NBER WORKING PAPER SERIES

CLIMATE ENGINEERING ECONOMICS

Garth Heutel
Juan Moreno-Cruz
Katharine Ricke

Working Paper 21711
http://www.nber.org/papers/w21711

NATIONAL BUREAU OF ECONOMIC RESEARCH
1050 Massachusetts Avenue
Cambridge, MA 02138
November 2015

This paper was prepared for the Annual Review of Resource Economics. Excellent research assistance was provided by Evgeniya Tsybina. The views expressed herein are those of the authors and do not necessarily reflect the views of the National Bureau of Economic Research.

Climate Engineering Economics
Garth Heutel, Juan Moreno-Cruz, and Katharine Ricke
NBER Working Paper No. 21711
November 2015
JEL No. Q54

ABSTRACT

This article reviews and evaluates the nascent literature on the economics of climate engineering. The literature distinguishes between two broad types of climate engineering: solar radiation management and carbon dioxide removal. We review the science and engineering characteristics of these technologies and analyze the implications of those characteristics on economic policy design. We discuss optimal policy and carbon price, inter-regional and inter-generational equity issues, strategic interaction in the design of international environmental agreements, and the sources of risk and uncertainty surrounding these technologies. Along with mitigation and adaptation, climate engineering technologies can be incorporated into future domestic and global climate policy design. More research on the topic is needed.

Garth Heutel
436 Andrew Young School
Department of Economics
Georgia State University
PO Box 3992
Atlanta, GA 30302-3992
and NBER
gheutel@gsu.edu

Juan Moreno-Cruz
School of Economics
Georgia Institute of Technology
221Bobby Dodd Way
Atlanta, Georgia 30332
juan.moreno-cruz@econ.gatech.edu

Katharine Ricke
260 Panama St.
Stanford, CA 94305
kricke@carnegiescience.edu

1 INTRODUCTION

Humans have emitted carbon dioxide and other greenhouse gases into the atmosphere for centuries. With population and economic output growing, atmospheric concentrations of carbon dioxide are rising at an increasing rate.[1] Moving the remainder of humanity out of poverty and into the middle class is expected to exacerbate this trend if policy actions are not taken to decarbonize the global energy system. The threat of climate change has influenced both domestic policy (e.g., the United States' Clean Power Plan), and international negotiating bodies like the United Nations Framework Convention on Climate Change (UNFCCC). Policy discussions and negotiations around climate change have focused mostly on actions to reduce emissions of greenhouse gases. Emission reductions are referred to as abatement or mitigation. Negotiations have started to pay dividends, but only slight ones. At the current pace, the world is headed towards atmospheric carbon dioxide concentrations between 550 parts per million (ppm) and 1000ppm by the end of this century, making the goal of restricting global temperature change to 2°C increasingly unlikely and a 4.0°C change increasingly plausible. Scientific evidence suggests that the amount of warming caused by even moderate continued emissions will affect human and natural systems for many generations. (Field & Van Aalst , 2014)

There are two alternative approaches to reducing risks from climate change besides abatement: adaptation and climate engineering. Adaptation reduces risk by making systems more resilient to climate change. Recognizing that climate impacts will be heterogeneous and often regressive, the international community has elevated adaptation on the agenda with the goal of helping poor nations cope with existing and inevitable climate change.

Climate engineering, also known as geoengineering,[2] is a more recent addition

[1]The average growth rate of carbon concentrations during the 1960s was 0.85 parts per million (ppm) per year, while the average rate between 2004 and 2014 was 2.11 ppm/year.

[2]Although the term "geoengineering" is perhaps more commonly used and more recognizable, in this paper we use the term "climate engineering" to clarify that these technologies are specifically addressing climate change. "Geoengineering" is also occasionally used to refer to geological engineering or geotechnical engineering. Another proposed term for climate engineering is "climate intervention"(National Research Council , 2015a,b).

to academic and policy conversations about climate risk. The economics literature on climate engineering is nascent. Here, we review that literature and discuss its implications for how this new set of instruments could help deal with climate change.

We start by briefly reviewing the relevant scientific concepts related to the two broad categories of climate engineering: carbon dioxide removal (CDR) and solar radiation management (SRM).[3] We describe the more salient characteristics of both sets of technologies, but the bulk of this review focuses on SRM, due to its fundamental differences from abatement and adaptation and its potential to disrupt the standard thinking about climate change policy.

There are three characteristics that make SRM the focus of the majority of climate engineering economics literature: 1.) SRM is inexpensive compared to abatement; 2.) SRM allows rapid action, which could circumvent some of the inertia of the Earth's carbon cycle; 3.) SRM imperfectly (or ineffectively) compensates for carbon dioxide-driven warming, and it may introduce unintended consequences. Because it is cheap, SRM offers the possibility of drastically reducing the costs of climate risk mitigation. But it is so cheap that it can feasibly be implemented by individual nations pursuing their own self-interest. Because it is fast, it may be able to serve as an insurance against uncertain future climate damages and climate tipping points. But because it can be rapidly implemented at any time, it has the potential to be used strategically by some actors and induce sub-optimal behavior in others. Our goal with this review is to explore these and other trade-offs.

The review below considers the main modeling frameworks and extensions that are currently used in the literature, the implications of those modeling choices, and the current set of conclusions. We then identify pathways for future research.[4]

[3]CDR is also known as direct air capture (DAC); SRM is also known as albedo modification (AM) or solar geoengineering (SGE).

[4]Our review complements recent reviews on the economics of climate engineering. Barrett (2014) focuses on governance issues and just studies SRM, not CDR. Klepper & Rickels (2012) and Klepper & Rickels (2014) provide overviews of both the science and economics of CDR and SRM. We synthesize the science/engineering and economic/policy literatures on CDR and SRM, and we compare both CDR and SRM to abatement. Wagner & Weitzman (2015), Chapter 5, provides a non-technical introduction to the economic issues associated with climate engineering.

2 SCIENCE AND ENGINEERING

Climate engineering has novel risk mitigation properties, both in terms of technological feasibility and physical effects on the climate system. These properties are what drive the distinct economics of climate engineering compared to abatement and adaptation.

While climate engineering is a term used to refer to technologies as disparate as sun-deflecting mirrors in space and orchestrated algal blooms, most approaches fall into two classes of technologies, which have little else in common than an unconventional approach to reducing climate change risks. The first class, solar radiation management (SRM), counteracts the warming effects of anthropogenic greenhouse gases by deflecting sunlight back into space before it can be absorbed by the Earth. The second class, carbon dioxide removal (CDR), reduces concentrations of the greenhouse gas carbon dioxide (CO_2) in the atmosphere directly.

In the remainder of this section, we introduce the basic scientific and technical properties of each of these climate engineering technologies and then compare and contrast those properties with those of abatement. As we will show after we introduce our economic model of climate engineering, it is the specific spatial and temporal properties of SRM and CDR that drive their unique economics. Since our main focus is the economics of climate engineering, we limit our citations in this section to only the most essential; an exhaustive review of the state and prospects of the science of climate engineering, including extensive literature citations, was published as a two-volume National Research Council report (National Research Council , 2015a,b).

2.1 Solar Radiation Management

2.1.1 Some basic science

About thirty percent of the incoming solar radiation is reflected back into space, while the rest is absorbed and re-emitted by the Earth. The radiative properties of the Sun's and the Earth's radiation are very different. The greatest portion of the radiation from the Sun is in the short wavelength visual spectrum, whereas the Earth emits radiation in the longer wavelength infrared. While the atmosphere does not interact much with incoming visual light from the sun, its greenhouse gases do interact substantially with infrared radiation emitted by the Earth's surface. This is why rising concentrations of greenhouse gases, such as CO_2, are causing the atmosphere and oceans to warm up.

Solar radiation management technologies would cool the Earth by reflecting a larger fraction of incoming solar radiation back into space before it can be absorbed and re-emitted by the Earth, thereby offsetting some or even all global-scale warming.

2.1.2 Brief description of different technologies

A number of engineering approaches have been proposed for disrupting the Earth's radiation balance in order to counteract the warming effects of greenhouse gases. These different technologies would be implemented anywhere from the surface of the Earth up to far outside the Earth's atmosphere. However, two types of technology currently discussed are considered both scalable and technically and economically feasible in near future: stratospheric aerosol albedo modification (SAAM) and marine cloud brightening (MCB).

SAAM is inspired by a natural analog: large volcanic eruptions that periodically reduce global temperatures by injecting large amounts of sulfate aerosol precursors into the stratosphere. This layer of the Earth's atmosphere is convectively stable, therefore it allows injected particles to remain reflecting light back into space for an average of 1-2 years, rather than the few days such particles reside nearer the Earth's surface. The long lifetime of these particles means that the effectiveness of SAAM would be fairly insensitive to day-to-day disruptions in implementation schemes, though in order to optimize stratospheric aerosol concentration and distributions, a continuous program would likely be preferred (Rasch et al. , 2008). The most likely approach to implementation is high-flying aircraft outfitted with aerosol precursor dispensing systems (McClellan et al. , 2012), but other dispersal systems involving technologies such as balloons, pipes, and artillery have also been evaluated (National Research Council , 2015a).

MCB would exploit a phenomenon called the Twomey effect, whereby the addition of small particles into low-lying clouds over the ocean creates more, smaller cloud droplets that are more reflective. Implementing MCB at scale would require the construction of a fleet of ships to spray salt or other fine particles into the lower atmosphere over areas of the ocean amenable to this type of intervention. A number of designs for such ships have already been developed (Salter et al. , 2008). Unlike SAAM, these particles would be short-lived, so continuous deployment is necessary for continuous effect.

2.1.3 Overview of Cost, Benefits, Risks, and Impacts

Direct costs for proposed SRM technologies range from very expensive (space mirrors) (Angel , 2006) to very cheap (SAAM). Because the costs are so low and the physical mechanisms so well understood, SAAM is considered the most feasible and likely approach to SRM presently. No significant innovations to existing technology are required for SAAM dispersal. Crutzen (2006) estimates a cost of USD 20-25bn/1-2years, based on the balloons and by artillery guns technology. (Robock et al., 2009) provides an overview of approximate costs of various technologies, ranging from USD 0,2 bn to USD 30 bn/year. (Katz, 2010) uses both data compilation and derivation to obtain estimates of some SRM technologies within a broader technology discussion. (McClellan et al., 2012) provides an overview of costs related to specific technologies, finding lower estimates of the cost to counteract the warming effects of a doubling of atmospheric CO_2 using existing technology at USD 1.1 bn/year and for new technology-at USD 0,6 bn/year.[5] Although exact estimates differ, using airplanes is commonly considered the lowest-cost technology.

While not nearly as "deployment ready" using existing technology, current cost estimates for MCB indicate that the direct costs for achieving global temperature reductions are also likely to be low relative to the cost of abatement. (National Research Council , 2015a)

Extensive climate modeling research shows that even relatively unsophisticated

[5]These various cost estimates are not directly comparable to each other, since all are for different amounts of SRM intensity ("radiative forcing").

implementations of SAAM appear to work surprisingly well to counteract the temperature and precipitation changes projected to occur with global warming, even at the regional scale (Caldeira & Wood , 2008; Ricke et al. , 2012). The mismatch, however, between countering warming from an increase in the Earth's radiation with cooling from a reduction in the Sun's radiation inevitably results in an imperfect reversal of global warming's impacts. These imperfections include relative overcooling of equatorial regions and undercooling of polar ones, an over-drying of the global hydrological cycle with restoration of global temperatures (Bala et al. , 2008), and accompanying shifts in global circulation patterns that result in continuing regional climate change even with global temperature stabilization (Ricke et al. , 2010).

SRM approaches also present the possibility of novel environmental risks. Introducing particles into a stratosphere that still contains significant amounts of CFCs creates a potential for stratospheric ozone destruction Tilmes et al. (2008). Large-scale deployment of SAAM could slow or even reverse the recovery of the stratospheric ozone hole. SRM also does nothing to address threats from ocean acidification, the process by which the atmospheric-to-ocean exchange of CO_2 reduces the pH of the surface ocean, leading to a multitude of effects on marine life (Orr et al. , 2005).

2.2 Carbon Dioxide Removal

2.2.1 Some basic science

One of the main challenges associated with reducing the risks of higher concentrations of CO_2 in the atmosphere is its long lifetime. While the ocean and biosphere are natural sinks that take up a portion of new CO_2 emissions, the rate at which they do so is limited and saturates as high atmospheric CO_2 concentrations persist. A significant fraction of emitted CO_2 remains in the atmosphere for thousands of years (Archer et al. , 2009). CDR technologies are a way of artificially increasing the capacity and uptake rate of carbon sinks.

2.2.2 Brief description of different technologies

A number of approaches for CDR are potentially viable. They include *bioenergy with carbon capture and sequestration* (BECCS), which captures carbon in plant biomass and subsequently sequesters the CO_2 produced in using the biomass to produce energy; *direct air capture*, in which a chemical sorbent such as an alkaline liquid is exposed to ambient air, removing CO_2; *enhanced weathering*, in which the carbonate or silicate reactions that naturally sequester atmospheric CO_2 over millennial timescales could be accelerated or supplemented; and *ocean fertilization*, in which large amounts of nutrients, most notably iron, would be dispersed on the ocean surface to enhance phytoplanktonic growth that would sequester CO_2 in biomass. (National Research Council , 2015b)

2.2.3 Overview of Cost, Benefits, Risks, and Impacts

All CDR technologies are estimated to have high direct costs, generally on par with or exceeding the costs of abatement. However, because CDR counteracts the root cause of emissions-driven climate change rather than masking its influence as SRM does, it has the same climate effects as abatement. Its notable improvement upon these more conventional approaches to controlling atmospheric CO_2 is the greater potential for reversibility of change, because CDR can remove past emissions and reduce concentrations faster than simply ceasing CO_2 emissions. Risks associated with CDR technologies tend to be localized, with the exception of ocean fertilization, for which studies indicate that deployment at scale would significantly disrupt ocean ecology.

The CDR technology with more potential to serve as a pure backstop technology is industrial air capture. The primary constituent cost is expected to be for carbon-free energy to power these machines. Estimates of the cost vary from USD $30/tCO_2$ (Lackner & Sachs , 2015) to over USD $600/tCO_2$ (Socolow et al., , 2011). Lackner et al. (2012) gives an extensive overview of publications dealing with costs of CDR, but they do not suggest any specific estimates. Lackner (2009) provides the estimate of CDR costs at USD $200/tCO_2$ during the prototype use and at USD $30/tCO_2$ in the commercial stage. House et al. (2011) estimates the current costs of CDR to be USD 1000/tCO2, and they are expected to decrease to USD 300/tCO2 by 2050. The authors also provide the energy costs of capturing and compressing CO_2. The variations in these estimated costs have substantial impact on potential deployment. At USD 30/tCO_2 this technology could fundamentally alter optimal climate risk mitigation pathways. At USD 600/tCO_2 it is a marginal player. At USD 1000/tCO_2 it is a thought experiment.

Other technologies offer the same general story of high costs and uncertain ranges. Kriegler et al. (2013) provide an cost overview of BECCS. The authors compare the costs of BECCS with existing CDR technologies and find that, at a cost of less than USD 0-1000/tCO_2 for the capture volumes of under 14000 Mt/yr. Rickels et al. (2012) estimate the unit costs for ocean iron fertilization at USD 22-119/tCO_2.

2.3 Characteristics of Abatement vs. SRM vs. CDR

The standard approach suggested for addressing climate change is the elimination of the source of those risks via de-carbonization of the energy system, that is, abatement. Because CO_2 is a long-lived global pollutant (Archer et al. , 2009), CO_2 abatement by one actor has a planetary effect, but one that is minuscule compared to all other emissions released or avoided. The only risks from CO_2 in the atmosphere that an emitter can reduce via abatement are those caused by his own future emissions. Each climate engineering technology provides a new point of leverage in this regard. SRM allows a single actor to counteract some of the effects from all emissions, both past and present, on a very short timescale and at low cost. CDR allows actors to reduce concentrations of CO_2 in the atmosphere, and thus the root cause of climate change, by removing both past and future emissions of themselves and others.

Excepting this potential for removing past emissions from the atmosphere, CDR technologies share many characteristics of traditional abatement approaches. They have high direct costs, are limited by relatively long time scales of effect, and perfectly reduce impacts of climate change (mostly by avoiding further change).

On the other hand, the constraints and characteristics of SRM differ vastly from abatement in several economically significant ways, beyond the obvious implications of low direct costs. First, there is spatial heterogeneity in its effects and, to an extent, its potential deployment. This physical characteristic equates to inefficiency in SRM's effectiveness managing climate risks and creates the potential for novel strategic behaviors. Second, the timescales for effective deployment, planned cessation, or abrupt termination of SRM are much shorter than those for abatement or CDR (at least in amounts physically feasible by currently known or imagined technologies). Finally, because of its imperfect compensation for the effects of CO_2-driven change, any SRM deployment will be accompanied by much larger scientific and technical uncertainties and risks than emissions reductions or CDR technologies. These scientific and technical uncertainties and risks translate into economic ones as well.

2.3.1 Spatial heterogeneity

Regional implementation The long atmospheric lifetime of CO_2 relative to tropospheric mixing timescales results in relatively little leverage over the distribution of forcing characteristics for anthropogenic emissions reductions and CDR. SRM, however, would likely allow for some control over the spatial distribution of sunlight-reflecting effects. In the case of SAAM, while strong stratospheric winds make management of the longitudinal distribution of reflective aerosols infeasible, there is potential for control over latitudinal distributions of aerosols, making it possible to reflect more sunlight in one hemisphere than another or over the poles than at mid-latitudes (Robock et al. , 2008). In the case of MCB, only certain areas of the atmosphere over sea are likely to be amenable to large increases in marine cloud reflectivity limiting spatial control (Latham et al. , 2012), though given these constraints, geoengineers would likely have a great deal of control over the relative magnitude of implementation between such regions. The end result of these spatial degrees of freedom is a certain amount of potential "tunability" in the regional climate effects of SRM (see, e.g., MacMartin et al. (2013)).

Regional response and impacts While the impacts of climate change itself exhibit abundant spatial heterogeneity (Walther et al. , 2002), the regional responses to emissions reductions and CDR are generally straightforward: the regional climate change is diminished or reversed. While this is not necessarily true for impacts due to irreversibility and threshold behavior of certain human and natural systems (Field & Van Aalst , 2014), to the first order, an increase or decrease in atmospheric CO_2 concentrations results in relatively linear scaling of regional climate effects.

In the case of SRM with a uniform application, temperature changes in all regions are reduced, as are precipitation changes in most regions (Kravits et al. , 2014). However, the amount of reduction in these changes proceeds at different rates for different regions as the amount of SRM is increased. As a result, it is almost certain that different regions, countries, and sectors would prefer different amounts and distributions of SRM. In addition, these preferences would be expected to diverge further if SRM is increased to compensate for rising atmospheric greenhouse gas concentrations (Ricke et al. , 2010). In some regions, hydrological changes caused by climate change are exacerbated by application of SRM (Kravits et al. , 2014).

2.3.2 Timescale asymmetry

Abatement is a process subject to a great deal of inertia. There is the political and social inertia associated with implementing effective policies, in particular if such policies depend upon international coordination. There is infrastructural inertia associated with transitioning the energy system to low or no carbon technology (Davis and Socolow , 2014). And there is carbon cycle inertia whereby a substantial fraction of past emissions remain in the atmosphere for thousands of years (Archer et al. , 2009).

Climate engineering technologies can be viewed as tools for circumventing some of these inertial issues. They can circumvent political inertia because they do not necessarily require international coordination to be physically effective and because they do not require overturning the powerful interests associated with the status quo energy economy. They can circumvent infrastructural inertia because they do not require technology-in-use to become obsolete or retired early before implementation. And to differing degrees, they can circumvent carbon cycle inertia as well.

CDR artificially supplements the natural carbon sinks that remove CO_2 from the atmosphere over time, making it possible to reduce atmospheric CO_2 concentrations within several decades without an instantaneous transition to a carbon-neutral economy. But it is still critically limited by the second law of thermodynamics, which makes it difficult to remove CO_2 molecules from an atmosphere made up mostly of oxygen and nitrogen.

SRM is not subject to the above constraints and can reduce global temperatures on very short timescales. As with large volcanic eruptions, a temperature response could be achieved within a year of deployment. This rapid response is the reason that some have suggested that SRM is a tool that could be deployed in response to a so-called "climate emergency" (Blackstock et al. , 2009), though the scientific evidence about whether SRM would be effective under such conditions is sparse (Sillmann et al. , 2015).

Termination Effects The rapid response of the climate to SRM cuts in two directions. It can achieve rapid cooling with its deployment but could also produce rapid warming with termination. Numerous modeling studies have shown that if SRM is used to counteract effects of global warming and then terminated without accompanying reductions in greenhouse gas concentrations, the climate would warm very rapidly, perhaps at rates many times those that would have been experienced absent SRM.

Matthews and Caldeira (2007) was the first work to highlight the rapid warming that could be expected if SRM were abruptly terminated and Jones et al., (2013) models uncertainty in the potential physical effects of abrupt termination of SRM use through a multi-model ensemble analysis. They find that the amount of warming that would occur depends upon its length of use, the amount of carbon emissions during the period of use and the relative efficiency of SRM in reducing global temperatures. Because some climate change impacts may depend as much on rates of temperature change as on magnitudes (Diffenbaugh and Field , 2013), this "termination effect" represents a novel climate-related risk. Some discussion of the risks associated with the termination effect is also presented in Robock et al. (2009) and Betz (2012).

The risks of termination effects is much higher for SRM than abatement or CDR. Reducing carbon emissions through abatement or through CDR affects the stock of carbon and therefore has long-lasting effects. Reducing temperatures through SRM, however, is temporary; the aerosol sulfates will leave the stratosphere within 1-2 years and must be nearly continuously replaced for SRM to be effective in the long-term. This leads to complications from termination effects that apply to SRM in a way that does not apply to CDR or to abatement.

2.3.3 Risk and Uncertainty

Our understanding of the Earth's climate is replete with uncertainty, and all policy options are plagued by this uncertainty. Abatement provides the lowest level of uncertainty, since avoiding emissions will prevent the future change that they otherwise would have caused.[6] CDR works by the same mechanism as abatement, but its effectiveness for any given technology type may be less certain because we do not yet know how well that technology will work.

Uncertainty associated with the effectiveness of SRM is very high. There is uncertainty associated with the technological efficiency of both SAAM and MCB. Moreover, because it does not address the root of the problem (greenhouse gas concentrations), the outcomes will certainly be different than with the other two. The extent of this difference is unknown. We can expect some significant regional hydrological anomalies associated with an SRM temperature-stabilized world. However, because even state-of-the-art climate models have difficulty predicting changes to regional precipitation and other hydrological indicators, let alone ecosystem impacts, uncertainty over the magnitude and distribution of the effects is large.

While the effectiveness of SRM is uncertain relative to abatement or CDR, SRM may reduce uncertainty relative to inaction under business as usual. One source of uncertainty in estimating climate impacts is the value of climate sensitivity, that is,

[6] There is still uncertainty over inertia in the climate system, and how much change would occur even with an instantaneous and total cessation of all greenhouse gas emissions.

the amount that the Earth will warm for a given amount of additional atmospheric CO_2. While the regional distribution of SRM and CO_2 forcings may be asymmetrical, a climate more sensitive to CO_2 is still similarly sensitive to other forcings, such as those from SRM. Thus, canceling CO_2 forcings with SRM would narrow the potential range of future global temperature changes considerably (Ricke et al. , 2012).

3 THE BASIC ECONOMICS OF CLIMATE ENGINEERING

3.1 Analytical Model

In this section, we present a simple, baseline economic model that can provide a framework for how to think about the economics of climate engineering. This model is very similar to the model of SRM presented in Heutel et al. (2015a), though here we include both SRM and CDR.

We consider a representative agent model, in an economy where there are external damages from pollution that can be alleviated either by reducing pollution (abatement or CDR) or by reducing the harmful effect of pollution (through SRM). There is a fixed stock of capital k that can be allocated towards production (k_p), abatement (k_a), CDR (k_{CDR}), or SRM (k_{SRM}), so that $k_p + k_a + k_{CDR} + k_{SRM} = k$. Gross output is $f(k_p)$, but net output can be reduced because of damages from pollution x. This is a static model without saving, so all net production is consumed: $y = c = f(k_p)(1 - d(x; k_{SRM}))$. The function $d \in [0, 1]$ is the damage function, expressed as the fraction of gross output that is lost due to pollution damages. We assume that d is increasing and convex. SRM affects how pollution reduces gross output: $d_k < 0$ and $d_{xk} < 0$, so that SRM reduces total and marginal damages.[7]

Baseline or business-as-usual pollution is normalized to be equal to the capital stock k, but it can be reduced through abatement or CDR. Thus, pollution $x = (1-\mu)k-\gamma$, where μ is the fraction of pollution abated and γ is the pollution removed

[7]These assumptions do not imply that there are no direct damages from implementing SRM, but they do assume that on net SRM is beneficial to society.

through CDR. Pollution abated μ is modeled as a fraction of total pollution k, while pollution removed from CDR is modeled as an absolute quantity.[8] The fraction of pollution that is abated is a function of the capital stock devoted to abatement, and the pollution removed through CDR is a function of the capital stock devoted to CDR: $\mu = g(k_a)$ and $\gamma = h(k_{CDR})$. We assume that both cost functions g and h are increasing and concave.

The planner's problem is to maximize net output subject to the resource constraint:

$$\max_{k_p, k_a, k_{SRM}, k_{CDR}} f(k_p)(1 - d(x; k_{SRM})) \tag{1}$$

such that

$$k = k_p + k_a + k_{CDR} + k_{SRM} \tag{2}$$

$$x = (1 - g(k_a))k - h(k_{CDR}) \tag{3}$$

The solution to this problem can be described by the following set of first-order conditions[9]:

$$f'(k_p^*)(1 - d(x^*; k_{SRM}^*)) = f(k_p^*)kg'(k_a^*)d_x(x^*; k_{SRM}^*) \tag{4}$$

$$f'(k_p^*)(1 - d(x^*; k_{SRM}^*)) = f(k_p^*)h'(k_{CDR}^*)d_x(x^*; k_{SRM}^*) \tag{5}$$

$$f'(k_p^*)(1 - d(x^*; k_{SRM}^*)) = -f(k_p^*)d_k(x^*; k_{SRM}^*) \tag{6}$$

These three equations represent setting the marginal benefit equal to the marginal cost for abatement, CDR, and SRM, respectively. The left-hand-side of each equation is the marginal benefit of an additional unit of productive capital k_p, which is the ability to produce and consume more output. It equals the marginal benefit of an additional unit of either abatement k_a, CDR k_{CDR}, or SRM k_{SRM}.

The first two equations are nearly identical to each other, and they imply that $kg'(k_a^*) = h'(k_{CDR}^*)$. The marginal cost of reducing a unit of pollution through abate-

[8] This is to reflect that CDR is not limited to reductions of present-day emissions but can take on the emissions of others, past and present, even resulting in negative pollution.

[9] We assume an interior solution and that the second-order conditions ensure a unique solution.

ment equals the marginal cost of reducing it through CDR. Because abatement and CDR are (in this model) perfect substitutes, this equimarginal condition must hold at the optimum. SRM, though, is not perfectly analogous to CDR or to abatement. The first-order conditions imply that $-d_k(x^*; k^*_{SRM}) = kg'(k^*_a)d_x(x^*; k^*_{SRM})$. The marginal benefit of an additional unit of SRM, in terms of reduced marginal damages, equals the marginal benefit of an additional unit of abatement, in terms of its reduced marginal damages times the cost of achieving those damages.

The model demonstrates how SRM and CDR both are alternative means of reducing climate change damages, and they should be employed at an efficient level dictated by equating marginal benefits. Of course, this simple model omits many important relevant features of the real world. For example, the model is static, though climate change is a dynamic problem. Moreno-Cruz & Smulders (2007) develop a model that incorporates climate dynamics and economic growth and show the main trade-offs presented in this simpler model remain true. But new insights are revealed. They find that for high levels of damages caused directly by atmospheric CO_2, climate engineering and abatement could act as strategic complements in the sense that climate engineering implementation would increase abatement efforts in the economy, and for lower CO_2 concentrations, climate engineering is still used acting as a strategic substitute for traditional abatement with the final objective of boosting the productivity of the economy.

3.2 Numerical Simulation Models

A number of papers have gone beyond a simple analytical model like this to consider the economics of climate engineering using a numerical simulation model. Several studies have adapted a commonly used integrated assessment model (IAM) called the Dynamic Integrated Climate Economy (DICE) model, described in Nordhaus (2008). The DICE model contains a representative agent model of economic production with exogenous technological growth, combined with a simple model of the Earth's climate and carbon cycle. Production generates carbon emissions, but those can be reduced in DICE through abatement. Carbon emissions increase carbon stocks in the atmosphere and the oceans, which in turn increase temperature. The temperature increase causes economic damages. The DICE model can be used to find the optimal dynamic path of abatement intensity and the optimal carbon price over time. But, the original DICE model does not include climate engineering.

Bickel & Lane (2009) adapt the DICE model to include both SRM and CDR (what they call air capture, AC). They provide a benefit cost analysis for various level of climate engineering intensity, and they find that climate engineering promises potentially large net benefits, though the uncertainty is substantial. In their model, only SRM passes the benefit-cost analysis; AC is prohibitively expensive. They consider three determined levels of SRM intensity, but they do not solve for the optimal SRM intensity level.

Heutel et al. (2015a) also modify DICE to include SRM, and they use it to solve for the optimal level of both abatement and geoengineering. They argue that SRM is a substitute for abatement, but an imperfect one because it lowers temperatures without reducing carbon concentrations. Thus, it does nothing to address damages directly caused by atmospheric carbon, such as ocean acidification which their model accounts for. They show that the optimal use of SRM depends on how much damage is caused directly by elevated atmospheric carbon dioxide concentrations.

3.3 Optimal Policy

Relatively few economics papers have studied how climate engineering factors into broader optimal climate policy schemes, using either theoretical or numerical simulation models. Barrett (2007) makes the argument that climate engineering can be part of an optimal climate policy portfolio, and Barrett (2008) expands on this idea.[10] Moreno-Cruz & Smulders (2010) uses a simple theoretical model to discuss optimal SRM policy; Moreno-Cruz & Keith (2013) extends that paper and calculates optimal policy in the presence of uncertainty.

[10] Barrett (2008) is titled "The Incredible Economics of Geonengineering," in response to SRM's very low costs relative to mitigation, and notes that "most economic analyses of climate change... have ignored geoengineering." (p.46)

Most numerical simulations consider a fixed level of SRM and perform a cost-benefit analysis. The analysis in Goes et al. (2011) mostly focuses on cost-benefit analysis, but they also perform simulations solving for optimal SRM and abatement levels. Their simulations are performed for different levels of damages from SRM. When damages are zero, they find that SRM is employed at full intensity and abatement is abandoned; this represents the corner solution where SRM is the only climate policy tool used. As the damages from SRM get higher, the optimal use of SRM gets lower and the optimal use of abatement gets higher. This demonstrates the fact that, in IAMs, SRM and abatement can be substitute policy instruments. In an optimal policy framework, when one is used more intensively, the other will be used less intensively. When SRM damages are zero, SRM is a perfect substitute for abatement and atmospheric CO_2 concentrations increase throughout the entire simulation period, while temperature quickly decreases back to its preindustrial level. When SRM damages are 3% of gross world product or higher, the optimal use of SRM is near zero.

Gramstad & Tjøtta (2010) modify DICE by including SRM and conducting a cost-benefit analysis, and they find that SRM passes the cost-benefit test. They also include a public choice model, wherein SRM may fail in practice due to political considerations although it is welfare-increasing.

Heutel et al. (2015a) also uses DICE with SRM to solve for optimal policy paths of both abatement and geoengineering. In their baseline simulations, the introduction of SRM reduces the optimal amount of abatement by up to 25%, relative to the optimal policy in the model without SRM. Abatement eventually reaches 100% (no emissions), albeit a few decades later than in the simulations without SRM, since in their model SRM is not a perfect substitute for abatement. Simulations that vary the parameter values describing how large direct damages from atmospheric CO_2 are demonstrate that when carbon concentrations account for a larger fraction of total climate damages, SRM is used less intensively.

3.3.1 Carbon Price

Because abatement and SRM can be viewed as substitute policy instruments, including an SRM option allows for less abatement along the optimal policy path. It follows that the optimal carbon price, set to provide an incentive for polluters to abate at the optimal level, will be lower in a model that includes SRM than in a model that does not. In other words, the exclusion of SRM may lead climate IAMs to overestimate the optimal carbon price.

Several papers demonstrate this result. In Bickel & Lane (2009), the carbon price falls by up to 50% relative to its level without SRM, depending on the intensity with which SRM is used. Heutel et al. (2015a) show that the carbon price under the optimal policy path is about 30%-45% lower than the model without SRM. Initially, the difference is not high, since both abatement and SRM are used sparsely. As optimal SRM and abatement use increases, the difference in the carbon price between the SRM and non-SRM simulations grows. Eventually, abatement reaches 100% both with and without SRM, and so the difference between the carbon prices under the two assumptions disappears. Still, their base-case simulation suggests that the optimal carbon price may be substantially biased by the introduction of SRM. The net deadweight loss from ignoring SRM peaks at around 1.6% of world output annually, under their base-case parameters.

4 EXTENSIONS AND COMPLICATIONS

While the analytical and theoretical models described above provide the basic intuition for thinking about the economics of climate engineering and climate engineering policy, many complicating factors remain. In this section, we describe how the literature has dealt with some such complications, including regional inequalities, strategic behavior, and risk and uncertainty. For the reasons listed above, these complications are almost exclusively associated with SRM, and for this reason we focus on the literature addressing this set of technologies.

4.1 Issues of Equity and Governance

Who, if anybody, can make a decision to implement climate engineering, and what should the temperature target be? In a recent review paper, Barrett (2014) provides surveys and analyzes the literature of climate engineering governance. We extend that review by explaining how the specific science and engineering characteristics of the different technologies result in unique governance issues.

This literature extends back to the 1990s, when the governance of SRM was first linked to the notion of democracy. Jamieson (1996) examines the basis for a right of all nations, and even individuals, to determine their climate future through global climate policies that adequately address possible damage arising from climate change. The same point was expressed fifteen years later by Corner & Pidgeon (2010), who further argue that some of the poorest countries, such as Sub-Saharan and Pacific nations, would be those most affected by climate engineering, and therefore their opinions arguably carry greater weight in the decision. Schneider (1996) argues that because of the potential for international conflict caused by implementation of SRM, it would be "irresponsible" to implement large-scale climate engineering before there is a high level of certainty about its effects and governance. This is further emphasised by Schelling (1996), who cautions that nations may engage in climate wars to defend and impose their preferred climate. That is, climate engineering can in principle create governance problems in excess of those already existing around climate change policy. Victor (2008) suggests specific norms for climate engineering deployment, while Ricke et al. (2013) and Weitzman (2015) develop specific mechanisms to determine climate engineering outcomes. In the remainder of this section we discuss studies that deal with issues of governance and interregional and intergenerational equity.

4.1.1 Interregional equity

Regional climates in a world where climate change is a product of elevated greenhouse gases and SRM will differ from those in a world with the same global temperature but no SRM. Because both greenhouse gas-driven climate change and SRM will have differential impacts across the globe, some countries will be better off than others if SRM is implemented, and different countries will likely prefer different amounts of global cooling.

Moreno-Cruz et al. (2012) uses a Residual Climate Response (RCR) model calibrated with climate model output to investigate the regional inequities that arise from the use of aerosol SRM to compensate for elevated atmospheric CO_2 concentrations. As its name implies, the RCR model evaluates the amount of damages that are left uncompensated for when SRM is used to restore average regional temperature or precipitation to its baseline level. The authors find consistently high efficiency of SRM in compensating for greenhouse gas-induced regional climate change (70%-99%). The effects differ significantly between population-, area-, and economy-based regional weighting criteria, and between precipitation and temperature optimization. For example, an SRM scheme can compensate for 97% of population-weighted precipitation changes but the same scheme only compensates for 69% of output-weighted temperature changes.

Kravits et al. (2014) extends the analysis in Moreno-Cruz et al. (2012), applying the RCR model to results from the multi-model Geoengineering Model Intercomparison Project ensemble developed in Kravitz et al. (2011). They find that the high efficiency demonstrated in Moreno-Cruz et al. (2012) is robust to climate model uncertainty for temperature, but less so for precipitation.

Moreno-Cruz et al. (2012) further define a Pareto-improving criterion that would determine the level of SRM that would benefit most regions in the world, without making any particular region worse off. In that work, the first region to reach its optimum as SRM is incrementally increased is Western Africa. A Pareto-optimal policy would implement this amount to ensure no region is made worse off by SRM. In this paper, the Pareto-optimal level of SRM compensates for 56% or more of the CO_2-induced damages. Kravits et al. (2014) extends this analysis to compare results for a variable relative weighting of temperature and precipitation and finds that for all but high weightings of precipitation (> 0.9), implementations of SRM that reverse 85% or more of global temperature change are all Pareto-improving.

All the previous papers are subject to the critique made explicit in Heyen et al.

(2015). These results are highly sensitive to the choice of metrics and baselines for determining regional preferences (i.e., the specification of the damage function and the reference temperature).

4.1.2 Interregional Strategic Behavior

The regional asymmetry of impacts from SRM can motivate strategic behavior. The dynamics of strategic incentives associated with SRM and implications for climate governance has been addressed in a number of economic theory papers. Weitzman (2015) investigates the idea of a "free driver" effect. Contrary to the usual free rider problem associated with abatement, low technology costs reverse the balance of benefits and burdens of coalition-building and create incentives to engage in unilateral climate engineering. This paper develops a model of externalities and incentives that suggests that strong mechanisms, such as a supermajority voting rule, are necessary to reach the social optimum. The ideas put forward in Weitzman (2015) are further developed in Heyen (2015), which incorporates R&D incentives for SRM climate engineering. That paper adopts a game-theoretic approach to analyse how the balance of benefits and costs of climate engineering affects country-level incentives to engage in climate engineering R&D. Though the model yields significant behavior restrictions, conclusions are similar to those obtained in other economic models of R&D: there are significant incentives for free-ridership in technology development, but the threat of the free-driver effect causes excessive investment in the technology and an R&D race.

A further step is taken by Ricke et al. (2013). The authors investigate the potential effects of climate engineering for a variety of regional players in a game-theoretic model and identify strategic incentives to engage in climate engineering. Diverse regional responses to climate engineering create incentives to form narrow coalitions and exclude excessive members rather than force them to participate. This parallels an idea of Millard-Ball (2012). Although that work is more concerned with the effects of the threat of unilateral climate engineering to global participation in abatement, he raises the question of exclusivity in governance of climate engineering.

Moreno-Cruz (2015) investigates free-rider and free-driver aspects in climate engineering and mitigation. The author finds that in symmetric or low-damage settings, the possibility of climate engineering reduces incentives for mitigation, while in a setting in which the damages from climate engineering are asymmetric or high, the incentive to avoid climate engineering causes very high levels of mitigation. The author also examines the free-driver notion and finds supporting evidence for excessive climate engineering under the free-driver scenario, similar to Weitzman (2015).

In Manoussi and Xepapadeas (2015), the authors extend the existing line of research by producing a model that is explicitly dynamic and allows for CO_2 accumulation. The paper provides a rich framework to analyze the delayed effect of mitigation on temperature relative to the more immediate effect of SRM on temperature. When the sources of asymmetry are climatic, there is no trade-off between SRM and emissions reduction. When the asymmetries are economic, the most productive country compensates an increase in emissions with SRM, just enough to counterbalance the global warming effects of their increased emissions.

4.1.3 Intergenerational Equity

The issue of intergenerational equity and climate engineering has only been briefly touched upon thus far in the literature. Burns (2011) delves into this topic in-depth, compiling a body of knowledge on ethics, philosophy, and international law to support the claim that SRM would violate the principle of intergenerational equity by imposing excessive environmental burdens on future generations.

Contrary to Burns (2011), Goeschl et al. (2013) finds a net positive effect associated with SRM via the intergenerational tranfer of SRM technology. In particular, this paper assumes that (i) the current generation cares about the future generation sufficiently to be concerned about the stock damages of atmospheric carbon, (ii) there may be a pro-SRM bias in the future, (iii) both abatement and R&D on SRM involve a cost today, and (iv) there is uncertainty about the damages associated with atmospheric carbon. The authors demonstrate that even in the absence of a pro-SRM bias, the presence of an SRM option offsets current abatement. Far from constituting an instance of "moral hazard" Bunzl (2009), this simply results from the partial substitutability between abatement and SRM that a current generation will rationally want to exploit.[11] Under this model, the presence of a pro-SRM bias constitutes an important source of potentially powerful strategic distortions between generations. Abatement efforts are not reduced by the availability of SRM, but rather abatement increases relative to the benchmark as the bias-driven distortion between generations increases. An altruistic current generation will partially offset a pro-SRM bias among the future generations by providing more abatement today, thus reducing the incentives to deploy SRM in the future.[12]

4.2 Risk and Uncertainty

Risk and uncertainty are of fundamental importance in the consideration of climate engineering because of the large uncertainties surrounding both the effects of climate change overall and those of climate engineering in particular. Here we review the publications in three sections: direct climate risks, termination effects, and climate tipping points.

4.2.1 Direct climate risks and insurance

Direct risks of climate engineering have received the most extensive treatment in economic models to date. Due to its global nature and lack of similarity with abatement approaches, SRM technologies introduce novel risks.

Moreno-Cruz & Keith (2013) introduce SRM in a simple economic model of climate change that is designed to explore the interaction between uncertainty in the climate's response to CO_2 and the risks of SRM in the face of carbon-cycle inertia. They use a two-stage decision framework in which the abatement decisions are made in the first period and SRM decisions are made in the second. In between periods, the decision maker learns the true sensitivity of the climate. Using this

[11] This same argument is made in Keith (2013), p. 127-135.

[12] Sterck (2011), Goes et al. (2011), and Betz (2012) also raise questions of emissions reductions and burdens from side effects on future generations.

framework, they find that SRM is used in the case of high climate sensitivity, even if the damages from SRM exceed the previously expected damages from climate change. If climate sensitivity is low, SRM is not used much and climate change is dealt only with abatement. Using the same framework, they find that learning about SRM — the value of information associated with reducing the uncertainty about the side-effects of SRM — can reduce the overall costs of climate change in the order of 10%, depending on the amount of learning.

Emmerling & Tavoni (2013) use the WITCH IAM to study SRM. Like Moreno-Cruz & Keith (2013), their study is focused on how uncertainty affects policy. They find that the introduction of SRM reduces the optimal amount of abatement, but only under the optimistic assumptions about SRM's effectiveness. Notably, their simulations suggest that the optimal level of emissions can be higher than business-as-usual emissions when an SRM option is deemed highly effective. Heutel et al. (2015a) also models uncertainty in climate sensitivity and in climate engineering damages, and they find that both sources of uncertainty have a larger effect on optimal SRM use than in optimal abatement.

Feichter & Leisner (2009) discuss general risks associated with climate engineering and conclude that, despite risks that prevent the deployment of climate engineering technologies immediately, more research is needed to investigate their potential applications. Betz (2012) provides an extensive discussion of risks through a formal logic analysis of debate over whether to invest in climate engineering research, following a similar line of reasoning to that presented through a decision analytical framework in Morgan & Ricke (2011). Galaz (2012) examines climate engineering from a perspective of planetary impacts and earth stewardship as a technological innovation, like many, that has both advantages and risks. Most of the above works argue for a cautious and responsible approach to climate engineering's evaluation and development. Regarding CDR, Williamson et al. (2012) discuss ongoing international efforts for climate engineering risk management as a part of a broader study of ocean fertilization technology.

4.2.2 Termination effects

Termination effects are a central topic in Goes et al. (2011). The authors use an extended DICE model to evaluate the risks associated with continuous, then abruptly terminated aerosol SRM deployment and the accompanying rapid increase in global temperature. The models in Goes et al. (2011) and Bickel & Agrawal (2013) consider SRM deployment in conjunction with an exogenous cause of intermittency; SRM is randomly stopped and unable to be restarted. SRM intermittency leads to high costs from climate damages, higher in some periods than even the business-as-usual case of no abatement or no emissions. In Goes et al. (2011), SRM fails cost-benefit tests, but Bickel & Agrawal (2013) argue that this is due to several modeling choices such as the discount rate, the form of the damage function, and the exogenous and abrupt intermittency of SRM. Under more general specifications, SRM passes a cost-benefit test.

4.2.3 Climate tipping points

Climate tipping points (CTPs) are uncertain and irreversible events that have large and lasting effects on the climate system and, potentially, the global economy. Some examples of CTPs include the collapse of the West Antarctic ice sheet or a disruption of the thermohaline circulation (Lenton et al. , 2008).

Most articles about CTPs have focused on climatological effects (Lockwood , 2011; Lenton et al. , 2008; Zickfeld et al. , 2010). The possibility of CTPs can affect optimal climate policy, and IAMs like DICE have been modified to include them (Lemoine & Traeger , 2014). Studies that focus on the economics of tipping points and SRM include Bellamy & Hulme (2011), Bickel (2013), Bickel & Agrawal (2013), and Heutel et al. (2015b).

Bickel (2013) uses an extension of DICE model to investigate different CTP scenarios and the potential efficacy of aerosol SRM technology in averting damage from reaching a CTP. He finds that SRM is a potentially effective technology in countering temperature change and CTPs, but remains cautious about its effectiveness given uncertainties over the technologies and their indirect costs. Bickel & Agrawal (2013) refer to CTPs as among the potential sources of economic damage from not using climate engineering, and they show that if the uncertainty and risks of business-as-usual are included in the analysis, SRM may eventually be an economically efficient policy instrument.

Heutel et al. (2015b) study how the presence of CTPs affects optimal abatement and SRM policy, by adapting the DICE model to include both SRM and CTPs. Their model considers three rules that govern the use of SRM: a total ban, freely allowing it, and allowing it only after reaching a CTP. They demonstrate that the presence of CTPs leads to more use of both abatement and SRM, since both help insure against the risk of crossing a CTP threshold. Under the rule where SRM cannot be used until the CTP is reached, policy costs are higher than under the rule where SRM can be used without restriction.[13]

5 CONCLUSIONS

Climate engineering has remained at the fringes of climate policy debate and academic economic research. The literature is growing, though, and much of it suggests that climate engineering technologies can have a substantial impact on climate policy and international climate negotiations. This may be especially true given the current difficulty that nations continue to face in coordinating a response to the climate change. CDR and SRM are two sets of technologies that offer climate risk mitigation alternatives. CDR offers a path towards decarbonization, with relatively low uncertainty and large benefits, but at very high costs. SRM is available at much lower direct costs, but comes with more uncertainty and does not address the root cause of climate change. The current literature has explored these technologies and identified them as non-trivial additions to the conventional slate of potential climate policy instruments. Literature exploring the economics of CDR is lacking. This is

[13]Bellamy & Hulme (2011) approaches the question of CTPs from the personal beliefs and societal perception perspective. In a sequence of quantitative and qualitative studies of public opinion on climate change and abatement, the authors refer to CTPs to identify public perception of the most undesirable outcomes of climate change.

in part due to the high expected costs of CDR technologies, and similarities in key characteristics between CDR and standard abatement techniques. The literature on SRM is more evolved, though still relatively small.

There are several directions where more research is needed in the near future. More research on the impacts and damages from climate engineering needs to be pursued. There are uncertainties associated with all aspects of climate change impacts, but those associated with climate engineering are exceptionally large. This research need extends not only to physical scientists and engineers, but also to economists. Attribution of impacts becomes more pressing once changes to the climate become deliberate. Compensation and liability are likely to be important aspects of any climate engineering policy, and will require mechanisms for monitoring and adjudication.

A second area of research need is the explicit modelling of SRM and CDR in conjunction with abatement and adaptation. As the climate continues to change, the incentives to invest in any particular form of climate risk mitigation strategy will change as well, and different regions will opt for different strategies. The literature has already started to address this issue, though it has thus far focused solely on effects on abatement, not adaptation.

Finally, we need to begin to explore specific mechanisms to ensure an efficient and equitable implementation of climate engineering technologies. While some early steps have been taken in this direction, we need to understand, from an economic perspective, how to create institutions that can accommodate these novel climate risk reduction strategies.

References

Aaheim, A., Romstad B., Wei, T., Kristjánsson, J. E., Muri, H., Niemeier, U., Schmidt, H. 2015. An economic evaluation of solar radiation management. *Science of the Total Environment*, 532, 61-69

Angel, R. 2006. Feasibility of cooling the Earth with a cloud of small spacecraft near the inner Lagrange point (L1). *Proceedings of the National Academy of Sciences*, 103(46), 17184-17189

Archer, D., Eby, M., Brovkin, V., Ridgwell, A., Cao, L., Mikolajewicz, U., Caldeira, K., Matsumoto, K., Munhoven, G., Montenegro, A., Tokos, K. 2009. Atmospheric Lifetime of Fossil Fuel Carbon Dioxide. *Annual Review of Earth and Planetary Sciences*, 37(1), 117-134

Bala, G., Duffy, P. B., Taylor, K. E. 2008. Impact of geoengineering schemes on the global hydrological cycle. *Proceedings of the National Academy of Sciences*, 105(22), 7664-7669

Barrett, S. 2007. A multitrack climate treaty system. In *Architectures for Agreement: Addressing Global Climate Change in the Post-Kyoto World*, Cambridge University Press, Cambridge.

Barrett, S. 2008. The Incredible Economics of Geoengineering. *Environmental and Resource Economics*, 39, 45-54

Barrett, S. 2014. Solar Geoengineering's Brave New World: Thoughts on the Governance of an Unprecedented Technology. *Review of Environmental Economics and Policy*, 8(2), 249-269

Bellamy, R., Chilvers, J., Vaughan, N. E., Lenton, T. M. 2012. A review of climate geoengineering appraisals. *Wiley Interdisciplinary Reviews: Climate Change*, 3(6), 597-615

Bellamy, R., Hulme, M. 2011. Beyond the Tipping Point: Understanding Perceptions of Abrupt Climate Change and Their Implications. *Weather, Climate and Society*, 48-60

Betz, G. 2012. The case for climate engineering research: an analysis of the "arm the future" argument. *Climatic Change*, 111, 473-485

Bickel, J. E. 2013. Climate engineering and climate tipping-point scenarios. *Environment Systems & Decisions*, 33(1), 152-167

Bickel, J. E., Agrawal, S. 2013. Reexamining the economics of aerosol geoengineering. *Climatic change*, 119(3-4), 993-1006

Bickel, J. E., Lane, L. 2009. An analysis of climate engineering as a response to climate change. *Copenhagen Consensus Center Report*, 40.

Blackstock, J. J., Battisti, D. S., Caldeira, K., Eardley, D. M., Katz, J. I., Keith, D. W., Patrinos, A. A. N., Schrag, D. P., Socolow, R. H. and Koonin, S. E. 2009. Climate Engineering Responses to Climate Emergencies. Novim, Santa Barbara.

Bunzl, M. 2009. Researching geoengineering: should not or could not? *Environmental Research Letters* 4(4), 045104

Burns, W. C. G. 2011. Climate Geoengineering: Solar Radiation Management and its Implications for Intergenerational Equity. *Stanford Journal of Law, Science & Policy*, 4(1), 37-55

Caldeira, Ken and Wood, Lowell. 2008. Global and Arctic climate engineering: numerical model studies. *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, 366(1882), 4039-4056

Corner, A., Pidgeon, N. 2010. Geoengineering the climate: The social and ethical implications. *Environment*, 52(1), 24-37

Crutzen, P. J. 2006. Albedo enhancement by stratospheric sulfur injections: A contribution to resolve a policy dilemma?. *Climatic Change*, 77(3-4), 211-219

Davis, Steven J. Socolow, Robert H. 2014. Commitment accounting of CO2 emissions. *Environmental Research Letters*, 9(8), 084018

Diffenbaugh, Noah S. and Field, Christopher B. 2013. Changes in Ecologically Critical Terrestrial Climate Conditions. *Science* 341(6145), 486-492

Emmerling, J., Tavoni, M. 2013. Geoengineering and abatement: a 'flat' relationship under uncertainty. *FEEM Working Paper* No. 31.

Feichter, J., Leisner, T. 2009. climate engineering: A critical review of approaches to modify the global energy balance. *The European Physical Journal Special Topics*, 176(1), 81-92

Field, Christopher B., Van Aalst, Maarten. 2014. Climate change 2014: impacts, adaptation, and vulnerability. IPPC.

Galaz, V. 2012. Geo-engineering, governance, and social-ecological systems: critical issues and joint research needs. *Ecology and Society*, 17(1), 24

Goes, M., Tuana, N., Keller, K. 2011. The economics (or lack thereof) of aerosol geoengineering. *Climatic Change*, 109(3-4), 719-744.

Goeschl, Timo, Daniel Heyen and J.B. Moreno-Cruz. 2013. The Intergenerational Transfer of Solar Radiation Management Capabilities and Atmospheric Carbon Stocks. *Environmental and Resource Economics*, 56(1), 85-104

Gramstad, K., Tjøtta, S. 2010. climate engineering: Cost benefit and beyond. Working paper No. 05/10. University of Bergen, Department of Economics.

Heutel, G., Moreno-Cruz, J., Shayegh, S. 2015a. Solar Geoengineering, Uncertainty, and the Price of Carbon. *National Bureau of Economic Research* wp No. w21355.

Heutel, G., Moreno-Cruz, J., Shayegh, S. 2015b. Climate Tipping Points and Solar Geoengineering. *National Bureau of Economic Research* wp No. w21589

Heyen, D., Wiertz, T., Irvine, P. 2015. Regional Disparities in Solar Radiation Management Impacts: Limitations to Simple Assessments and the Role of Diverging Preferences. Forthcoming *Climatic Change.*

Heyen, Daniel. 2015. Strategic Conflicts on the Horizon: R&D incentives for Environmental Technologies. *AWI Discussion Paper* No. 584.

House, K. Z., Baclig, A. C., Ranjan, M., van Nierop, E. A., Wilcox, J., Herzog, H. J. 2011. Economic and energetic analysis of capturing CO2 from ambient air. *Proceedings of the National Academy of Sciences*, 108(5), 20428-20433

Jamieson, D. 1996. Ethics and intentional climate change. *Climatic Change*, 33(3), 323-336

Jones, A., Haywood, J. M., Alterskjoer, K., Boucher, O., Cole, J. N. S., Curry, C. L., Irvine, P. J., Ji, D., Kravitz, B., Kristjansson, J. E., Moore, J. C., Niemeier, U., Robock, A., Schmidt, H., Singh, B., Tilmes, S., Watanabe, S., Yoon, J.-H. 2013. The impact of abrupt suspension of solar radiation management (termination effect) in experiment G2 of the Geoengineering Model Intercomparison Project (GeoMIP). *Journal of Geophysical Research: Atmospheres*, 118, 9743-9752

Katz, J. I. 2010. Stratospheric albedo modification. *Energy & Environmental Science*, 3, 1634-1644

Keith, D. 2000. Geoengineering the climate: History and prospects. *Annual Review of Energy and the Environment*, 25(1), 245-284

Keith, D. 2013. *A case for climate engineering*. MIT Press.

Klepper, G., Rickels, W. 2012. The real economics of climate engineering. *Economics Research International*, 1-20

Klepper, G., Rickels, W. 2014. climate engineering: Economic Considerations and Research Challenges. *Review of Environmental Economics and Policy*, 8(2), 270-289

Kravitz, B., Robock, A., Boucher, O., Schmidt, H., Taylor, K. E., Stenchikov, G., & Schulz, M. 2011. The geoengineering model intercomparison project (GeoMIP). *Atmospheric Science Letters*, 12(2), 162-167.

Kravitz, Ben, MacMartin, Douglas G, Robock, Alan, Rasch, Philip J, Ricke, Katharine L, Cole, Jason N S, Curry, Charles L, Irvine, Peter J, Ji, Duoying, Keith, David W, Egill Kristjansson, Jan, Moore, John C, Muri, Helene, Singh, Balwinder, Tilmes, Simone, Watanabe, Shingo, Yang, Shuting, Yoon, Jin-Ho. 2014. A multi-model assessment of regional climate disparities caused by solar geoengineering. *Environmental Research Letters*, 9, 074013.

Kriegler, E., Hall, J. W., Held, H., Dawson, R., Schellnhuber, H. J. 2013. Is atmospheric carbon dioxide removal a game changer for climate change mitigation?. *Climatic Change*, 118, 45-57

Lemoine, D., Traeger, C. 2014. Watch your step: Optimal policy in a tipping climate. *American Economic Journal: Economic Policy*, 6(1), 137-166.

Lackner, K. S. and Sachs, J. D. 2005. A Robust Strategy for Sustainable Energy. *Brookings Papers on Economic Activity* 2: 215-284.

Lackner, K. S. 2009. Capture of carbon dioxide from ambient air. *European Physical Journal*, 176, 93-106

Lackner, K. S., Brennan, S., Matter, J. M., Park, A.-H. A., Wright, A., van der Zwaan, B. 2012. The urgency of the development of CO2 capture from ambient air. *Proceedings of the National Academy of Sciences*, 109(33), 13156-13162

Lafforgue, G., Magné, B., Moreaux, M. 2008. Energy substitutions, climate change and carbon sinks. *Ecological Economics*, 67, 589-597

Latham, John and Bower, Keith and Choularton, Tom and Coe, Hugh and Connolly, Paul and Cooper, Gary and Craft, Tim and Foster, Jack and Gadian, Alan and Galbraith, Lee and Iacovides, Hector and Johnston, David and Launder, Brian and Leslie, Brian and Meyer, John and Neukermans, Armand and Ormond, Bob and Parkes, Ben and Rasch, Phillip and Rush, John and Salter, Stephen and Stevenson, Tom and Wang, Hailong and Wang, Qin and Wood, Rob. 2012. Marine cloud brightening. *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences* 370(1974) 4217-4262

Leisner, T., Mueller-Klieser, S. 2010. Aerosolbasierte Methoden des climate engineering. Eine Bewertung. *Technikfolgenabschatzung-Theorie und Praxis*, 19(2), 25-32

Lenton, T. M., Held, H., Kriegler, E., Hall, J. W., Lucht, W., Rahmstorf S., Schellnhuber, H. J. 2008. Tipping elements in the Earth's climate system. *Proceedings of the National Academy of Sciences*, 105(6), 1786-1793

Lockwood, J. G. 2011. Abrupt and sudden climatic transitions and fluctuations: a review. *International Journal of Climatology*, 21(9), 1153-1179

MacKerron, G. 2014. Costs and economics of geoengineering. Climate Geoengineering Governance. *W*orking Paper Series: 013

MacMartin, Douglas G. and Keith, David W. and Kravitz, Ben and Caldeira, Ken. 2013. Management of trade-offs in geoengineering through optimal choice of non-uniform radiative forcing. *Nature Climate Change*, 3, 365-368

McClellan, J., Keith, D. W., Apt, J. 2012. Cost analysis of stratospheric albedo modification delivery systems. *Environmental Research Letters*, 7(3), 1-8

Manoussi, V, Xepapadeas, A. 2015. Cooperation and Competition in Climate Change Policies: Mitigation and Climate Engineering when Countries are Asymmetric. *Environ Resource Economics.* DOI: 10.1007/s10640-015-9956-3

Matthews Damond, Caldeira Ken. 2007. Transient climate-carbon simulations of planetary geoengineering. *Proceedings of the National Academy of Sciences of the United States of America*, 104(24), 9949-9954

Mercer, A. M., Keith, D. W., Sharp, J. D. 2011. Public understanding of solar radiation Management. *Environmental Research Letters*, 6, 1-9

Millard-Ball, A. 2012. The Tuvalu Syndrome. Can geoengineering solve climate's collective action problem?. *Climatic Change*, 110, 1047-1066

Moreno-Cruz, J. B. Mitigation and the Geoengineering Threat. *Resource and Energy Economics*, 41, 248-263

Moreno-Cruz J. B. Sjak Smulders. Geoengineering and Economic Growth: Making Climate Change Irrelevant or Buying Time? 2007 *Meeting of the International Energy Workshop*

Moreno-Cruz J. B. and S. Smulders. 2010. Revisiting the economics of climate change: the role of geoengineering, mimeo. http://works.bepress.com/morenocruz/4.

Moreno-Cruz, J. B., Ricke, K. L., Keith, D. W. 2012. A simple model to account for regional inequalities in the effectiveness of solar radiation management. *Climatic Change*, 110(3-4), 649-668

Moreno-Cruz, J. B., Keith, D. W. 2013. Climate policy under uncertainty: a case for solar geoengineering. *Climatic Change*, 121(3), 431-444.

Morgan, M. G., Ricke, K. L. 2011. *Cooling the earth through solar radiation management: The need for research and an approach to its governance.* International Risk Governance Council. Geneva, Switzerland.

Moriarty, P., Honnery, D. 2014. Future Earth: declining energy use and economic output. *Foresight*, 16(6), 512-526

Murphy, D. M. 2009. Effect of Stratospheric Aerosols on Direct Sunlight and Implications for Concentrating Solar Power. *Environmental Science and Technology*, 43(8), 2784-2786

National Research Council. 2015a. *Climate Intervention: Reflecting Sunlight to Cool Earth*. Washington, DC: The National Academies Press.

National Research Council. 2015b. *Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration*. Washington, DC: The National Academies Press.

Nordhaus, W. D. 2008. A Question of Balance: Weighing the Options on Global Warming Policies. Yale University Press. New Haven, CT.

Orr, James C., Fabry, Victoria J., Aumont, Olivier, Bopp, Laurent, Doney, Scott C., Feely, Richard A., Gnanadesikan, Anand, Gruber, Nicolas, Ishida, Akio, Joos, Fortunat, Key, Robert M., Lindsay, Keith, Maier-Reimer, Ernst, Matear, Richard, Monfray, Patrick, Mouchet, Anne, Najjar, Raymond G., Plattner, Gian-Kasper, Rodgers, Keith B., Sabine, Christopher L., Sarmiento, Jorge L., Schlitzer, Reiner, Slater, Richard D., Totterdell, Ian J., Weirig, Marie-France, Yamanaka, Yasuhiro, Yool, Andrew. 2005. Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms. *Nature*, 437 (7059), 681-686

Parkhill, K., Pidgeon, N. 2011. Public Engagement on Geoengineering Research: Preliminary Report on the SPICE Deliberative Workshops. *U*nderstanding Risk Working Paper 11-01

Rasch, P. J., P. J. Crutzen and D. B. Coleman. 2008. Exploring the geoengineering of climate using stratospheric sulfate aerosols: The role of particle size. Geophysical Research Letters 35(2). DOI:10.1029/2007GL032179.

Ricke, Katharine L., Morgan, M. Granger, Allen, Myles R. 2010. Regional climate response to solar-radiation management. *Nature Geoscience*, 3, 537-541

Ricke, Katharine L., Rowlands, Daniel J., Ingram, William J., Keith, David W. and Granger Morgan, M. 2012. Effectiveness of stratospheric solar-radiation management as a function of climate sensitivity. *Nature Climate Change*, 2, 92-96

Ricke, K. L., Moreno-Cruz, J. B., Caldeira, K. 2013. Strategic incentives for climate geoengineering coalitions to exclude broad participation. *Environmental Research Letters*, 8(1), 1-8

Rickels, W., Rehdanz, K., Oschlies, A. 2010. Methods for greenhouse gas offset accounting: A case study of ocean iron fertilization. *Ecological Economics*, 69, 2495-2509

Rickels, W., Rehdanz, K., Oschlies, A. 2012. Economic prospects of ocean iron fertilization in an international carbon market. *Resource and Energy Economics*, 34, 129-150

Rickels, W., Lontzek, T. S. 2012. Optimal global carbon management with ocean sequestration. *Oxford Economic Papers*, 64, 323-349

Robock, A., Oman, L., Stenchikov, G. L. 2008. Regional climate responses to geoengineering with tropical and Arctic SO2 injections. *Journal of Geophysical Research*, 113(D16).

Robock, A., Marquardt, A., Kravitz, B., Stenchikov, G. 2009. Benefits, risks, and costs of stratospheric geoengineering. *Geophysical Research Letters*, 36(19), L19703

Salter, Stephen, Sortino, Graham, Latham, John. 2008. Sea-going hardware for the cloud albedo method of reversing global warming. *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences.* 366(1882), 3989-4006

Schelling, T.C., 1996. The economic diplomacy of geoengineering. *Climatic Change* 33, 291-302.

Schneider, S. H. 1996. Geoengineering: Could - or should - we do it?. *Climatic Change*, 33(3), 291-302

Sillmann, Jana, Lenton, Timothy M., Levermann, Anders, Ott, Konrad, Hulme, Mike, Benduhn, Francois, Horton, Joshua B. 2015. Climate emergencies do not justify engineering the climate. *Nature Climate Change*, 5(4), 290-292

Socolow, R. et al. (2011), Direct Air Capture of CO2 with Chemicals: A Technology Assessment for the APS Panel on Public Affairs, Ridge, NY: American Physical Society.

Sohngen, B., Mendelsohn, R. 2003. An Optimal Control Model of Forest Carbon Sequestration. *American Journal of Agricultural Economics*, 85(2), 448-457

Sterck, O. 2011. Geoengineering as an alternative to mitigation: specification and dynamic implications. IRESDiscussion Papers No 2011035

Tilmes, Simone, Moeller, Rolf, Salawitch, Ross. 2008. The Sensitivity of Polar Ozone Depletion to Proposed Geoengineering Schemes. *Science* 320(5880), 1201-1204

Victor, D. G. 2008. On the regulation of geoengineering. *Oxford Review of Economic Policy*, 24(2), 322-336.

Wagner, G., Weitzman, M. L. 2015. *Climate shock: the economic consequences of a hotter planet.* Princeton University Press.

Walther, G. R., Post, E., Convey, P., Menzel, A., Parmesan, C., Beebee, T. J., Fromentin, J., Hoegh-Guldberg, O., Bairlein, F. Ecological responses to recent climate change. *Nature*, 416(6879), 389-395

Weitzman, M. 2015. A Voting Architecture for the Governance of Free-Driver Externalities, with Application to Geoengineering. *The Scandinavian Journal of Economics*, 17(4), 1049-1068.

Williamson, P., Wallace, D. W. R., Law, C. S., Boyd, P. W., Collos, Y., Croot, P., Denman, K., Riebesell, U., Takeda, S., Vivian, C. 2012. Ocean fertilization for geoengineering: A review of effectiveness, environmental impacts and emerging governance. *Process Safety and Environmental Protection*, 90(6), 475-488

Wrigley, T. M. 2006. A combined mitigation/geoengineering approach to climate stabilization. *Science*, 314(5798), 452-454.

Zhou, S., Flynn, P. C. 2005. Geoengineering downwelling ocean currents: A cost assessment. *Climatic Change*, 71(1-2), 203-220

Zickfeld, K., Morgan, M. G., Frame, D. J., Keith, D. W. 2010. Expert judgments about transient climate response to alternative future trajectories of radiative forcing. *Proceedings of the National Academy of Sciences*, 107(28), 12451-12456