping of the natural and human impacts of SRM will remain computationally limited, the integration of climate emulators with impact assessment could allow for some comparisons and improved understanding of the trade-offs among SRM options beyond a small and idealized set of scenarios (Irvine et al., 2017).

24.3 CLIMATE RESPONSES TO SOLAR RADIATION MANAGEMENT

Stratospheric aerosol injections, based on a volcanic analogue, operate as follows: solar radiation is scattered back to space and the surface cools (Robock, 2000). By studying observations and using volcanism as an analogue for SAI, Trenberth and Dai (2007) pointed out the possibility that drought, particularly in the tropics, could result from SAI. Many of the larger eruptions in the past millennium have also forced El Niño/Southern Oscillation (ENSO) variability (Emile-Geay et al., 2007; Maher et al., 2015; Khodri et al., 2017).

A "rich get richer, poor get poorer" paradigm states that, with global warming, increased moisture convergence in areas that already get a lot of precipitation will result in the "wet getting wetter," while increased moisture divergence in dry areas will result in the "dry getting drier" (Held and Soden, 2006). However, this paradigm does not hold up in an SRM world, where the response is very different from that under global warming. Tilmes et al. (2013) analyzed the hydrological cycle under geoengineering regimes where the solar constant was reduced to achieve preindustrial temperatures in a high CO_2 world and compared that to year 1850 preindustrial conditions. They found a strong reduction in global monsoon rainfall, including in the Asian and West African monsoon regions (see also Fig. 24.1). This illustrates the trade-offs in SRM effects on temperature and precipitation so that no currently feasible SRM technique is able to return the climate to a preindustrial state (Kravitz et al., 2013). Modeling of SAI that achieves $\sim 0.9°C$ of cooling over 40 years when compared against a concurrent simulation of Representative Concentration Pathway (RCP) 6.0 leads to a 3% reduction in precipitation (Xia et al., 2016).

If SAI were ever terminated abruptly, since the sulfate layer that reflects incoming solar radiation and reduces global mean temperature could only persist, without replenishment, for a couple of years, the climate would return rapidly to what it would have been had geoengineering not been imposed (Fig. 24.1). In geoengineering experiments that simulate SAI sufficient to generate a temperature reduction of $1-1.5°C$ when compared to a scenario with a 1% increase in CO_2 per year, that same amount of warming would occur over a 5 to 10-year period following termination (Jones et al., 2013). This rate of warming is approximately an order of magnitude faster than what would occur with global warming. The consequence of rapid termination would be to compress the equivalent temperature change experienced during multiple decades of global warming into less than one decade. Such rapid termination of geoengineering would not be a desirable policy response, but in the absence of international comity about how to respond to global warming, a climate policy response that includes rapid termination is possible.

There is no single aerosol optical depth, or latitudinal distribution of aerosol optical depth for sulfuric acid aerosols that could achieve a spatially uniform cooling that would be equally desirable everywhere (Ricke et al., 2013). Particular regions have distinct preferences for what constitutes an optimal climate, let alone what constitutes an optimal response to climate change. Thus, with currently feasible SRM technologies, it is unlikely that any single stratospheric geoengineering regime could be implemented that would be simultaneously optimal for all regions. Even if the average global temperature could be reduced with stratospheric geoengineering, there would still be important regional differences (e.g., Kravitz et al., 2013). For example, the northward shift in the jetstream in the Northern Hemisphere that has been shown to occur in observations of winters after volcanism and in model simulations of stratospheric geoengineering could lead to precipitation decreases in areas that receive a large percentage of their rainfall from midlatitude storms. Many of these incentives are alien to the mitigation discussion, which assumes a global collective interest. Therefore, unlike with mitigation, because different geoengineering approaches may have disparate regional impacts, powerful alliances could form to elevate specific climate engineering interests of benefit to some nations and at the expense of others (Ricke et al., 2013).

Geographical limitations on where effective MCB is possible may be an important constraint on its potential efficacy to reduce global mean temperature and avoid temperature-dependent effects of global warming. Jones et al. (2009, 2012) applied a global mean radiative forcing of $\sim 1\ Wm^{-2}$ from MCB in the North Pacific, South Pacific, and South Atlantic. This led to a decrease in global mean temperature of $\sim 0.5°C$ relative to a moderate emissions mitigation scenario (RCP4.5). However, local climate change brought about by MCB led to substantial increases in precipitation in India and declines in northeast South America. How political coalitions would develop in an MCB-world versus an SAI-world is not known, but future research on MCB may emphasize the potential to use the technology as a regional approach to either supplement SAI, or deal with specific regional climate impacts, such as rapid warming in areas near coral reefs (Latham et al., 2013).

24.4 AGRICULTURAL IMPACTS

Changes in temperature, precipitation, solar radiation, surface air quality, and CO_2 concentration all impact agricultural productivity. SRM would impact all of these factors affecting agriculture. As changes in these factors become more severe the impacts on agricultural productivity will be exacerbated and will vary by crop and by region, generating potential winners and losers with respect to agriculture for a given geoengineering deployment. Here, we summarize knowledge on the impact of each factor on crop yields and the interactions among them.

24.4.1 Temperature

The length of the growing season is defined as the longest continuous period of time in a year that soil temperature and moisture conditions can support plant growth. Increases in the number and the magnitude of extreme daily maximum temperature events would limit the growing season and negatively affect agricultural production, often causing steep declines in yield or even crop failure when the temperature threshold (e.g., $>30°C$) of a particular cultivar is crossed (Carleton and Hsiang, 2016). Surprisingly, so far, effective adaptation to climate in agriculture has been modest, even when warming effects are gradual (Carleton and Hsiang, 2016). Thus, SRM might provide a potentially useful tool to reduce temperature impacts on agriculture. Indeed, with no changes in agriculture practices, models suggest cooling from SRM would benefit crop production across the tropics as crops are released from heat stress while it would damage crops in high latitudes as SRM would bring temperature below the optimal level for crop growth (Xia et al., 2014).

24.4.2 Precipitation

Evapotranspiration is the removal of water from soil through evaporation from the soil surface and transpiration from plants. Precipitation affects crop production coupled with temperature by determining the evapotranspiration rate of crops. There is the potential for large regional differences in precipitation-mediated agricultural impacts from SAI. In particular, a reduction in monsoon rainfall is a potential consequence of SAI (Robock et al., 2008; Tilmes et al., 2013) exposing countries such as India—where agriculture productivity is largely governed by the monsoon circulation—to potential negative agricultural impacts. However, as the cooling effect of SAI also reduces surface evaporation (Tilmes et al., 2013), reduced precipitation may not necessarily result in decreasing soil moisture—the available water for plant growth. Further studies are needed to understand how precipitation change from geoengineering would affect agriculture.

24.4.3 Solar Radiation

Solar radiation reaching Earth's surface is the primary driver of plant photosynthesis. Plant photosynthesis tends to increase nonlinearly with incident photosynthetically active radiation (PAR), and saturates at light levels that are often exceeded on bright days during the growing season. Once a saturation level is reached, the photosynthesis process stops, as does crop growth. In contrast, under cloudy skies or those with light-scattering aerosols, incoming radiation is more diffuse, producing a more uniform irradiance of the plant canopy with a smaller fraction of the canopy likely to be light-saturated (Mercado et al., 2009). As a result, such diffuse radiation results in higher light use efficiencies by plant canopies and has much less tendency to cause canopy photosynthetic saturation (Roderick et al., 2001). In addition, diffuse radiation leads to plant radiation use efficiencies at least twice those for direct sunbeam radiation (Gu et al., 2002). Hence, the net effect on photosynthesis of radiation changes associated with an increase in clouds or scattering aerosols depends on the balance between a reduction in the total PAR (which tends to reduce photosynthesis) and an increase in the diffuse fraction of the PAR (which tends to increase photosynthesis). SAI, which would scatter incoming sunlight, would decrease total solar radiation but increase diffuse radiation reaching the surface. This diffuse radiation enhancement would promote terrestrial plant photosynthesis and may benefit agriculture (Xia et al., 2016).

24.4.4 Surface Ozone Concentration

Surface ozone adversely affects agriculture (e.g., Mauzerall and Wang, 2001; Ainsworth et al., 2012). The causes of this reduction in agricultural productivity include reduced plant net photosynthesis, increased susceptibility of crops to disease, and reduced growth rate (Mauzerall and Wang, 2001). Avnery et al. (2011) concluded that in the year 2000 ozone-induced global crop yield reductions ranged from 8.5−14% for soybeans, 3.9−15% for wheat, and 2.2−5.5% for maize in comparison to the theoretical yield without ozone damage. Artificially reducing solar insolation with sulfate SAI would cause changes in atmospheric chemistry and dynamics that would impact surface ozone concentration, with strong regional differences. For example, if SRM started at 2020 and continued for 50 years, sunshade geoengineering would increase surface ozone concentration whereas sulfate SAI would reduce surface ozone concentration (Xia et al., 2017), and may thus benefit agriculture.

24.4.5 Ultraviolet (UV) Radiation

UV irradiance at Earth's surface is dependent on latitude, altitude, cloud coverage, and season. Under sulfate SAI, both the optical properties of the aerosols themselves and the depletion of the stratospheric ozone layer—which protects the Earth's surface from UV radiation from the Sun—would impact surface UV radiation exposure (Heckendorn et al., 2009; Tilmes et al., 2012). The amount of sulfate injection and its distribution determine stratospheric ozone depletion and changes in global cloud coverage. Simulating SAI of 2 million tons of sulfur per year, Tilmes et al. (2012) predicted a UV radiation increase of 6% and 12% in northern and southern high latitudes, respectively. Heckendorn et al. (2009) found that an injection of 5 million tons per year would cause a stratospheric ozone depletion of 7 and 11% in northern and southern high latitudes which would result in surface UV increases of 21 and 33%, respectively.

Since the ozone hole was discovered there have been extensive studies on the potential damage to plants from UV (reviewed by Ballaré et al., 2011). Field experiments manipulating UV showed that with a 20−30% UV increase due to a 10% ozone depletion, the reduction in plant growth rate was 6% or less (Allen et al., 1998; Ballaré et al., 2011). Whether increased UV radiation damages or benefits crop production is debated (e.g., Wargent and Jordan, 2013; Williamson et al., 2014). Increased UV inhibits leaf expansion (Searles et al., 2001) with smaller and fewer leaves slowing plant growth, but plants may also adapt to higher UV environments by producing pigmentation compounds that reduce UV penetration and protect plant photosynthesis (Bassman, 2004). Further studies are needed on whether UV radiation changes from SAI would impact crop yields. However, the above-mentioned increases in surface UV predicted for sulfate SAI are mild and restricted to high latitude regions such that the impact on agriculture may be relatively small, with the potential exception of regions already exposed to the ozone hole. Proposals to use alternative aerosol particles such as calcite for SAI may instead increase stratospheric ozone (Keith et al., 2016) and reduce UV surface radiation, potentially increasing plant growth.

24.4.6 Combined Effects on Agriculture

Very few studies have examined SRM impacts on agriculture in any detail. Pongratz et al. (2012) built a statistical model using observations of temperature, precipitation, CO_2 concentration, and crop yields, and used climate model output to study agriculture impacts of sulfate injection geoengineering. Global rice, maize, and wheat yields were predicted to increase due to the combination of CO_2 fertilization and reduced heat stress in sulfate injection geoengineering compared to a doubling of CO_2 without geoengineering. However, possible rice yield losses were predicted to occur in the middle latitudes of the Northern Hemisphere.

Xia et al. (2014) used a process-based crop model, the Decision Support System for Agrotechnology Transfer (DSSAT), to simulate crop responses to sunshade geoengineering in China. The crop model used the output from 10 global climate models that simulated the GeoMIP G2 scenario—starting in 2020, a reduction in solar radiation to balance a 1% per year increase in CO_2 concentration (1pctCO2) for 50 years. Without changing land management practices, compared to CO_2 fertilization and climate change from a 1% per year increase in CO_2, the effect of SRM with CO_2 fertilization was predicted to have little impact on rice production in China (-3.0 ± 4.0 million tons per year). This is because the CO_2 fertilization effect compensates for the negative effects on rice production of changes in precipitation, temperature, and sunlight from SRM. In contrast, SRM was predicted to increase Chinese maize production by 18.1 ± 6.0 Mt/yr ($13.9 \pm 5.9\%$) relative to 1pctCO2 because lower temperatures from SRM reduced heat stress in more heat-sensitive maize seeds. The termination of SRM showed negligible impacts on rice production but led to a 19.6 Mt/yr (11.9%) reduction of maize production.

A recent study on groundnuts in India found that, relative to climate change from a moderate emissions scenario (RCP4.5), groundnut yields decreased up to 20% for a scenario with SAI sufficient to offset all temperature increase from RCP4.5 (Yang et al., 2016). Yield reductions were mainly a result of enhanced water stress from reduced summer monsoon rainfall. When SAI was terminated, the groundnut yield tended back to the level of the RCP4.5 scenario. Yang et al. considered changes in temperature, precipitation, solar radiation, and CO_2. However, since the comparison was between scenarios which have the same CO_2 concentration, the CO_2 fertilization effect was canceled out.

A single study has simulated crop responses to MCB geoengineering. Parkes et al. (2015) focused on spring wheat in northeastern China and groundnut in West Africa under global warming from a 1% CO_2 increase per year (capped at 560 ppm), and compared this with a MCB scenario for three ocean regions (North Pacific, South Pacific, and South

Atlantic) totaling 5% of the global ocean surface. Relative to the global warming scenario, MCB was predicted to increase yields for both wheat and groundnuts and reduce crop failure rates as a result of cooling and, in the West African case, enhanced precipitation.

To date, agriculture impact studies have considered climate changes of temperature, precipitation, and total solar radiation. However, other climate factors discussed at the beginning of this section, including UV, partitioning of solar radiation (diffuse and direct), and ozone are important to agriculture. Crop model improvements are needed to include these processes, and to further understanding of how solar geoengineering impacts on agriculture will vary by crop and by region. In addition, climate changes from solar geoengineering might influence the ecology of pest and pathogen species, as well as the crop transport and storage chain. Further studies that include these ecosystem and economic impacts are needed to fully understand how geoengineering might influence agriculture and food availability.

24.5 ECOLOGICAL IMPACTS

Assessments of the ecological impacts of SRM are extremely limited, especially regarding impacts on biodiversity and ecosystems. The creation of a high CO_2 and low temperature climate that could result from SRM is unprecedented in recent Earth history. This lack of historical analogues limits inference of ecological impacts and raises novel questions about how organisms and ecosystems may respond (McCormack et al., 2016).

24.5.1 Productivity on Land and in the Oceans

Increased CO_2 concentrations increase plant photosynthesis (Allen et al., 1987) and reduce transpiration, improving plant water-use efficiency (reviewed by Leakey et al., 2009). These direct effects of CO_2 are a major driver of vegetation change, increasing plant growth across the tropics, especially in arid regions. Because SRM does not reduce CO_2 concentrations this CO_2 fertilization effect is common to scenarios with and without SRM. However, changes in other climate variables due to SRM have potentially significant impacts on plant productivity. Compared to global warming without SRM, sunshade geoengineering is predicted to increase net primary productivity (NPP)—a measure of the total carbon flux from the atmosphere to plants—in tropical regions by reducing heat stress on plants, but decrease NPP at high latitudes as reduced temperature increases from SRM prevent the increased plant growth forecast to occur in these cold regions with global warming (Glienke et al., 2015). However, this result varies among models mainly due to model inclusion or exclusion of a nitrogen cycle (Jones et al., 2013; Glienke et al., 2015). In addition to these regional effects of cooling on vegetation growth, SAI may increase plant photosynthetic rates due to the increase in diffuse radiation from an aerosol layer producing a more uniform irradiance of the plant canopy (Xia et al., 2016). Theoretically, under SAI, the combination of enhanced diffuse radiation and cooling would increase plant photosynthesis, and the cooling would suppress plant and soil respiration, as shown by a modeling study of the effects of the Mt. Pinatubo eruption in 1991 (Mercado et al., 2009). Those effects from SAI are expected to increase the land carbon sink substantially, moderating CO_2 increases. However, these benefits may be overstated as SAI simulations have not yet included nitrogen and phosphorous nutrient limitations on plant growth explicitly, and the increase in photosynthesis due to more diffuse light may be balanced by a decrease in photosynthesis from the lower direct sunlight due to SAI (Kalidindi et al., 2014).

Similar to SAI, relative to no geoengineering, MCB is predicted to increase terrestrial NPP in the tropics and suppress NPP at high latitudes (Jones et al., 2012). However, an important difference is the potential for stronger differences in NPP responses among tropical regions, depending on which ocean regions are selected for MCB. In particular, climate simulations show MCB in the South Atlantic could reduce precipitation in the Amazon or northeastern South America substantially with corresponding negative impacts on plant productivity (Jones et al., 2009; Jones et al., 2012).

Only two studies have assessed potential impacts of SRM on marine ecosystem productivity, none for SAI. Using an Earth system model, Partanen et al. (2016) found that MCB decreased global ocean NPP slightly ($\sim 1\%$) compared to global warming without MCB. However, there were major regional differences in NPP due to reduced light availability in regions where MCB was deployed, especially off the coast of Peru where phytoplankton growth is light-limited in the model. In contrast, Hardman-Mountford et al. (2013) suggest a 90% reduction of light from MCB would redistribute but not decrease NPP within the water column. However, their model used a one-dimensional water column (i.e., depth cross-section) for a single region, and although it depicts the marine ecosystem in more detail than Partanen et al. (2016) it does not include movement of nutrients across regions as in an Earth system model. A clear next step is to repeat the Hardman-Mountford et al. (2013) study in a water column more typical of water columns in candidate MCB regions.

24.5.2 Biodiversity and Ecosystem Impacts

To avoid extinction from climate change, species can either respond by adapting to new conditions within their current geographic ranges or by moving to track their climate conditions across space (e.g., geographic range shifts) or time (e.g., earlier spring emergence). Only a single study has assessed potential SRM impacts on global biodiversity. By calculating climate velocities—the speeds and directions that species would need to move to track climate changes (i.e., to stay in their climate niche)—Trisos et al. (2018) estimated that were SRM ever terminated abruptly the movement speeds required to keep pace with climate change would likely exceed dispersal capacities for many species, increasing local extinction risk in marine and terrestrial biodiversity hot spots compared to global warming without SRM.

In the ocean, studies have assessed tropical coral reef responses to SRM. Anomalously high ocean temperatures induce coral bleaching when corals eject their photosynthetic symbionts, often resulting in colony death. By reducing sea surface temperatures, both SAI and MCB could reduce the likelihood of high temperature events, enhancing coral reef survival and the extent of suitable habitat compared to global warming without SRM (Latham et al., 2013; Kwiatkowski et al., 2015). Compared to a reference global warming scenario without SRM, ocean acidification would increase slightly under SRM due to the increased solubility of CO_2 in cooler water (Keller et al., 2014). Although corals are sensitive to increasing ocean acidification this was of secondary importance to heat stress in the maintenance of suitable coral habitat (Couce et al., 2013; Kwiatkowski et al., 2015).

On land, positive effects of SRM on plant productivity have the potential to drive significant change in grassland and savannah biomes. Elevated CO_2 concentration has been suggested as a major driver of tree and shrub invasion into tropical grassy ecosystems (Bond and Midgley, 2000, 2012), with negative impacts for grassland biodiversity, ecotourism, and livestock grazing. Additional cooling from SRM could further advantage C3 photosynthetic trees over C4 photosynthetic grasses, speeding up the woody encroachment of grassland biomes and the transformation of savannahs to closed forests. Enhanced woody thickening of these ecosystems could reduce wildfire frequencies relative to global warming without geoengineering and alter the global carbon cycle. Earth system models that include dynamic vegetation and wildfire dynamics are needed to further understand the potential impacts of SRM on terrestrial tropical biomes.

In the case of SAI, deposition of sulfate aerosols will in general increase the acidity of precipitation which is known to damage ecosystems when the sulfate is sufficiently concentrated. However, for an injection of 5 million tons of SO_2 per year, Kravitz et al. (2009) found that only ecosystems already close to thresholds for acid rain deposition would be susceptible to damage.

24.6 HEALTH IMPACTS

There have been no quantitative studies published of SRM impacts on human health. Sunshade geoengineering could increase surface ozone (Nowack et al., 2016; Xia et al., 2017) which, in addition to reducing crop yields (Mauzerall and Wang, 2001), would have substantial negative impacts on human health (Silva et al., 2013). In contrast, simulations of atmospheric chemistry suggest SAI would decrease surface ozone (Xia et al., 2017), but with an increase of UV radiation, which increases the risk of skin cancer (Tilmes et al., 2012). Aerosols from SAI would be deposited at the Earth's surface posing a risk of chronic health effects from prolonged exposure. Most aerosols proposed for SAI have known or suspected negative effects on respiratory and cardiovascular health with other health effects such as metabolic abnormalities depending on the aerosol (Effiong and Neitzel, 2016). A preliminary study by Eastham (2015) suggested that for sulfate SAI almost all of the descending aerosols would be removed by wet deposition so that the direct contribution of sulfate aerosols to aerosol particulate matter at the surface would be very low. The same analysis suggested that, per degree of cooling, sulfate SAI could result in an additional 26,000 premature deaths per year. However, these direct impacts from SAI on human health are likely minor compared to the direct and indirect effects from changes in crop yield, heat-related mortality, drought, or flood exposure under geoengineered climates. The inclusion of these impacts into integrated assessments is required to generate more complete forecasts of solar geoengineering impacts on human health relative to other global warming scenarios.

24.7 CONCLUSION

Little is known about the potential environmental and social impacts of SRM. The increasing attention on SRM as a potential tool to offset climate impacts, buying time for additional mitigation, CDR, and adaptation efforts, demands development of more policy-relevant SRM scenarios and their inclusion into the mainstream of climate impacts assessment. Ultimately decisions on whether and how to deploy SRM will be based primarily on the potential for SRM to reduce environmental and social impacts. Estimates of these impacts must be up to the task.

ACKNOWLEDGMENTS

Trisos is supported by U.S. National Science Foundation grant DBI-1052875. Gabriel, Robock, and Xia are supported by U.S. National Science Foundation grants GEO-1240507 and AGS-1617844.

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