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GLOBAL CLIMATE GOVERNANCE IN 3D: MAINSTREAMING GEOENGINEERING WITHIN A UNIFIED FRAMEWORK

Gabriel Weil*

ABSTRACT

The failure of conventional climate change mitigation to reduce climate-related risks to tolerable levels has spurred interest in more unconventional—and riskier—climate interventions. What currently sounds like science fiction could become a reality in the not-so-distant future: planes blasting particles into the sky to block the sun, vast deserts covered with mirrors, algae sucking carbon into the depths of the ocean. Scholars tend to lump all these unconventional climate measures together in a fuzzy category called "geoengineering," and set them apart from conventional climate change mitigation. But the characteristics of climate interferences vary across three distinct dimensions, which the mitigation-geoengineering dichotomy fails to capture. First, interventions operate via different mechanisms, such as altering the atmospheric concentration of greenhouse gases or changing the fraction of incoming solar radiation absorbed by the earth. Second, the characteristic duration of interferences varies from several days to millennia. Third, interferences differ in terms of leverage—the scale of climate impact achievable with a fixed investment of resources. This Article argues that global climate governance would be best served

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by a unified approach that addresses all climate interferences based on these three dimensions. In such a unified framework, influence over multilateral decisions to deploy risky, high-leverage interventions could be used as an incentive to induce greater national investment in safer, more expensive decarbonization efforts. Scientific uncertainty should not deter early action on geoengineering governance; it should be viewed as an opportunity to lock in agreement on neutral principles while national governments remain behind a partial veil of ignorance regarding their interests.

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INTRODUCTION

Climate change threatens to impose enormous costs on human civilization over the next century. Estimates of the expected economic damages range from a net present value of $43 trillion to over $200 trillion.[1] While the existential risks to human civilization are hotly debated, credible estimates suggest that the likelihood of existential catastrophe-level warming by the year 2100 may be as high as 3.5%.[2] However, the current global governance regime for mitigating climate change is largely failing.[3] In the decades since scientists first alerted us to the greenhouse effect and policymakers began declaring their best intentions for avoiding the dangers of climate change—global emissions have continued to rise.[4] The non-binding and unenforceable pledges governments made as part of the Paris Agreement—which is widely viewed as the high water mark of global cooperation to mitigate climate change—fall far short of what is needed to limit global warming to 2°C, let alone the increasingly fashionable goal of limiting warming to 1.5°C.[5] Many countries are not even on track to meet their inadequate Paris pledges, and the United States temporarily withdrew from the agreement entirely.[6]

The current governance framework for climate change focuses on two broad categories of measures: mitigation and adaptation.[7] Mitigation refers to efforts to reduce the severity of climate change, mostly by reducing greenhouse gas ("GHG") emissions.[8] Whereas, adaptation refers to efforts to minimize the economic, social,

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[1] PAUL WATKISS, TOM DOWNING, CLAIRE HANDLEY & RUTH BUTTERFIELD, EUR. COMM'N DG ENV'T, THE IMPACTS AND COSTS OF CLIMATE CHANGE, at iv, 43, 46 (2005), https://digital.library.unt.edu/ark%3A/67531/metadc29337/m2/1/high_res_d/final_report2.pdf [https://perma.cc/HP2Q-G4ZA].

[2] John Halstead, *Stratospheric Aerosol Injection Research and Existential Risk*, 102 FUTURES 63, 67 (2018). Existential catastrophes include both extinction events and permanent or irrevocable collapse of human civilization. *See generally id.*

[3] Gabriel Weil, *Incentive Compatible Climate Change Mitigation: Moving Beyond the Pledge and Review Model*, 42 WM. & MARY ENV'L L. & POL'Y REV. 923, 960 (2018) [hereinafter Weil, *Beyond the Pledge*].

[4] *Global Greenhouse Gas Emissions Data*, EPA, https://www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data [https://perma.cc/CH4B-TYGL].

[5] Weil, *Beyond the Pledge*, *supra* note 3, at 927.

[6] Stephen Leahy, *Most Countries Aren't Hitting 2030 Climate Goals, and Everyone Will Pay the Price*, NAT'L GEOGRAPHIC (Nov. 5, 2019), https://www.nationalgeographic.com/science/article/nations-miss-paris-targets-climate-driven-weather-events-cost-billions#close [https://perma.cc/755E-KKBP].

[7] James Meadowcroft, *Climate Change Governance* 7 (World Bank Grp., Working Paper 4941, 2009).

[8] *See id.*

and human costs of climate change.[9] Scholars and policymakers also research and discuss a third category of climate interventions that has not been deployed at significant scale or been the subject of significant policy attention: geoengineering.[10]

Geoengineering is deliberate large-scale intervention in the earth's climate system to moderate global warming.[11] Geoengineering techniques are typically divided into two categories: solar radiation management and carbon dioxide removal.[12] The categorization of CO_2 removal along with solar radiation management as geoengineering is controversial, with some scholars arguing that CO_2 removal should be treated more like conventional mitigation.[13]

As the magnitude of present climate impacts and near-term climate risks increases in the coming decades, interest in geoengineering is likely to grow. Given the significant cross-border externalities, positive and negative, associated with many unconventional climate interventions, there is a strong case for some form of global governance in this domain. Indeed, there is burgeoning literature addressing governance of geoengineering research and deployment. However, this literature largely treats geoengineering in isolation.[14]

The separation between geoengineering and mitigation/adaptation is artificial and fuzzy.[15] For instance, consider the ongoing debate over whether CO_2 removal

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[9] *See id.*

[10] THE ROYAL SOC'Y, GEOENGINEERING THE CLIMATE: SCIENCE, GOVERNANCE AND UNCERTAINTY 5 (2009).

[11] *Id.* at 29.

[12] *Id.* at 1.

[13] David Keith, *Why I Am Proud to Commercialize Direct Air Capture While I Oppose Any Commercial Work on Solar Geoengineering*, HARV. UNIV.: DAVID KEITH'S RSCH. GRP. (June 4, 2018), https://keith.seas.harvard.edu/blog/why-i-am-proud-commercialize-direct-air-capture-while-i-oppose-any-commercial-work-solar [https://perma.cc/7KR7-8X73] [hereinafter Keith, *Opposing Commercial Solar*].

[14] *See, e.g.,*, David A. Wirth, *Engineering the Climate: Geoengineering as a Challenge to International Governance*, 40 B.C. ENV'T L. REV. 413 (2013); David G. Victor, *On the Regulation of Geoengineering*, 24 OXFORD REV. ECON. POL'Y 332 (2008) [hereinafter Victor, *Geoengineering Regulation*]; Martin L. Weitzman, *A Voting Architecture for the Governance of Free-Driver Externalities, with Application to Geoengineering*, 117 SCANDINAVIAN J. ECON. 1049 (2015); Ian D. Lloyd & Michael Oppenheimer, *On the Design of an International Governance Framework for Geoengineering*, 14 GLOB. ENV'T POL. 45 (2014).

[15] David W. Keith, *Geoengineering the Climate: History and Prospect*, 25 ANN. REV. ENERGY ENV'T 245, 248 (2000) [hereinafter Keith, *Geoengineering the Climate*].

should be classified as geoengineering along with solar radiation management.[16] In terms of the legal and regulatory treatment of geoengineering and geoengineering-adjacent activities, this definitional dispute largely misses the point.

Stratospheric aerosol injection, marine cloud brightening, and space-based sunshielding, are examples of solar radiation management that are universally classified as geoengineering.[17] However, other interferences, like black carbon emissions abatement, boreal and temperate deforestation, and painting building rooftops white, also reduce net radiative flux at least in part by increasing the fraction of incoming solar radiation reflected back into space.[18] These latter interferences, though typically not considered forms of geoengineering, are thus properly classified as forms of solar radiation management. A similar analysis applies to CO_2 removal interferences. Ocean iron fertilization, direct air capture, enhanced weathering, and afforestation are sometimes classified as geoengineering.[19] Carbon capture, utilization, and storage ("CCUS") from power plants and industrial facilities, by contrast, is typically classified as conventional mitigation, as is forest preservation.[20]

Climate interferences vary along at least three distinct dimensions, which are often collapsed into existing categorizations.[21] First, interferences operate via different mechanisms, either by—changing the atmospheric concentration of GHGs, reducing the quantity of solar radiation absorbed by the earth, or through some combination of both.[22] Second, the duration over which interferences exert a direct climate forcing ranges from days to millennia.[23] Third, interventions vary widely in

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[16] *See id.* at 247.

[17] For a general background of the history and definition of "geoengineering," *see id.* at 247–59.

[18] *See* Fred Pearce, *Urban Heat: Can White Roofs Help Cool World's Warming Cities*, YALE ENV'T 360 (Mar. 7, 2018), https://e360.yale.edu/features/urban-heat-can-white-roofs-help-cool-the-worlds-warming-cities [https://perma.cc/WW3Y-9EAE]. White roofs can be thought of as solar radiation management, mitigation, and adaptation, since they increase the earth's surface albedo, reduce demand for building cooling services (which are often emission-intensive), and reduce the human cost of rising global average temperature. *Id.*

[19] *See* Keith, *Geoengineering the Climate*, *supra* note 15, at 256.

[20] *See id.* at 267.

[21] *See infra* Part III.

[22] *See infra* Section III.A.

[23] *See infra* Section III.B.

terms of leverage—the ratio of expected climate impact to quantity of resources required for deployment.[24]

Instead of compressing this multi-dimensional variation into a sharp dichotomy, this Article seeks to situate unconventional climate interferences in a broader climate governance framework. Variations along each dimension warrant differences in their treatment under international law, but these variations do not map neatly onto the traditional distinction between mitigation, adaptation, and geoengineering.

In geopolitical terms, governance of solar radiation management is more tractable than governance of GHG emissions.[25] For reasons that will be explained below, unilateral deployment of solar radiation management is easier to prevent than unilateral failure to decarbonize.[26] This means that conventional climate governance could potentially benefit from integration with geoengineering governance, rather than the latter serving as an unhelpful distraction. The following analysis will show that substantial gains could accrue from early action to establish principles and decision structures for deployment of unconventional climate interventions, but any effort to permanently rule out deployment of specific interventions would be a mistake. Scientific uncertainty regarding the precise effects of various interventions, often viewed as a reason to put off decisions about geoengineering governance, should instead be viewed as an opportunity to lock in agreement on a basic governance framework before countries have full knowledge of their interests.

My argument proceeds as follows. Part I provides an overview of the range of existing and potential climate interferences, highlighting their key features. Part II surveys the geoengineering governance literature, identifying the blind spots that this Article seeks to address: the lack of a clear distinction between geoengineering and conventional mitigation, the potential for constructive linkage between the governance of qualitatively different climate interferences, and the potential benefits of locking in agreement on neutral governance principles while countries are still behind a partial veil of ignorance regarding their own interests. Part III develops the three dimensions framework, under which climate interferences are classified by their mechanism of action (III.A), duration (III.B), and leverage (III.C). Part IV analyzes issues that arise at the intersection of multiple dimensions, including the potential for termination shock for short-duration, high-leverage interferences

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[24] *See infra* Section III.C.

[25] Sikina Jinnah et al., *Toward Legitimate Governance of Solar Geoengineering Research: A Role for Sub-State Actors*, 21 ETHICS POL'Y & ENV'T 362, 364 (2018).

[26] *See infra* Section IV.C.

(IV.A); optimal climate risk management portfolios (IV.B); the relative governability of different climate interferences (IV.C); the concern that the availability of risky, high-leverage interventions will dampen investment in safer, low-leverage interventions like conventional mitigation (IV.D); and options for leveraging influence over the decision to deploy risky, high-leverage interventions to motivate greater investment in conventional mitigation (IV.E). Part V concludes that insights from the foregoing analysis favor early action to establish a unified approach to climate governance that accounts for each of the three dimensions of variation and exploits opportunities for cross-interference linkage to motivate stronger global cooperation in managing climate risk.

I. OVERVIEW OF CLIMATE INTERFERENCES

A climate interference is an action that alters the Earth's thermal balance. Almost all significant climate interferences operate via radiative forcing—changes in the balance of solar radiation absorbed, reflected, and reemitted back into space. In this Article, the term interference is used neutrally, to refer to both warming-inducing and cooling-inducing actions. In this sense, humans have been engaging in climate interferences for millennia and doing so at a globally significant scale for over two centuries.[27]

Until the last few decades, these interferences have all been unintended byproducts of other human activities, mostly related to the combustion of fossil fuels for heating, electricity, transportation, and industrial processes.[28] Agriculture has also been a significant source of human climate interferences, over and above the use of fossil energy therein, via both changes in land use and methane emissions from cattle, rice paddies, etc.[29] These interferences have mostly acted by increasing the atmospheric concentration of GHGs, which trap heat in the atmosphere and prevent

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[27] Johannes Friedrich & Thomas Damassa, *The History of Carbon Dioxide Emissions*, WORLD RES. INST. (May 21, 2014), https://www.wri.org/insights/history-carbon-dioxide-emissions [https://perma.cc/8QZ2-4CNW].

[28] Hannah Ritchie, Max Roser & Pablo Rosado, *CO_2 and Greenhouse Gas Emissions*, OUR WORLD IN DATA, https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions [https://perma.cc/YJZ5-25AX].

[29] Hannah Ritchie, *Food Production is Responsible for One-Quarter of the World's Greenhouse Gas Emissions*, OUR WORLD IN DATA (Nov. 6, 2019), https://ourworldindata.org/food-ghg-emissions [https://perma.cc/JY3X-9GUH].

it from escaping into space.[30] However, land use changes and emissions of black carbon also alter the Earth's land surface albedo, changing the fraction of solar radiation that is absorbed by the Earth's surface.[31] Deforestation also produces changes in evapotranspiration and cloud formation that alter the albedo as seen from the top of the atmosphere.[32] These latter interferences can be thought of as unintended forms of negative (i.e., warming-inducing) solar radiation management.

Byproduct effects are still the dominant source of human climate interference.[33] However, the scientific understanding of climate change has led to a second class of intentional climate interferences, or climate interventions. To date, these have mostly been efforts to reduce byproduct interferences.[34] These efforts typically operate by reducing consumption of the goods and services whose production leads to byproduct interferences or by shifting production patterns such that the same goods and services are produced with fewer byproduct interferences.[35] Examples of consumption-based interventions include avoiding air travel; reducing car trips; weatherizing homes and offices so less heating and cooling is needed; tolerating indoor temperatures closer to the outdoor temperature; living in smaller dwellings; and eating less meat.[36] Examples of production-based interventions include shifting power generation from coal to natural gas or from fossil generation to wind, solar, hydro, geothermal, nuclear, or other carbon-free sources; improving vehicle fuel economy, power plant heat rates, and industrial process efficiency; electrification of heating and transportation; and improving ruminant livestock feed quality and

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[30] GUNNAR MYHRE ET AL., *Anthropogenic and Natural Radiative Forcing*, *in* CLIMATE CHANGE 2013: THE PHYSICAL SCIENCE BASIS 661 (2011).

[31] *Id.* at 662. Albedo is the proportion of radiation that is reflected off a surface. *Albedo*, BRITANNICA, https://www.britannica.com/science/albedo [https://perma.cc/7UFE-JWEC].

[32] G. Bala, K. Caldeira, M. Wickett, T.J. Phillips, D.B. Lobell, C. Delire & A. Mirin, *Combined Climate and Carbon-Cycle Effects of Large-Scale Deforestation*, 104 PROC. NAT'L ACAD. SCI. 6650, 6650 (2007).

[33] *Climate Forcing*, NOAA CLIMATE.GOV, https://www.climate.gov/maps-data/climate-data-primer/predicting-climate/climate-forcing [https://perma.cc/YK56-BVDL].

[34] To reduce in this context means to produce less byproduct interference than would have occurred in a counterfactual scenario where no effort is made to do so. This does not necessarily imply an absolute reduction relative to the amount of byproduct interference in a prior period.

[35] *See generally* BILL GATES, HOW TO AVOID A CLIMATE DISASTER: THE SOLUTIONS WE HAVE AND THE BREAKTHROUGHS WE NEED (2021).

[36] *See generally id.*

selectively breeding cattle to reduce enteric methane fermentation.[37] Many interventions involve a combination of reduced/substituted consumption and decreases in the GHG emissions intensity of production.[38]

As with the unintended byproduct interferences, a small portion of this second class of climate interferences operates at least in part through the solar radiation management channel. Black carbon emissions abatement attenuates the reduction in the Earth's surface albedo, meaning a higher fraction of incoming solar radiation is reflected back into space.[39] Some conservation-based constraints on land use change have the same effect.[40] White roofs and cool pavements increase the surface albedo of urban land, acting through the solar radiation management channel, in addition to decreasing consumption of cooling services, and playing a role in local adaptation.[41] Some efforts at forest preservation have an albedo *decreasing* effect that can more than offset the cooling effect of carbon sequestration.[42]

Climate change mitigation policies can take many forms, from market-based approaches like carbon taxes and cap-and-trade to flexible efficiency and carbon-intensity standards to prescriptive regulations to public investment in clean technology research, development, and deployment.[43] What most existing climate change policies have in common is that they seek to further reduce or eliminate the warming interferences that occur as a byproduct of other human activities.[44] That is, they seek to reduce or shift consumption away from GHG-intensive goods and services and/or reduce the emissions intensity of production. The net result of this second wave of climate interferences has only a decrease in the growth rate of GHG

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[37] REDUCE GREENHOUSE GAS EMISSIONS FROM AGRICULTURAL PRODUCTION, WORLD RES. INST., https://research.wri.org/sites/default/files/2019-07/G_REP_Food_Course5_web.pdf [https://perma.cc/S34D-HVQD].

[38] Kristian S. Nielsen, Sander van der Linden & Paul C. Stern, *How Behavioral Interventions Can Reduce the Climate Impact of Energy Use*, 4 JOULE 1613, 1613 (2020).

[39] *What is Black Carbon?*, CTR. FOR CLIMATE & ENERGY SOLS. (Apr. 2010), https://www.c2es.org/wp-content/uploads/2010/04/what-is-black-carbon.pdf [https://perma.cc/8G9U-YP23].

[40] Bala et al., *supra* note 32, at 6650.

[41] Pearce, *supra* note 18.

[42] Bala et al., *supra* note 32, at 6650.

[43] ESWARAN SOMANATHAN ET AL., *National and Sub-National Policies and Institutions*, *in* CLIMATE CHANGE 2014: MITIGATION OF CLIMATE CHANGE 1155–56 (2014).

[44] *See id.* at 1156.

emissions and other byproduct interferences, with the absolute magnitude of anthropogenic interference continuing to rise.[45]

Some unconventional climate interventions also fit this broad description. For instance, CCUS for emissions from power plants or industrial facilities is probably best thought of as decreasing the carbon intensity of production. CCUS's close cousin, direct air capture, and other negative emissions technologies like afforestation and reforestation, enhanced weathering, ocean fertilization, and bioenergy with carbon capture and sequestration ("BECCS"), by contrast, represent a third class of climate interference.[46] These are interventions that seek to reduce atmospheric GHG concentrations by pulling previously emitted CO_2 out of the atmosphere.[47] That is, these climate interventions are neither a byproduct of economic activity nor an attempt to directly reduce those byproduct interferences.[48] However, the intended effect of all these interventions is to act through the atmospheric GHG concentration channel.[49] Most of these interventions are well understood but have not been deployed at a significant scale.

A fourth category of interference is intentional affirmative (i.e. cooling) solar radiation management.[50] With the arguable exception of cool roofs and other urban adaptation interventions like cool pavements, intentional affirmative solar radiation management has not been deployed at an operational scale.[51] Potential intentional affirmative solar radiation management interventions include stratospheric aerosol injection, space-based sunshielding, marine cloud brightening, and surface-based methods like placing reflective materials on deserts or arctic sea ice.[52] Stratospheric aerosol injection, the most commonly discussed form of solar radiation management, involves injecting aerosol particles like sulfates into the upper atmosphere—

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[45] EPA, *supra* note 4. There was a dip in emissions in 2020 due to the COVID-19 pandemic, but this was not primarily driven by climate policy and emissions soon recovered. *See id.*

[46] *See* discussion *infra* Section III.C.

[47] *See infra* Section IV.C.4.

[48] *Id.*

[49] *See infra* Part III.

[50] These interventions can be thought of as efforts to cure, rather than prevent, the harmful effects of climate change. *See* Michael Pappas, *Prevention and Cure*, LOY. L.A. L. REV. 1067, 1074–75 (2021).

[51] *See infra* Section III.C.1.

[52] L. Field, D. Ivanova, S. Bhattacharyya, V. Mlaker, A. Sholtz, R. Decca, A. Manzara, D. Johnson, E. Christodoulou, P. Walter & K. Katuri, *Increasing Arctic Sea Ice Albedo Using Localized Reversible Geoengineering*, 6 EARTH'S FUTURE 882, 882 (2018).

mimicking the effect of a volcano.[53] This intervention was first proposed in the mid-1970s and gained greater attention after the 1991 eruption of Mount Pinatubo in the Philippines, which resulted in a temporary global cooling that peaked at about 0.5°C.[54] An advantage of stratospheric aerosol injection is that the effects would be more uniformly distributed than for localized solar radiation management interventions like marine cloud brightening or surface albedo enhancement.[55] However, there is significant uncertainty about the magnitude of the stratospheric aerosol injection cooling response and concerns about the secondary effects stratospheric aerosol injection deployment could have, such as on stratospheric ozone and high-altitude tropospheric clouds.[56]

Space-based sunshielding might involve transporting terrestrial reflective materials or collecting nearby reflective materials at the L1 Lagrange point, the point between the sun and the earth where the gravitational pull of the two bodies cancel out.[57] The L1 Lagrange point is about 1.5 million kilometers from Earth, which is about 1/100 of the distance to the sun.[58] Space-based sunshielding could achieve relatively uniform reductions in the intensity of incoming sunlight.[59] It would also avoid any significant impact on ozone depletion or tropospheric clouds, but would be much more expensive to implement than stratospheric aerosol injection.[60]

Marine cloud brightening would entail increasing the quantity of cloud-condensation nuclei in low-level marine clouds in relatively dust-free parts of the marine atmosphere with the objective of increasing the reflectivity and possibly also the longevity of stratus clouds.[61] This could be implemented by releasing a hydrophilic powder like finely ground sea salt from marine vessels or aircrafts.[62]

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[53] *See* THE ROYAL SOC'Y, *supra* note 10, at 29.

[54] *Id.*

[55] *Id.* at xi.

[56] *Id.*

[57] *Id.* at 32.

[58] NEIL J. CORNISH, THE LAGRANGE POINTS 4 (1998), https://map.gsfc.nasa.gov/ContentMedia/lagrange.pdf [https://perma.cc/G7V2-GGG3].

[59] THE ROYAL SOC'Y, *supra* note 10, at 33.

[60] *Id.*

[61] *Id.* at 27.

[62] *Id.*

While the albedo-enhancing effects of this cloud brightening would be localized, modeling studies suggest that doubling the natural cloud-droplet concentration in all such clouds would increase the cloud-top albedo sufficiently to compensate, roughly, for a doubling of atmospheric CO_2.[63]

Desert-based surface solar radiation management might involve covering deserts with a reflective polyethylene-aluminum surface, which could increase mean albedo from 0.36 to 0.80.[64] Sea ice-based surface albedo enhancement, might involve placing highly reflective floatable glass microspheres on the Arctic sea ice.[65] It would operate by increasing the albedo of the sea ice itself and mitigating sea ice melt, thereby reducing the surface area of regions with low albedo like the Arctic ocean water.[66]

Cirrus cloud thinning, while typically classified as geoengineering, is not best understood as a form of solar radiation management. Like other clouds, cirrus clouds both reflect incoming sunlight (a cooling effect) and absorb outgoing infrared radiation (a warming effect).[67] However, unlike other clouds, on average, the warming effect of infrared radiation absorption outweighs the cooling effect of the reflecting incoming sunlight.[68] Thinning cirrus clouds by seeding them with an aerosol like bismuth tri-iodide would proportionately reduce both the reflection of incoming sunlight and the absorption of outgoing infrared radiation. So, while cirrus cloud thinning is expected to produce net cooling, it would actually increase the quantity of solar radiation that reaches the earth's surface.[69] In other words, cirrus cloud thinning produces a negative solar radiation management effect as an unintended byproduct of reducing infrared radiation absorption. The primary intended effect of reducing infrared radiation absorption is more akin to reducing the atmospheric concentration of a short-lived GHG that does not contribute to ocean acidification than to solar radiation management, except that the effects are localized.

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[63] *Id.* Substantial uncertainty remains regarding this estimate. *See* NAT'L ACADS. OF SCIS., ENG'G, & MED., REFLECTING SUNLIGHT: RECOMMENDATIONS FOR SOLAR GEOENGINEERING RESEARCH AND RESEARCH GOVERNANCE 46–48 (2021).

[64] THE ROYAL SOC'Y, *supra* note 10, at 26.

[65] Field et al., *supra* note 52, at 883.

[66] *Id.*

[67] Joonsuk Lee, Ping Yang, Andrew E. Dessler, Bo-Cal Gao & Steven Platnick, *Distribution and Radiative Forcing of Tropical Thin Cirrus Clouds*, 66 J. ATMOSPHERIC SCI. 3721, 3727 (2009).

[68] *Id.* at 3729.

[69] David L. Mitchell & William Finnegan, 4 *Modification of Cirrus Clouds to Reduce Global Warming*, ENV'T RSCH. LETTERS No. 045102, Dec. 2009, at 1.

II. SILOED GEOENGINEERING GOVERNANCE

As suggested above, the existing literature has largely treated geoengineering governance as its own domain, distinct from climate change mitigation via reduction of GHG emissions. Most scholarship on geoengineering governance takes one or more of the following three approaches: (A) characterizing the technical, economic, and strategic paradigms posed by geoengineering interventions; (B) surveying the existing corpus of international law to identify principles and instruments that may be applicable to geoengineering governance; and (C) proposing particular design features for the governance of geoengineering research and deployment, including both substantive principles and procedural approaches like voting rules and instrument choice. Papers in this area tend to limit their scope to governance of a subset of solar radiation management interventions—though some also include certain forms of CO_2 removal in their analysis.

As Part III will make clear, however, there is no clear separation between conventional climate change mitigation and geoengineering since climate interferences vary independently along three distinct dimensions. Section III.D argues that the failure to recognize this fact is the most important shortcoming of the existing geoengineering governance literature. This literature also neglects both opportunities for constructive linkage between the governance of different climate interventions and potential advantages of acting early to secure agreement on neutral governance principles before countries have full knowledge of their interests.

A. Technical, Economic, and Strategic Paradigms

The most prominent finding in the technical, economic, and strategic domain is that some geoengineering interventions offer much higher leverage over climate outcomes than conventional mitigation interventions.[70] Scott Barrett promoted an extreme version of this finding, characterizing the economics of geoengineering as "incredible," meaning the direct cost of slowing or reversing warming via stratospheric aerosol injection is orders of magnitude lower than doing so via conventional mitigation.[71] This observation led Barrett and some other scholars to conclude that excessive or premature unilateral deployment is the most worrisome potential failure mode for geoengineering governance.[72] Martin Weitzman argued

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[70] Edward A. Parson & Lia N. Ernst, *International Governance of Climate Engineering*, 14 THEORETICAL INQUIRIES L. 307, 313–14 (2013).

[71] Scott Barrett, *The Incredible Economics of Geoengineering*, 39 ENV'T RSCH. ECON. 45, 49 (2008).

[72] *See id.* at 46; Weitzman, *supra* note 14, at 1050; Lloyd & Oppenheimer, *supra* note 14, at 46.

that these greatly reduced direct costs flipped the collective action problem of climate change mitigation on its head.[73] Instead of facing a free-rider problem, where the difficulty is in motivating countries to bear their portion of the mitigation burden, we are said to face a free-*driver* problem, where the challenge is in preventing a single country from deploying geoengineering at too great a scale or under circumstances when the world as a whole would be better off with no deployment.[74]

As discussed below in Section IV.C, Joshua Horton pushes back on this analysis, arguing that several factors greatly reduce the likelihood of unilateral deployment.[75] Edward Parson and Lia Ernst similarly downplay the risk of unilateral deployment, pointing out that the rapid decay of high-leverage solar radiation management means that any would-be geoengineer would need the wherewithal to continue deployments indefinitely and be prepared to defend their operations from potential military attack.[76] But Parson and Ernst do worry that the availability of high-leverage geoengineering interventions could generate severe international conflict over whether, when, and how to deploy them.[77] David Victor, by contrast, expresses concern about a "greenfinger," a wealthy individual or other subnational actor who engages in geoengineering without the support of any national government.[78] Daniel Bodanksy argues that this "greenfinger" scenario is structurally similar to terrorism, in that "individuals have the capacity to do things with huge, and potentially damaging, effects for the global community."[79] He argues that this homology favors developing "an international regime for geoengineering that requires parties to control geoengineering activities within their jurisdiction, and that clarifies which states have jurisdiction over activities outside of national territory."[80]

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[73] *See* Weitzman, *supra* note 14, at 1050.

[74] *See id.*

[75] Joshua B. Horton, *Geoengineering and the Myth of Unilateralism: Pressures and Prospects for International Cooperation*, 4 STAN. J.L. SCI. & POL'Y 56, 59 (2011).

[76] Parson & Ernst, *supra* note 70, at 332–33.

[77] *Id.* at 330.

[78] David G. Victor, M. Granger Morgan, Jay Apt, John Steinbruner & Katharine Ricke, *The Geoengineering Option*, FOREIGN AFFS., Mar.–Apr. 2009, at 64, 72.

[79] DANIEL BODANSKY, GOVERNING CLIMATE ENGINEERING: SCENARIOS FOR ANALYSIS 25 (2011) (discussion paper for the Harvard Project on Climate Agreements).

[80] *Id.* at 26.

Another central theme that emerges is the claim that solar radiation management, in addition to being cheap, is also "fast" and "imperfect."[81] Solar radiation management is said to be fast because, once deployed, it results in a much more rapid reduction in temperature compared to emissions abatement or carbon removal—on the order of months to a year compared to decades for carbon removal.[82] Solar radiation management is said to be imperfect because it produces a different mix of climate effects than changes in atmospheric GHG concentrations, such that it is impossible to use the latter to exactly offset the former.[83] This "imperfection" of solar radiation management is examined in greater detail in Section III.A.

Because we have less experience with large-scale solar radiation management than with GHG emissions, the effects of solar radiation management are also more uncertain.[84] The fast-acting and temporary nature of some forms of solar radiation management has also generated concern about the potential for "termination shock," rapid warming that would occur if solar radiation management were suddenly halted.[85] These concerns have led some scholars to characterize solar radiation management as "dangerous" rather than merely "imperfect."[86] Fast, cheap, and imperfect/dangerous solar radiation management is sometimes contrasted with carbon removal, which is said to be "slow and expensive, yet effective."[87] For similar reasons, David Keith, a prominent solar radiation management researcher, declares that he is "proud to commercialize direct air capture" while he opposes any commercial work on solar radiation management and objects to lumping the two types of interventions together under the common label of geoengineering.[88]

The third significant strain within the first approach to geoengineering governance scholarship is concern about the so-called moral hazard problem. This

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[81] David W. Keith, Edward Parson & M. Granger Morgan, *Research on Global Sun Block Needed Now*, NATURE, Jan. 27, 2010, at 426, 426.

[82] *Id.*

[83] *Id.*

[84] Martha Fitzgerald, *Prison or Precaution: Unilateral, State-Mandated Geoengineering Under Principles of International Environmental Law*, 24 N.Y.U. ENV'T L.J. 256, 262 (2016).

[85] *Id.* at 265.

[86] *Id.* at 263.

[87] *Id.* at 265.

[88] Keith, *Opposing Commercial Solar*, *supra* note 13.

issue is addressed in detail in Section IV.C under the more precise label of risk compensation. The basic worry is that perceived availability of a cheap and easy solution to climate change will undermine the already inadequate political impetus supporting decarbonization.[89] While scholars disagree about both the magnitude of the moral hazard problem and the appropriate response to it, it is widely recognized as an issue worth taking seriously.[90] This problem is most acute for potential high-leverage interventions like stratospheric aerosol injection, but some scholars also worry that negative emissions technologies like direct air capture could induce a similar effect, licensing policymakers to believe they can defer costly actions to reduce emissions because technology will allow us to suck the carbon back out of the atmosphere.[91]

B. *Existing International Legal Instruments Applicable to Geoengineering*

Scholars have identified several treaties, principles, and customary rules of international law that potentially bear on geoengineering. These include the Convention on Biological Diversity ("CBD"), the 1996 Protocol of the London Dumping Convention, the Vienna Convention for the Protection of the Ozone Layer (including its better known Montreal Protocol), the Convention on Long-Range Transboundary Air Pollution, the United Nations Framework Convention on Climate Change ("UNFCCC"), the United Nations Convention on the Law of the Sea, the Environmental Modification Convention, the principle of Prevention of Transboundary Harm, the precautionary principle/approach, and the practice of environmental impact assessment.

Scholars disagree regarding the capacity of these existing legal instruments to meaningfully constrain geoengineering research and deployment. Parson and Ernst claim that "the early literature on [geoengineering] governance has established that no current international law constrains or regulates the specific activities that might be contemplated in [geoengineering] field research or potential future deployment."[92] They argue that no proposed geoengineering measures would necessarily violate the terms of UNFCCC, the Montreal Protocol, or the Convention

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[89] Albert C. Lin, *Does Geoengineering Present a Moral Hazard?*, 40 ECOLOGY L.Q. 673, 685 (2013).

[90] Keith et al., *supra* note 81, at 427; Lloyd & Oppenheimer, *supra* note 14, at 52; Gernot Wagner & Christine Merk, *Moral Hazard and Solar Geoengineering*, *in* GOVERNANCE OF THE DEPLOYMENT OF SOLAR GEOENGINEERING 135, 137 (2019).

[91] Kevin Anderson & Glen Peters, *The Trouble with Negative Emissions*, 354 SCI. 182, 182–83 (2016).

[92] Parson & Ernst, *supra* note 70, at 320.

on Long-Range Transboundary Air Pollution. Parson and Ernst also point out that the Environmental Modification Convention only restricts interventions undertaken for military or other hostile purposes, and that the CBD decision discouraging geoengineering lacks legal force due to the advisory nature of the language used and the non-binding nature of all CBD decisions.[93] Finally, they assert that obligations for environmental protection under the United Nations Convention on the Law of the Sea and customary international law principles "are so broad and vague that they provide at most a normative background to inform states' negotiation of specific obligations or constraints rather than representing existing obligations."[94]

Conversely, Tuomas Kuokkanen and Yulia Yamineva argue that "it appears that there are no compelling reasons at this stage to start elaborating new rules. Indeed, existing general international law and environmental treaties appear to be sufficient to deal with geoengineering issues."[95] They maintain that customary rules of international law do meaningfully apply to geoengineering. In particular, they point to states' duty to prevent transboundary pollution and to conduct an environmental impact assessment for all large-scale projects, and they express confidence that international dispute bodies would enforce these principles.[96] Ralph Bodle agrees that the duty to prevent transboundary harm applies to geoengineering, but worries that states will find it difficult to attribute any harm they may suffer to another state's particular geoengineering acts.[97] David Reichwein and his coauthors offer a detailed examination of state responsibility under customary rules of international law for potential harms caused by stratospheric aerosol injection.[98] Echoing Bodle, they point out that the claimant state would bear the burden of demonstrating a causal link between the stratospheric aerosol injection deployment and any environmental harm under the applicable evidentiary standard.[99] They also

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[93] *Id.* at 322. Ralph Bodle also makes the same point about the Environmental Modification Convention. *See* Ralph Bodle, *Geoengineering and International Law: The Search for Common Legal Ground*, 46 TULSA L. REV. 305, 313 (2010).

[94] Parson & Ernst, *supra* note 70, at 322.

[95] Tuomas Kuokkanen & Yulia Yamineva, *Regulating Geoengineering in International Environmental Law*, 7 CARBON & CLIMATE L. REV. 161, 165 (2013).

[96] *Id.* at 162.

[97] Bodle, *supra* note 93, at 311.

[98] *See* David Reichwein, Anna-Maria Hubert, Peter J. Irvine, Francois Benduhn & Mark G. Lawrence, *State Responsibility for Environmental Harm from Climate Engineering*, 5 CLIMATE L. 142 (2015).

[99] *Id.* at 153.

point to ICJ jurisprudence holding that the precautionary principle "may serve to lower the standard of proof to avoid all-or-nothing verdicts" in cases where serious or irreversible damage is threatened.[100] Bodle is more circumspect about the implications of the precautionary principle for geoengineering, pointing out that geoengineering *proponents* could just as easily rely on it to justify geoengineering deployment to prevent serious or irreversible harms from unabated climate change.[101] In this sense, risky geoengineering epitomizes Cass Sunstein's argument that the precautionary principle fails to offer meaningful guidance, particularly in contexts that involve risk-risk tradeoffs.[102]

Reichwein and his coauthors also question the appropriate remedy should an act of stratospheric aerosol injection be found wrongful.[103] Ordinarily, the responsible state would be obligated to cease the wrongful act, make appropriate assurances and guarantees of non-repetition, and make reparation for any injury caused.[104] But sudden cessation of stratospheric aerosol injections could result in rapid warming (see Section IV.A on termination shock for a detailed examination of this issue) that could result in harms greater than those resulting from the initial deployment.[105]

Kuokkanen and Yamineva also maintain that the Convention on Long-range Transboundary Air Pollution and its protocols dealing with sulphur emissions would apply to stratospheric aerosol injection and that the Vienna Convention and Montreal Protocol would govern any interventions that might impact the ozone layer.[106] Daniel Bodansky agrees that the Montreal Protocol would be relevant to stratospheric aerosol injection, but views it as "a likely forum for discussions" rather than a source of extant binding law.[107] Kuokkanen and Yamineva also point to the 1996 Protocol of the London Dumping Convention and the 2010 CBD as potential sources of specific rules governing ocean fertilization (addressed specifically in the Protocol) and other geoengineering interventions, but recognize that they do not amount to a

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[100] *Id.* at 166.

[101] Bodle, *supra* note 93, at 311.

[102] *See generally* Cass R. Sunstein, *Beyond the Precautionary Principle*, 151 U. PA. L. REV. 1003 (2003).

[103] Reichwein et al., *supra* note 98, at 151.

[104] *Id.*

[105] *Id.* at 150.

[106] Kuokkanen & Yamineva, *supra* note 95, at 162.

[107] BODANSKY, *supra* note 79.

complete governance framework.[108] The consensus opinion in the literature appears to be closer to Parson and Ernst's view than Kuokkanen and Yamineva's. While there is a plausible case that the existing instruments of international law may have a more practical effect on geoengineering research and deployment than Parson and Ernst suggest, the case that the existing body of international law is "sufficient to deal with geoengineering" issues is fairly weak.

C. Procedural and Substantive Geoengineering Governance Design Features

There is also significant disagreement regarding the best forum, structure, and content of geoengineering governance. Albert Lin argues that geoengineering governance should be addressed within the structure of the UNFCCC.[109] In making his case, Lin emphasizes the UNFCCC's broad mission to "protect the climate system," and the fact that it already has an established forum (the Conference of the Parties) and technical bodies like the IPCC and the Subsidiary Body for Scientific and Technological Advice to draw on.[110] Lin also emphasizes the UNFCCC's universal membership and perceived legitimacy as key selling points.[111] He concludes that, "[g]iven the potential substitutability of geoengineering projects for emissions reductions, it makes no sense to develop an entirely separate international regime to address geoengineering."[112]

Ian Lloyd and Michael Oppenheimer, by contrast, stress the importance of limiting membership to ensure the effectiveness of any geoengineering governance regime.[113] Specifically, they propose that membership be limited at the outset to countries that are both likely to suffer severe impacts from climate change by 2050 and have the economic and technical capacity to deploy solar radiation management

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[108] Kuokkanen & Yamineva, *supra* note 95, at 162–63.

[109] Albert C. Lin, *Geoengineering Governance*, 8 ISSUES IN LEGAL SCHOLARSHIP 1, 18 (2009).

[110] *Id.* at 18–19.

[111] Albert Lin, *The Relevance of the Climate Change Regime to Governance of Solar Geoengineering*, *in* GOVERNANCE OF THE DEPLOYMENT OF SOLAR GEOENGINEERING 125 (2019). Choosing the UNFCCC as the primary forum for geoengineering would entail all the benefits and burdens of an organization with 197 member states. *See What is the United Nations Framework Convention on Climate Change?*, UNITED NATIONS CLIMATE CHANGE, https://unfccc.int/process-and-meetings/the-convention/what-is-the-united-nations-framework-convention-on-climate-change [https://perma.cc/YEE6-ME5Q].

[112] Lin, *supra* note 111, at 19.

[113] Lloyd & Oppenheimer, *supra* note 14, at 47.

at scale.[114] While Lloyd and Oppenheimer recognize that the eventual inclusion of states that are highly vulnerable to climate change but not capable of solar radiation management might be necessary to maintain legitimacy, they emphasize that smaller groups have less preference divergence and are more likely to achieve collective goals.[115] They also explicitly warn against subsuming geoengineering governance under existing global climate or environmental negotiating processes, which they worry would exacerbate the moral hazard problem.[116] Lloyd and Oppenheimer instead favor a new governing body with weak legalization designed to encourage participation.[117] While they acknowledge that stronger legalization and enforcement mechanisms would make the regime more effective, they worry that premature legalization would endanger its political viability.[118] The initial substantive goals of Lloyd and Oppenheimer's regime would be a temporary moratorium on deployment of solar radiation management and cooperation on research.[119] Parson and Ernst implicitly critique this set of objectives by claiming that, given the need for large-scale field experiments, there is no sharp distinction between research and deployment.[120]

David Victor also cautions against premature legalization, but for different reasons than Lloyd and Oppenheimer.[121] He predicts that although most countries would favor a ban on geoengineering, some would want to retain the option, producing deadlock.[122] Victor also warns that "most treaties on geoengineering will be useless or actively harmful because, at present, experts and governments do not know enough about the scope and hazards of possible geoengineering activities to frame a meaningful treaty negotiation."[123] However, he argues that an informal taboo

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[114] *Id.* at 52–54.

[115] *Id.* at 47.

[116] *Id.* at 56.

[117] *Id.*

[118] *Id.* at 55–56.

[119] *Id.* at 47.

[120] Parson & Ernst, *supra* note 70, at 326.

[121] DAVID G. VICTOR, GLOBAL WARMING GRIDLOCK: CREATING MORE EFFECTIVE STRATEGIES FOR PROTECTING THE PLANET 194 (2011) [hereinafter VICTOR, GLOBAL WARMING GRIDLOCK].

[122] *Id.*

[123] Victor, *Geoengineering Regulation*, *supra* note 14, at 325.

against geoengineering would be even worse.[124] A taboo, Victor warns, is likely to constrain cautious and responsible countries the most, leaving less responsible countries and individuals free to determine the manner and timing of any geoengineering deployments.[125] Ultimately, Victor favors a bottom-up approach, featuring "an active geoengineering research programme, possibly including trial deployments, that is highly transparent and engages a wide range of countries that might have (or seek) geoengineering capabilities. That approach would be designed to explore the safest and most effective options while also socializing a community of responsible geoengineers."[126] Despite their joint reticence regarding a highly legalized approach, Victor's prescription thus diverges from that of Lloyd and Oppenheimer in both structure and content, favoring broad participation and no moratorium or taboo against deployment.[127] Victor also rejects Lin's endorsement of the UNFCCC as the forum for geoengineering governance, arguing that uncertainties and gaps in our understanding about geoengineering render it "particularly ill-suited to the consensus-oriented IPCC process."[128]

Parson and Ernst similarly reject the notion that there will be "a clear boundary between an early period of 'scientific' [geoengineering] governance and some later period of 'operational' governance."[129] Instead, they expect geoengineering intervention decisions to depend on uncertain scientific judgments that are likely to be increasingly influenced by national and regional interests as the severity of both climate impacts and the scale of proposed interventions increase.[130] Parson and Ernst entertain the notion that geoengineering governance needs warrant the "development of the functional equivalent of a global state."[131] But they ultimately reject this

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[124] *Id.*

[125] *Id.*

[126] *Id.*

[127] *Id.*

[128] *Id.*

[129] Parson & Ernst, *supra* note 70, at 329. Lin acknowledges the fuzziness of the distinction between geoengineering research and governance but nonetheless favors a distinct regime for governance of geoengineering research on the grounds that deployment governance may distract from the important issues in governance and grouping the two together may lead policymakers to downgrade their assessment of importance of geoengineering governance. Albert C. Lin, *The Missing Pieces of Geoengineering Research Governance*, 100 MINN. L. REV. 2509, 2516 (2016).

[130] Parson & Ernst, *supra* note 70, at 329.

[131] *Id.* at 331.

conclusion, arguing that the most high-stakes and potentially divisive questions can be safely deferred until "advances in scientific understanding, or in perceived risks and interests in climate change, may make them less fraught than the starkest current speculation suggests."[132] Finally, Parson and Ernst suggest that there may be an opportunity for constructive linkage between governance of geoengineering and conventional mitigation.[133] In this regard, they share some common ground with Lin, though they do not explicitly endorse the UNFCCC as the proper forum for geoengineering governance.[134] Parson and Ernst also share Lloyd and Oppenheimer's caution with regard to premature legalization, but break with them in rejecting a moratorium on deployment as a substantive goal. Although there are some differences in emphasis, Parson and Ernst's prescriptions are broadly aligned with Victor's. Finally, it is worth noting that Parson takes up the topic of linkage more fully in later solo work; his linkage ideas are discussed in Section IV(E).

Kuokkanen and Yamineva share other scholars' skepticism regarding a new treaty on geoengineering. They note the difficulties likely to be encountered in reaching an agreement and caution that "commencing negotiations on a treaty on geoengineering would be unwise at the time when the negotiations under the UNFCCC are undergoing a critical stage of developing a future mitigation and adaptation framework."[135] This runs counter to Parson and Ernst's relative optimism regarding the potential for constructive engagement between geoengineering governance and mitigation. Kuokkanen and Yamineva worry about filling the gaps and addressing the fragmented nature of the existing corpus of international law applicable to geoengineering.[136] To address this concern, they advise greater coordination between bodies like the London Protocol and Convention, the CBD, and the UNFCCC.[137] Kuokkanen and Yamineva also endorse the ongoing strengthening of the United Nations Environment Program, suggesting it could coordinate international policy discussion and technical work on geoengineering.[138] They align with Lin in their desire to work through existing institutions, but break

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[132] *Id.*

[133] *Id.* at 335.

[134] *Id.*

[135] Kuokkanen & Yamineva, *supra* note 95, at 165.

[136] *Id.*

[137] *Id.*

[138] *Id.* at 166.

with him in rejecting the UNFCCC as the primary forum for geoengineering governance. They diverge more sharply from Lloyd and Oppenheimer in endorsing both a highly legalized approach to geoengineering governance and working through existing structures with near-universal representation. Kuokkanen and Yamineva also differ from Victor in their support for formalization but align with him in their joint skepticism regarding an early move to a comprehensive treaty. Finally, their divergence from Parson and Ernst mostly stems from their prior disagreement regarding the practical efficacy of existing legal instruments.

Weitzman, building on his free-driver externality formulation, proposes a voting rule for resolving interstate disagreements over the desirability of geoengineering deployment.[139] He assumes that the risks associated with geoengineering are asymmetric, such that the costs of over-deployment significantly exceed the costs of under-deployment.[140] He "somewhat arbitrarily" proposes that overdoing geoengineering is three times as bad as underdoing it, but the formalism he presents could be applied to any chosen ratio.[141] Under a stylized set of assumptions, including that counter-geoengineering is prohibitively difficult, he shows that this corresponds to a voting system that requires a three-fourths majority to initiate or increase geoengineering deployment.[142] Weitzman further specifies that this vote would be taken in a sort of global legislative general assembly, in which each country would have voting weight proportional to its population.[143] He also suggests that there should be an executive branch empowered to carry out decisions of the general assembly and assess penalties for noncompliance, as well as a judicial body to adjudicate conflicts.[144] This proposal diverges from Lin in rejecting the consensus-oriented UNFCCC; from Lloyd and Oppenheimer in favoring universal membership and a highly legalized structure; and from Victor, Parson and Ernst in favoring a top-down, prescriptive regime that is biased against deployment. It also runs counter to Kuokkanen and Yamineva's desire to work through existing institutions that do not operate under this sort of framework. Weitzman does not examine whether agreement to join and abide by such a governance regime is plausible given the existing incentive structure and distribution of power and interests.

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[139] Weitzman, *supra* note 14, 1049.

[140] *Id.* at 1055.

[141] *Id.* at 1065.

[142] *Id.*

[143] *Id.*

[144] *Id.*

D. Synthesis and Gaps

This Article seeks to address three interrelated shortcomings of this literature. First, and most importantly, the existing literature mostly treats geoengineering as an analytically distinct category that can be cleanly separated from conventional mitigation. Second, except for Parson and Ernst, scholars have downplayed the potential for constructive linkage between the governance of geoengineering and conventional mitigation. Finally, the existing literature has highlighted the complications introduced by attempting to negotiate rules for geoengineering from within a fog of scientific uncertainty, but has neglected the possibility that this provides an opportunity for states with potentially divergent interests to reach agreement on neutral principles for resolving disputes while they are still behind a partial veil of ignorance with regard to their precise interests.[145]

Accounting for these three blind spots in the literature would militate in favor of a more integrated climate governance regime that acts early to settle on a framework for governance of high-leverage solar radiation management deployment. If, as I will show in Part III, there is no clean separation between geoengineering and mitigation, this clearly strengthens the case for an integrated framework. Likewise, if control over decisions regarding eventual multilateral deployment of high-leverage solar radiation management can be leveraged to support decarbonization in the interim, it makes sense to start using that leverage as soon as possible by quickly getting the basic unified climate governance framework in place. Finally, if the fog of scientific uncertainty also serves as a partial veil of ignorance obscuring states' assessment of their own interests, this also favors early action to secure agreement on neutral principles of geoengineering governance.[146] The existing siloed approach to geoengineering is a barrier to timely action to build a governance framework for deployment of risky, high-leverage climate intervention that can also promote cooperation on decarbonization.

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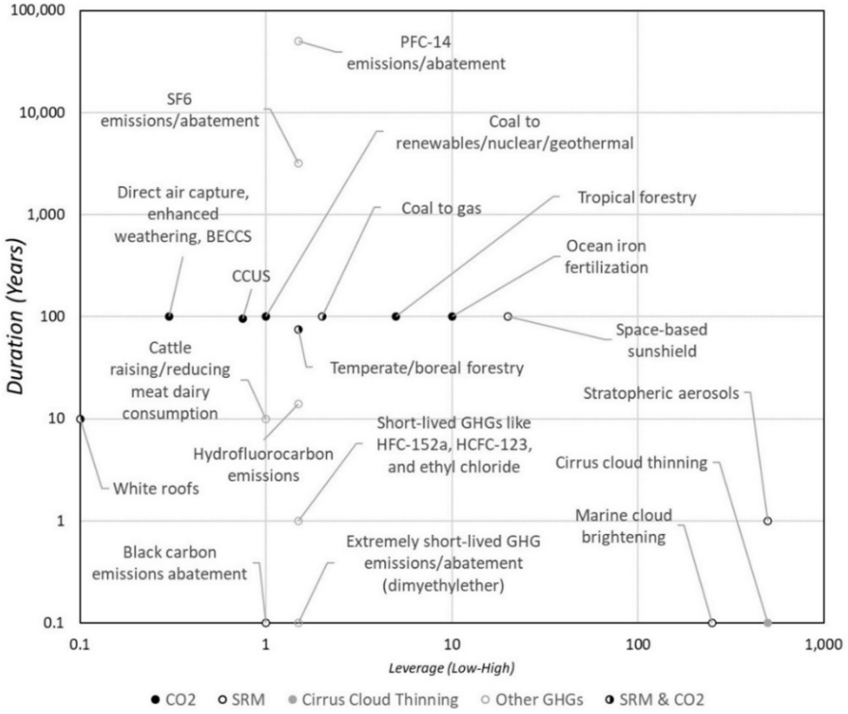
[145] Daniel Heyen does argue that uncertainty about geoengineering risks "may be helpful in a multi-agent world, both because it increases incentives for cooperation and because it increases incentives for cooperation and because it may discourage free-driver behavior." Daniel Heyen, *Risk Governance and the Strategic Role of Uncertainty*, *in* HARV. PROJECT ON CLIMATE AGREEMENTS: GOVERNANCE OF THE DEPLOYMENT OF SOLAR GEOENGINEERING 91, 91 (Feb. 2019), https://geoengineering.environment.harvard.edu/files/sgrp/files/harvard_project_sg_governance_briefs_volume_feb_2019.pdf [https://perma.cc/DD8Q-RK4P]. But this is an argument for maintaining scientific uncertainty, not for early action to lock in neutral principles while engaging in research to reduce that uncertainty.

[146] *See generally* JOHN RAWLS, A THEORY OF JUSTICE (Otfried Höffe ed., Joost den Haan trans., 1971).

III. THE THREE DIMENSIONS

Climate interferences vary along three dimensions. First, they operate via different mechanisms; most interferences rely primarily on altering atmospheric GHG concentrations or changing the reflectiveness of the earth's surface or atmosphere. Second, they vary in duration over several orders of magnitude. Finally, some interferences offer higher leverage, meaning both the maximum climate impact is large compared to the resources required to deploy it and the associated risks and uncertainties are magnified.[147] Figure 1 below shows how different interferences vary independently along all these dimensions:

Figure 1: Climate Interferences' Locations Along Three Key Dimensions



This scatterplot is intended as a qualitative visualization of the way climate interferences vary along each of three independent dimensions. There is significant uncertainty regarding the leverage and duration of several of these interferences, so the specific point estimates should not be interpreted as indicating confidence in any precise value. Some interferences, like fuel switching from coal to gas, operate on multiple timescales. Leverage estimates are based on an estimate of the cost of producing a given amount of total radiative forcing over time, normalized to the

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[147] Parson & Ernst, *supra* note 70, at 313.

leverage of marginal CO_2 emissions abatement interventions. This does not account for other aspects of leverage, including geographic scope and collateral risks, costs, and benefits. These aspects are addressed for each interference in Section III.C.

The following sections analyze each of these dimensions in turn, showing where different interferences fall along each dimension and how this should inform governance.

A. Dimension One: Mechanism of Climate Forcing

GHGs trap infrared radiation emitted from the earth, reducing the flow of heat from the earth into space.[148] GHG emissions abatement and CO_2 removal interventions both operate by reducing the atmospheric concentration of GHGs (relative to some counterfactual, not necessarily in absolute terms), allowing more heat to escape the earth's atmosphere.[149] The solar radiation management interventions typically discussed in the geoengineering context reduce the quantity of solar radiation that reaches the earth's surface, either by blocking it in outer space (space-based sunshield), reflecting it in the stratosphere (stratospheric aerosol injection), or reflecting it in other parts of the atmosphere (marine cloud brightening).[150] Net solar radiative flux can also be managed via changes in the earth's surface albedo, the proportion of the incident light or radiation that is reflected by the earth's surface.[151] Just as a black shirt of the same material will tend to heat up more than a white shirt on a sunny summer day, darker parts of the earth's surface absorb more solar radiation.[152] Some changes in the earth's surface albedo, like the melting of white arctic ice caps giving way to dark ocean waters, act as positive feedback accelerating the effects of other warming interferences.[153] But humans can also act directly to change the albedo through changes in land use or by placing reflective particles on the earth's surface.[154]

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[148] THE ROYAL SOC'Y, *supra* note 10, at 3.

[149] *Id.* at 1.

[150] *Id.*

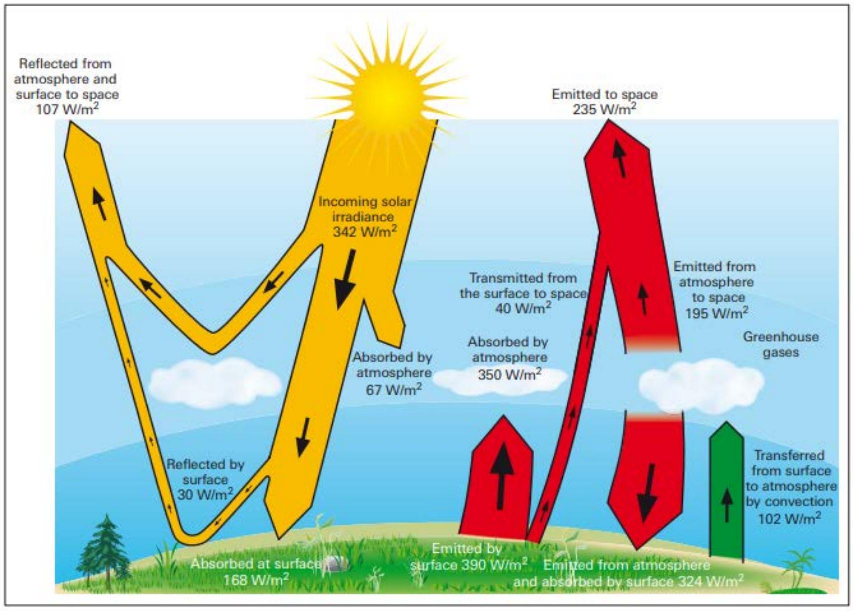
[151] *Id.* at 23.

[152] *Id.* at 24.

[153] *Id.*

[154] *Id.* at 25.

Figure 2: Earth's Energy Balance



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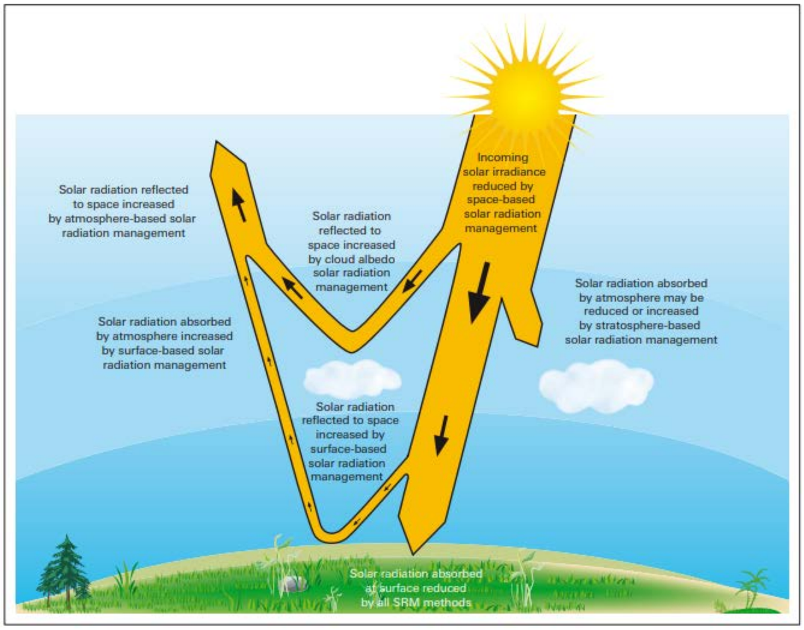
[155] *Id.* at 2. Watts per square meter is a measure or irradiance/radiative forcing, the flux of energy per unit of surface area. For reference, a doubling of atmospheric is estimated by the IPCC to cause a radiative forcing of 3.7 watts per square meter. Gunnar Myhre, Catherine Lund Myhre, Piers M. Forster & Keith P. Shine, *Halfway to Doubling of CO_2 Radiative Forcing*, NATURE GEOSCIENCE 710, 710 (2017).

Figure 3: Adding Solar Radiation Management to the Mix



[156]

Some interferences, like white roofs, operate through both the solar radiation management and GHG channels, the latter via reduced demand for cooling services.[157] Other interferences, like afforestation, forest preservation, and deforestation, can have opposing effects in the solar radiation management and GHG channels.[158] Preserving or planting boreal and temperate forests can decrease the earth's albedo, amounting to a negative (warming-inducing) solar radiation management interference, in addition to the intended (cooling-inducing) GHG interference.[159] Others, like cirrus cloud thinning, do not fit neatly into either category.

There are three key differences between atmospheric GHG concentration interferences and solar radiation management interferences of relevance to global

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[156] THE ROYAL SOC'Y, *supra* note 10, at 23.

[157] *Id.* at 25.

[158] Bala et al., *supra* note 32.

[159] *Id.*

governance. First, solar radiation management interferences do not directly address ocean acidification, whereas interferences that reduce the atmospheric concentration of CO_2 would mitigate ocean acidification in tandem with reducing expected warming.[160] Even if solar radiation management interferences otherwise mimicked GHG interferences, this would be a significant shortcoming that would militate against treating solar radiation management interferences as favorably as CO_2 interferences per unit of radiative forcing. Those who are particularly concerned with ocean acidification, moreover, may worry that the potential to reduce global temperatures and extreme weather events with solar radiation management may dampen incentives for decarbonization and thereby exacerbate ocean acidification. However, it is possible that other non-CO_2 interferences could somewhat ameliorate the ocean acidification problem.[161] Note also that this first feature of solar radiation management interferences is shared by abatement or removal of GHGs other than CO_2 and by cirrus cloud thinning. To the extent that the objection to solar radiation management is its failure to address ocean acidification, we should be equally concerned about strategies that emphasize abatement of GHGs like methane, nitrous oxide, and fluorinated gases.

Second, solar radiation management would imperfectly counteract atmospheric GHG-driven climate change. Depending on the precise pattern of deployment, the effects on precipitation and temperature are likely to be somewhat uneven.[162] Solar radiation management tends to cool the tropics more than the poles, such that the tropics may have to be cooled below pre-industrial temperatures to stop the melting of polar ice sheets.[163] Solar radiation management is also more effective at reducing

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[160] NAT'L RSCH. COUNCIL, CLIMATE INTERVENTION: REFLECTING SUNLIGHT TO COOL EARTH 41 (2015). *But see* David W. Keith, Gernot Wagner & Claire L. Zabel, *Solar Geoengineering Reduces Atmospheric Carbon Burden*, NATURE CLIMATE CHANGE, at 617, 617 (2017) ("Solar geoengineering reduces the carbon burden, and therefore ocean acidification, due to the three pathways explored here: carbon-cycle feedback, reduced permafrost melting, and reduced energy-sector emissions.") (endnotes omitted).

[161] VICTOR, GLOBAL WARMING GRIDLOCK, *supra* note 121, at 184.

[162] Jesse L. Reynolds & Joshua B. Horton, *An Earth System Governance Perspective on Solar Geoengineering*, EARTH SYS. GOVERNANCE, Mar. 2020, at 2.

[163] Nicholas J. Lutsko, Jacob T. Seeley & David W. Keith, *Estimating Impacts and Trade-Offs in Solar Geoengineering Scenarios with a Moist Energy Balance Model*, 47 GEOPHYSICAL RSCH. LETTERS, Apr.–May 2020, https://keith.seas.harvard.edu/files/tkg/files/2020_may_lutsko-seeley-keith.pdf [https://perma.cc/US7H-82WT]. *But see* Simone Tilmes et al., *CESM1(WACCM) Stratospheric Aerosol Geoengineering Large Ensemble Project*, 99 BULL. AM. METEOROLOGICAL. SOC'Y 2361 (2018) (suggesting that strategic injection at multiple sites could greatly reduce the unevenness of induced cooling).

anthropogenic precipitation anomalies than temperature.[164] This means that, for a given temperature target, solar radiation management interventions are expected to lead to a drier world than GHG interventions or cirrus cloud thinning. The environmental, economic, and social consequences of each class of intervention will vary significantly across regions. While both GHG interventions and solar radiation management interventions produce winners and losers, the tradeoff between precipitation and temperature inherent in solar radiation management interventions may heighten these discrepancies and increase the scope for conflict.[165] At the very least, we can be confident that there is unlikely to be a consensus on either the optimal temperature to target using solar radiation management or the optimal mix between solar radiation management and GHG interventions. However, given the substantial and geographically uneven extraterritorial costs imposed by countries that emit GHGs (i.e., all countries), it is not clear that the unequal effects of solar radiation management present a novel governance challenge.

Third, solar radiation management interferences, once implemented, would produce changes in global temperatures much faster than GHG interferences.[166] GHG interferences increase or decrease the rate at which GHGs are emitted or removed from the atmosphere.[167] But the radiative forcing produced by GHGs is dependent on the stock of GHGs in the atmosphere—the result of cumulative GHG emissions and removals over the full history of the earth's atmosphere.[168] Unlike other pollution, such as acid rain precursors, dramatically reducing emissions of CO_2—the most important GHG—has little short-term effect on its atmospheric

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[164] David Keith, Daniel Raimi & Elizabeth Wason, *Reflecting on Solar Geoengineering, with David Keith*, RES. RADIO (May 12, 2020), https://www.resourcesmag.org/resources-radio/reflecting-solar-geoengineering-david-keith/ [https://perma.cc/96BA-4HJA].

[165] *See* Douglas G. MacMartin, Peter J. Irvine, Ben Kravitz & Joshua B. Horton, *Technical Characteristics of a Solar Geoengineering Deployment and Implications for Governance*, 19 CLIMATE POL'Y 1325 (2019). *But see* Jesse L. Reynolds, Andy Parker & Peter Irvine, *Five Solar Geoengineering Tropes That Have Outstayed Their Welcome*, 4 EARTH'S FUTURE 562, 565 (2016) (arguing that only very large-scale solar radiation managements deployments would results in net reductions in precipitation compared to a low-GHG baseline).

[166] THE ROYAL SOC'Y, *supra* note 10, at x.

[167] Diego Villarreal, *Understanding GHG Emissions: Stock vs. Flows*, COLUM. CLIMATE SCH.: STATE OF THE PLANET (July 18, 2011), https://news.climate.columbia.edu/2011/07/18/understanding-ghg-emissions-stock-vs-flows/ [https://perma.cc/3W5H-BDX3].

[168] *Id.*

concentration of CO_2.[169] Changes in the flow of GHGs take decades to significantly alter atmospheric GHG concentrations.[170]

Solar radiation management interferences, by contrast, can realize their full effect on radiative forcing relatively soon after implementation. It does take as long as a few years for the climate system to fully adjust to a sudden change in radiative forcing and settle at a new temperature equilibrium, but this is much faster than the decades that sustained GHG interferences take to realize their full effects.[171] This relative timeliness of solar radiation management interferences should not be confused with the duration dimension discussed in the next section, which measures how long an interference lasts once it has taken effect.

This difference has two important implications for governance. First, solar radiation management interferences—particularly high-leverage and quickly deployable solar radiation management interventions like stratospheric aerosol injection—have the potential to stave off climate emergencies and provide near-term relief.[172] This capacity could enable humanity to prevent the climate system from passing through potential tipping points that could lead to runaway warming or other catastrophic outcomes. It could also provide relief from existing or imminent climate-related hardships on a timescale that is meaningful to individual humans—e.g., by shaving the peak off warming in a scenario where we overshoot the global temperature stabilization target. If a strong global governance framework were to take these options off the table, this would greatly limit human capacity to cope with certain forms of climate risk. Second, the relative immediacy of solar radiation management may make it more tempting for some countries to deploy in a manner that could foreseeably benefit them at the expense of other countries. This is a particular concern with forms of solar radiation management that generate a localized change in albedo (see Section III.C.2 for more on this point).

A fourth difference that is often claimed between solar radiation management and GHG interferences is leverage. That is, it is sometimes said that solar radiation management is cheap enough to do at such a scale that one country or even a rich

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[169] THE ROYAL SOC'Y, *supra* note 10, at x.

[170] *Id.*

[171] *Id.*

[172] Simon Nicholson, *Solar Radiation Management*, WILSON CTR. (Sept. 30, 2020), https://www.wilsoncenter.org/article/solar-radiation-management [https://perma.cc/LB4C-QMQP].

individual could substantially alter the earth's climate.[173] While the merits of this claim are questionable with regard to any solar radiation management interferences, what is clear is that it is not an inherent feature of solar radiation management. A space-based sunshield, for instance, is likely to be an exceedingly expensive undertaking, and localized forms of solar radiation management like marine cloud brightening and surface albedo enhancement may be affordable but are limited in their leverage over the entire earth's climate.[174] Stratospheric aerosol injection, not the solar radiation management category in general, is what offers greater leverage and lower cost to implement than cooling GHG interventions.[175] Also, *warming* GHG interferences (i.e., GHG emissions) are also quite cheap and are still not subject to meaningful restrictions under international law. Accordingly, leverage is a distinct dimension from the mechanism of climate forcing. Likewise, while it is sometimes claimed that solar radiation management interferences are impermanent, in contrast to the permanent effects of avoided emissions, neither claim captures the full truth. While the duration of interferences is indeed an important consideration, both solar radiation management and GHG interferences span a large and overlapping range of durations, which we will consider in the following section.

B. Dimension Two: Duration

The timescale of potential climate interferences ranges from a few days to thousands of years.[176] As used here, timescale refers to the length of time during which an interference has a direct impact on temperatures. This is distinct from latency/timeliness, which refers to the delay between implementation of an interference and the realization of its impact on temperatures. Typically, the direct effect of a climate interference can be summarized in terms of its radiative forcing over time.[177] These direct effects do not include feedback effects, through which even short duration climate interferences can produce semi-permanent changes in

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[173] Barrett, *supra* note 71.

[174] *See* THE ROYAL SOC'Y, *supra* note 10.

[175] *Id.*

[176] The atmospheric lifetimes of GHGs range from 0.015 years (dimethylether) to 50,000 years (PFC-14). Curt Hull, *GHG Lifetimes and GWPs: For Ozone-Depleting Substances and Their Replacements*, CLIMATE CHANGE CONNECTION (Aug. 7, 2009), https://climatechangeconnection.org/wp-content/uploads/2014/08/GWP_AR4.pdf [https://perma.cc/7JZ3-XDFA].

[177] *Climate Change Indicators: Climate Forcing*, EPA, https://www.epa.gov/climate-indicators/climate-change-indicators-climate-forcing [https://perma.cc/3R6C-XXP2].

the climate, since such feedback is variable and largely independent of the nature of the initial interference.[178]

Ultra-short duration interferences, on the order of days to weeks, include marine cloud brightening, cirrus cloud thinning, and emissions of extremely short-lived GHGs like dimethyl ether.[179] Short duration climate interferences, on the order of one year, include stratospheric aerosol injection, and emissions of short-lived GHGs like HFC-152a, HCFC-123, and ethyl chloride.[180] Medium duration interferences, on the order of ten years, include emissions of methane, and temporary creation or preservation of carbon sinks (e.g., preserving a forest for ten years, after which the stored carbon is released).[181] Long duration interferences, on the order of 100 years, include emissions and removal of CO_2 and nitrous oxide, as well as space-based sunshielding (duration is uncertain and depends on precise implementation details).[182] Ultra-long duration interferences, on the order of 1,000–50,000 years include emissions of extremely long-lived GHGs like sulfur hexafluoride (3,200 years) and PFC-14 (50,000 years).[183]

Notably, both GHG interferences and solar radiation management interferences span most of this range. Therefore, to the extent that it is appropriate for governance of climate interferences to distinguish between shorter and longer duration interferences, those distinctions would need to be drawn within each class of interference. Also, it is hard to predict the duration of some interferences. For instance, avoiding carbon emissions via energy conservation leaves accessible fossil resources for future years, which could result in higher future emissions and a much shorter effective duration than the atmospheric lifetime of CO_2. A similar analysis applies to preserved or newly planted forests, which may burn down in a forest fire. Likewise, the duration of direct air capture, BECCS, and CCUS tops out at the

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[178] *Id.*

[179] *See* THE ROYAL SOC'Y, *supra* note 10; Hull, *supra* note 176.

[180] *Id.*

[181] Hull, *supra* note 176.

[182] Scott C. Neubauer & J. Patrick Megonigal, *Moving Beyond Global Warming Potentials to Quantify the Climatic Role of Ecosystems*, 18 ECOSYSTEM 1000 (2015). CO_2 does not have a characteristic lifetime since multiple processes are involved in its removal. *See id.* Instead, 50% of CO_2 emissions are removed from the atmosphere within 37 years, but it takes 500 years for 72% of CO_2 emissions to be removed, and 22% of emissions remain in the atmosphere indefinitely. *See id.*; *see also* THE ROYAL SOC'Y, *supra* note 10, at 33.

[183] Hull, *supra* note 176.

atmospheric lifetime of CO_2 (at which point the CO_2 would have naturally been removed from the atmosphere anyway) but could be lower if there are leaks. Some interferences also act on multiple timescales. For instance, shifting energy generation from coal to natural gas reduces CO_2 emissions (long duration), but increases methane emissions (medium duration).[184]

Duration matters because stabilizing the climate system will require a semi-permanent balance of radiative forcing.[185] Short duration interferences must be continued, repeated, or replaced, or their effects will fade out. Thus, while temporary interferences may produce real benefits, they would have to be continued indefinitely or supplemented with other interferences to serve as part of a long-term stabilization strategy. In the context of stratospheric aerosol injection and some other solar radiation management interventions, this has given rise to concerns over so-called termination shock—that is, rapid warming that could result from sudden termination of a significant short duration solar radiation management intervention.[186] This scenario will be discussed in greater detail in Section IV.A, but for now it is important to note that the theoretical potential for termination shock exists any time a short duration interference is implemented at scale. Solar radiation management interferences do not present a unique termination shock concern. Temporary abatement of short-lived GHGs followed by renewed emissions of them could theoretically produce a similar "termination shock" if done at sufficient scale. To the extent there is a difference between the two scenarios, it lies in the perceived implausibility of quickly restarting emissions of short-lived GHGs after a phase-out and the potential for solar radiation management to operate at a greater scale than phase-out of short-lived GHGs.

How should global governance discriminate between shorter and longer duration interferences? A good place to start would be at the existing procedures of cost-benefit analysis ("CBA"). CBA typically applies a geometric discount rate to the monetized future costs and benefits of an interference, such that each year an

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[184] *See* Stefan Ladage, Martin Blumenberg, Dieter Franke, Andreas Bahr, Rüdiger Lutz & Sandro Schmidt, *On the Climate Benefit of a Coal-to-Gas Shift in Germany's Electric Power Sector*, SCI. REPS. (2021), https://www.nature.com/articles/s41598-021-90839-7 [https://perma.cc/9E4K-VFG6].

[185] *See* A. Sokolov, S. Paltsev, H. Chen, M. Haigh, R. Prinn & E. Monier, *Climate Stabilization at 2˚C and Net Zero Carbon Emissions*, MIT JOINT PROGRAM ON THE SCI. & POL'Y OF GLOBAL CHANGE (2017), https://globalchange.mit.edu/publication/16629 [https://perma.cc/E724-JDA5].

[186] Victor Brovkin, Vladimir Petoukhov, Martin Claussen, Eva Bauer, David Archer & Carlo Jaeger, *Geoengineering Climate by Stratospheric Sulfur Injections: Earth System Vulnerability to Technological Failure*, 92 CLIMATIC CHANGE 243, 248 (2009).

effect is delayed, its value decreases by a percentage known as the discount rate.[187] The U.S. government typically uses discount rates ranging from 3–7%, reflecting individuals' time preference, benefit realization risk, and the opportunity cost of diverting present resources from alternative investments.[188] In my previous articles, I argued that pure time preference is normatively unsustainable as a rationale for discounting.[189] This implies that policy discount rates should be lower, at least for interferences whose costs primarily displace present consumption rather than long-term investment. Other scholars have argued that standard discounting practices are inappropriate for intergenerational problems like climate change.[190] These scholars also tend to favor substantially lower rates.[191]

The methods used for calculating the global warming potential ("GWP") of different GHGs offer a second potential starting point. Unfortunately, these methods are a conceptual muddle. GHGs differ across two relevant dimensions, their atmospheric lifetime, and their instantaneous radiative forcing per unit of mass. These two factors vary independently of one another. To compare the potency of two or more GHGs, these dimensions are typically collapsed into one number. This greatly facilitates monetization of the benefits of emissions abatement. However, standard GWP values are calculated using a rectangular integration of radiative forcing per unit mass over some specified time horizon, usually twenty, fifty, or a hundred years.[192] This means that all years within the integration window are given equal weight, but zero weight is given to years outside that window. This approach

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[187] J.E. de Steiguer, *A Student's Guide to Cost Benefit Analysis for Natural Resources, Lesson 4—The Mechanics of Discounting*, UNIV. OF ARIZ., https://cals.arizona.edu/classes/rnr485/ch4.htm [https://perma.cc/ERD3-F3TY].

[188] OFF. OF MGMT. & BUDGET, EXEC. OFF. OF THE PRESIDENT, CIRCULAR A-4 (2003), https://obamawhitehouse.archives.gov/omb/circulars_a004_a-4/ [https://perma.cc/G2H3-5BZG].

[189] Gabriel Weil, *Individual Preferences in Policy Analysis: A Normative Framework*, 50 TEX. ENV'T L.J. 55, 63 (2020) [hereinafter Weil, *Individual Preferences*].

[190] *See* SIR NICHOLAS STERN, THE ECONOMICS OF CLIMATE CHANGE: THE STERN REVIEW 31–32 (2007), http://mudancasclimaticas.cptec.inpe.br/~rmclima/pdfs/destaques/sternreview_report_complete.pdf [https://perma.cc/U47E-K3R4]; Lawrence H. Goulder & Roberton C. Williams III, *The Choice of Discount Rate for Climate Change Policy Evaluation* (Nat'l Bureau of Econ. Rsch., Working Paper No. 18301, 2012), https://www.nber.org/system/files/working_papers/w18301/w18301.pdf [https://perma.cc/J7ZJ-C4LX]; Thomas Sterner & U. Martin Persson, *An Even Sterner Review: Introducing Relative Prices into the Discounting Debate*, 2 REV. ECON. & POL'Y 61 (2008).

[191] *Id.*

[192] *See* Gabriel Weil, *The Carbon Price Equivalent: A Metric for Comparing Climate Change Mitigation Effort Across Jurisdictions*, 125 DICK. L. REV. 475 (2021).

produces relative weightings of different GHGs that are highly sensitive to the choice of time horizon. In prior work I have also argued that GWP calculations should abandon the rectangular integration approach in favor of a smooth geometric weighting decay modeled on cost-benefit discounting (e.g., effects in each successive year are weighted 3% less than the previous year, moving asymptotically down toward zero weight).[193]

Three other, more extreme, approaches are also possible. On one extreme, governance could focus on stabilizing instantaneous radiative forcing. That is, it could ignore the duration of an interference entirely and focus only on its immediate or peak impact. I hope the problems with this myopic approach are obvious. On the other extreme, governance could focus entirely on long-term stabilization, ignoring short duration interferences unless they are expected to be sustained indefinitely. Under this approach, stratospheric aerosol injection could only count as a positive benefit if it could be expected to be sustained permanently or only phased out in conjunction with a carbon removal program that replaced its net radiative forcing. A similar analysis would apply to abatement of short-lived GHGs, for which a permanent abatement would count as a one-time reduction in long-term radiative forcing. Moreover, merely accelerating the timing of permanent abatement would be irrelevant, as it would not change the long-run energy balance. Like its counterpart extreme, this approach of totally ignoring unsustained near-term costs and benefits is also deeply misguided and normatively unsustainable.

A less extreme version of long-termism would weigh radiative forcing in all time-periods equally. That is, climate interferences would be valued in terms of the integral of their impact on radiative forcing in all future time periods going out to infinity. For GHG emissions, this would depart from the standard practice of using a 100-year integration period for calculation of CO_2 equivalents, extending the integration period out to the full atmospheric lifetime for each gas. This approach would assign much greater weight to long-duration interferences, while still accounting for near-term costs and benefits. Despite its extremity, this zero-discounting approach is not without its appeal. As noted above, in prior work I have argued that pure time preference is an illegitimate basis for discounting the future.[194] We are no more justified in discounting the welfare of our future selves or our descendants than we are in undervaluing the welfare of people who are distant from us in space, ethnicity, or class in our own time.

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[193] *See id.*

[194] Weil, *Individual Preferences*, *supra* note 189, at 59–60.

The problem is that opportunity cost, declining marginal utility, and benefit/cost realization risk mean that the expected welfare effects of time-delayed interferences are less than for interferences whose effects are more concentrated in the near-term, all else being equal. Opportunity cost matters because costly interventions to reduce net radiative forcing many years out may displace alternative investments that would enable a richer future to achieve greater impact with the same resources. Declining marginal utility matters because richer future people may suffer less from diverting resources to address climate change than present people would suffer from the same diversion of resources. Benefit/cost realization risk matters because the further out in the future a cost or benefit is, the more likely it is that no one is around to enjoy it. For instance, in about 7.6 billion years, the Sun is expected to expand to swallow the earth and likely destroy any remaining life.[195] At the very least, then, it would be silly to count benefits that are delayed by 8 billion years equally with those expected next week.

To be sure, the duration of climate interferences is generally limited to hundreds or thousands of years, but there are still non-climate catastrophic risks like natural or engineered pandemics, supervolcano eruptions, asteroid impacts, nuclear war, and poorly aligned artificial intelligence that could lead to human extinction or the irrecoverable destruction of human civilization in the next century. Toby Ord, a scholar at Oxford's University's Future of Humanity Institute, estimates the combined existential risk to human civilization from these and other sources over the next century to be about one in six.[196] If human civilization is permanently destroyed before some climate interference has fully played out, the remaining value of that interference would be greatly, if not entirely, diminished. Likewise, if future people colonize the galaxy or develop advanced climate control technology, the value of present climate interferences would also drop considerably. For these reasons, we should reject the zero-discounting approach.

Everyone who rejects a myopic focus on immediate or peak radiative forcing can agree that all else being equal, interference with a longer duration is more consequential. However, the two standard approaches also agree that for a given total effect over an infinite time horizon, effects that are very distant in time matter less. In comparing shorter and longer duration climate interferences, any governance framework should treat the question of future orientation consistently. In my view, the sensible approach would be something close to existing CBA discounting practices, but with a lower discount rate that subtracts out the component of market interest rates attributable to pure time preference. Regardless of one's view on this

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[195] Constance Holden, *Out of the Frying Pan*, 319 SCI. 1465 (2008).

[196] *See* TOBY ORD, THE PRECIPICE: EXISTENTIAL RISK AND THE FUTURE OF HUMANITY (Hachette, 2020).

normative question, however, there is no clear distinction to be drawn between interferences typically classified as geoengineering and those classified as climate change mitigation. The potential for termination shock does warrant special attention, however. Since the risk of termination shock depends on multiple dimensions, it is addressed separately in Section IV.A.

C. Dimension Three: Leverage

That brings us to the third dimension on which climate interferences vary: leverage. The concept of leverage as used in this Article incorporates both the ratio on an interference's resource requirements to its maximum effect size and its risks and uncertainties.[197] A high-leverage investment portfolio can produce great returns if things go well, but also carries a relatively high probability of being totally wiped out, as we saw in the 2008 financial crisis.[198] This dimension captures multiple ways in which interferences with the same primary mechanism (solar radiation management or atmospheric GHG concentration) and similar duration can still have important differences relevant to climate governance. These include direct implementation costs, scale of maximum feasible deployment, resource requirements, timeliness, uncertainty of effect size, geographic scope and evenness of climate impacts, and non-climate environmental risks and externalities. This Section will catalogue these features for the major existing and proposed climate interferences, starting with: (1) globally dispersed solar radiation management; (2) localized solar radiation management interferences; (3) cirrus cloud thinning; (4) carbon removal interventions; and (5) interferences that involve avoiding new emissions of GHGs; and (6) interferences that involve generating new emissions of GHGs.

Since most of the key governance questions associated with leverage relate to its interaction with other dimensions, this analysis is mostly reserved for Part IV. As

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[197] Strictly speaking, the components of leverage (as defined here) are not perfectly correlated. An interference can be risky without having a high ratio of maximum effect size to resource requirements. In principle, geographic scope could also be broken out as a distinct dimension. Variations in each of the parameters are noted in the discussion below, but I judged that the analytical clarity gained by separating them out into distinct dimensions would be outweighed by the risk of rendering the overall framework unwieldy. Timelines, though noted here, are primarily accounted for under the mechanism of action dimension. Multiple commenters have also suggested public acceptance or controversy as potential dimension. In my judgment, controversy and public acceptance are downstream of the physical properties of climate interferences, as expressed in the three-dimensions framework presented herein, and arise from interactions between these three dimensions.

[198] Eva Sadej, *How Leverage Works in Investments*, BLUELEAF, https://www.blueleaf.com/articles/how-leverage-works-in-investments/ [https://perma.cc/K5HD-FY2P].

you will see below, GHG interferences (other than GHG emissions that occur as an unintended byproduct of otherwise useful activities) are all low leverage. However, solar radiation management interferences range from very low leverage to extremely high leverage. While all solar radiation management interferences have the qualitative effects described in Section III.A, low-leverage interventions like white roofs could not feasibly be deployed at a sufficient enough scale to raise the sort of governance issues associated with high-leverage interventions like stratospheric aerosol injection.

1. Non-Localized Solar Radiation Management

Injecting sulfate aerosol precursors into the stratosphere might make the daytime sky slightly whiter and reduce the density of solar radiation available for solar power and photosynthesis.[199] Depending on the substance used, it might also exacerbate stratospheric ozone depletion.[200] Stratospheric aerosol injection's precise dynamics are still poorly understood, so there is substantial uncertainty regarding the magnitude of its climate impact and possible feedback effects, though this uncertainty could likely be substantially reduced with further research.[201] These risks, combined with the potentially high leverage and relatively short duration of stratospheric aerosol injection, have generated concern regarding termination shock—the rapid warming that might result from sudden ceasing of stratospheric aerosol injection.[202] This issue is addressed below in Section IV.A.

Aerosols injected into the stratosphere are likely to spread evenly along the line of latitude of injection, and to migrate poleward. This means that the latitude of injection will significantly affect the resulting climate and weather patterns.[203] Even at a given latitude, there is likely to be significant variation in the nature and

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[199] Alan Robock, Allison Marquardt, Ben Kravitz & Georgiy Stenchikov, *Benefits, Risks, and Costs of Stratospheric Geoengineering*, 36 GEOPHYSICAL RSCH. LETTERS No. 039209, Oct. 2009, https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2009GL039209.

[200] *Id.*

[201] NAT'L RSCH. COUNCIL, *supra* note 160, at 182–84.

[202] Brovkin et al., *supra* note 186, at 248.

[203] *See* George A. Ban-Weiss & Ken Caldeira, *Geoengineering as an Optimization Problem*, 5 ENV'T RSCH. LETTERS No. 034009, Sept. 2010, https://iopscience.iop.org/article/10.1088/1748-9326/5/3/034009/pdf.

desirability of the changes in temperature and precipitation resulting from stratospheric aerosol injection.[204]

Crude stratospheric aerosol injection could likely be deployed within a few years, though decades more research may be needed to fully understand potential side effects and feedback loops.[205] Once deployed, stratospheric aerosol injection would start to reduce temperatures within a year.[206] Stratospheric aerosol injection would offer much greater leverage and lower implementation costs compared to other interventions. In theory, the direct cost to deploy stratospheric aerosol injection at a scale sufficient to substantially reduce global warming could be as low as $2 billion dollars per year,[207] though other estimates suggest a minimum annual cost of $10 billion.[208] Even extending stratospheric aerosol injection in perpetuity, the present discounted direct cost could be as low as $100 billion.[209] This compares to estimates on the order of $500 billion to $1 trillion *per year* for the global cost of conventional mitigation.[210] However, the total implementation cost of stratospheric aerosol injection is likely to be significantly higher than the direct deployment costs. Other implementation costs associated with responsible stratospheric aerosol injection deployment would likely include a large-scale observation and modeling effort to monitor the impacts of any stratospheric aerosol injection intervention, high-level security to protect the deployment infrastructure, and excess deployment capacity to maintain steady injections in the event of primary equipment malfunction or destruction.[211] Compensation may also need to be paid to countries that claim to be harmed by an stratospheric aerosol injection effort. Finally, it is common for the final cost of large public projects, particularly those that rely on novel technologies,

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[204] THE ROYAL SOC'Y, *supra* note 10, at 30.

[205] *Id.* at 31.

[206] *Id.*

[207] Wake Smith & Gernot Wagner, *Stratospheric Aerosol Injection Tactics and Costs in the First 15 Years of Deployment*, 13 ENV'T RSCH. LETTERS No. 124001, Nov. 2018, at 1; Barrett, *supra* note 71.

[208] Ryo Moriyama, Masahiro Sugiyama, Atsushi Kurosawa, Kooiti Masuda, Kazuhiro Tsuzuki & Yuki Ishimoto, *The Cost of Stratospheric Climate Engineering Revisited*, 22 MITIGATION & ADAPTATION STRATEGIES FOR GLOB. CHANGE 1207, 1207 (2017).

[209] Victor, *Geoengineering Regulation*, *supra* note 14, at 326.

[210] Per-Anders Enkvist, Tomas Nauclér & Jerker Rosander, *A Cost Curve for Greenhouse Gas Reduction*, MCKINSEY Q. (2007), https://www.mckinsey.com/business-functions/sustainability/our-insights/a-cost-curve-for-greenhouse-gas-reduction.

[211] Reynolds et al., *supra* note 165, at 564–65.

to significantly exceed initial estimates.[212] Even with these caveats, however, stratospheric aerosol injection is likely to be at least an order of magnitude cheaper to implement than marginal conventional mitigation interventions.[213] This uniquely high leverage raises several important potential governance challenges addressed later in this Article, including termination shock (Section IV.A), unilateral deployment (Section IV.B), and risk compensation (Section IV.C).

At much greater direct cost, space-based sunshielding would eliminate most of the environmental risks and externalities of stratospheric aerosol injection that are not inherent to solar radiation management. In particular, ozone depletion and daytime sky whitening risks could be entirely eliminated, unless the space launches required to construct a space-based sunshield pollute the upper atmosphere with aerosols.[214] The radiative forcing produced by space-based solar radiation management would also be uniform across both longitude and latitude.[215] Reduced density of solar radiation for solar power and photosynthesis would remain issues. Space-based sunshielding is also less likely to lead to unpredictable feedback effects.[216] However, unlike some other long-duration interventions, it may be difficult to reverse.[217]

The main problem with space-based sunshielding is that the implementation cost is likely to be too high, about twenty-five times the direct implementation cost of stratospheric aerosol injection, and it may not even be feasible using the technologies that are likely to be available over the coming decades.[218] In terms of timeliness, it would likely take several decades to deploy or gather reflectors to the

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[212] Gordon MacKerron, *Costs and Economics of Geoengineering* 13 (Univ. of Oxford Climate Geoengineering Governance Working Paper Series, Working Paper No. 13, 2014), https://web.archive.org/web/20160512203151/http://www.geoengineering-governance-research.org/perch/resources/workingpaper13mackerroncostsandeconomicsofgeoengineering.pdf.

[213] Parson & Ernst, *supra* note 70, at 315.

[214] David Keith, Oliver Morton, Yomay Shyur, Pete Worden & Robin Wordsworth, *Reflections on a Meeting About Space-Based Solar Geoengineering*, HARV. SOLAR GEOENGINEERING RSCH. PROGRAM (Mar. 17, 2020), https://geoengineering.environment.harvard.edu/blog/reflections-meeting-about-space-based-solar-geoengineering [https://perma.cc/RS5P-GLKC].

[215] *Id.*

[216] THE ROYAL SOC'Y, *supra* note 10, at 33.

[217] *See id.* at 32–34.

[218] *Id.* at 35.

L1 Lagrange point.[219] Nonetheless, its presence as a theoretical option is useful for disentangling the objections to stratospheric aerosol injection that are inherent to solar radiation management interferences from those based on duration and leverage.

2. Localized Solar Radiation Management

Marine cloud brightening, because of its localized radiative forcing effects, would have even greater geographic heterogeneity of costs and benefits than non-localized solar radiation management interventions like stratospheric aerosol injection and space-based sunshielding.[220] This increases the unpredictability of the climatic effects, which could include disruption of ocean currents and weather patterns. Like stratospheric aerosol injection and space-based sunshielding, marine cloud brightening would decrease the intensity of sunlight reaching the earth's surface.[221] However, these effects would be concentrated in the oceans, where there is less solar energy generation. Depending on the material used for cloud-condensation nuclei, it could also cause pollution when the injected particles quickly rain out.[222] This would not be a problem if refined sea salt were used, but that could increase the salinity of the ocean surface.[223]

Like stratospheric aerosol injection, crude marine cloud brightening would likely start to reduce temperatures within a year, though its efficacy on any timescale is controversial.[224] Marine cloud brightening faces somewhat greater technical barriers to implementation but could be deployed within years or decades. Further research to characterize its risks and effects is needed before responsible deployment.[225] The uncertainty regarding the direct radiative forcing effects is significantly greater than for stratospheric aerosol injection.[226] While it probably has lower direct costs and is more technically feasible than space-based sunshielding, the affordability of marine cloud brightening is more uncertain than for stratospheric aerosol injection. In particular, it may be quite expensive to produce sufficient

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[219] *Id.* at 32.

[220] Keith et al., *supra* note 164.

[221] NAT'L RSCH. COUNCIL, *supra* note 160, at 120.

[222] THE ROYAL SOC'Y, *supra* note 10, at 27.

[223] NAT'L RSCH. COUNCIL, *supra* note 160, at 121.

[224] THE ROYAL SOC'Y, *supra* note 10, at 28.

[225] *Id.*

[226] Keith et al., *supra* note 164.

quantities of cloud-condensation nuclei particles to implement marine cloud brightening at scale, given their ultra-short atmospheric lifetimes at low altitude.[227] Also, unlike stratospheric aerosol injection and space-based sunshielding, marine cloud brightening would eventually experience diminishing returns to scale, with its maximum radiative forcing limited to around -4.0 W/m^2.[228]

Surface albedo enhancement methods like building cool roofs and pavements or placing reflective materials on deserts or sea ice have their own costs and risks. Like marine cloud brightening, the effects of localized increases in surface albedo are non-uniform across the globe, with unpredictable effects on weather patterns.[229] Given the limited scale of urban albedo enhancement, significant negative external effects from cool roofs and pavements are unlikely, even if those interventions were maximally deployed.[230] By the same token, the upside of these interventions is mostly limited to local adaptation benefits; the leverage in directly reducing warming is about 1/10 that of conventional mitigation measures and 1/10000 that of stratospheric aerosol injection.[231] But cool roofs can also lower energy consumption by reducing demand for air conditioning, thereby enabling lower carbon emissions.[232]

Desert albedo enhancement offers the largest potential scale, amounting to -4.0 W/m^2 of radiative forcing if all desert land (about 10% of earth's land surface) were covered with reflective surfaces.[233] However, reflective surfaces would likely interfere with other land use, limiting the feasible scale somewhat.[234] The cost of materials, deployment, and maintenance are also potentially very large for this intervention, on the order of five times that of conventional mitigation and five thousand times that of stratospheric aerosol injection per unit for radiative forcing.[235] Nonetheless, desert albedo enhancement could be deployed fairly rapidly if desired

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[227] THE ROYAL SOC'Y, *supra* note 10, at 28.

[228] *Id.* at 36.

[229] *Id.* at 22–26.

[230] *Id.* at 25.

[231] *Id.* at 35.

[232] *Id.* at 25.

[233] *Id.* at 26.

[234] *Id.*

[235] *Id.* at 26, 35.

and temperatures would start to fall soon after deployment.[236] Both local ecosystem disruption and negative non-local effects on weather and rainfall patterns are significant risks that warrant further study before deployment.[237]

The potential scale of arctic sea ice albedo enhancement is less well known, but probably much smaller than for deserts, given the smaller surface area involved. One study suggests that widespread deployment could reduce arctic temperatures by as much as 1.5°C and induce substantial thickening of sea ice.[238]

Somewhat counterintuitively, the localized forms of solar radiation management may present a greater risk of negative climatic outcomes for other countries. While the radiative forcing from these interventions is localized, the global climate system is inherently interconnected by flows of heat and momentum.[239] Localized interventions intended to address specific regional climate-related hazards will produce unpredictable distant climatic effects that are likely to present new hazards.[240] This highly unequal distribution of climate impacts suggests that, at any given scale of deployment, localized solar radiation management interventions actually present a more significant governance challenge than more geographically uniform solar radiation management interventions like stratospheric aerosol injection and space-based sunshielding.[241]

3. Cirrus Cloud Thinning

Cirrus cloud thinning, an ultra-short duration geoengineering intervention which operates primarily via a mechanism other than solar radiation management or atmospheric GHG concentration, has a different risk profile. Like solar radiation management interventions, it would do nothing to mitigate ocean acidification.[242] However, its effect on climate and weather would be more like GHG concentration interventions, except localized.[243] This means cirrus cloud thinning would not produce the same reduction in global average precipitation that solar radiation

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[236] *Id.* at 26.

[237] *Id.*

[238] Field et al., *supra* note 52, at 882.

[239] Keith et al., *supra* note 164.

[240] *Id.*

[241] *Id.*

[242] Mitchell & Finnegan, *supra* note 69.

[243] *See* Lee et al., *supra* note 67.

management interventions would.[244] However, like other localized interventions, it would have highly non-uniform and unpredictable effects on weather patterns, including changes in the seasonal and geographic distribution of precipitation.[245]

The magnitude of radiative forcing from cirrus cloud interventions is also highly uncertain and it is possible some cirrus interventions could produce net warming.[246] Estimates of the maximum radiative forcing achieved via cirrus cloud thinning range from -0.80 W/m^2 to -1.80 W/m^2, with central estimates around -1.55 W/m^2 or about 1°C of net cooling.[247] The implementation costs of cirrus cloud thinning are also highly uncertain, but early estimates suggest it could be cheaper than stratospheric aerosol injection, since it could be implemented by the existing fleet of airliners while travelling their ordinary routes.[248] Due to its negative solar radiation management component, cirrus cloud thinning would actually produce a localized increase in the intensity of solar radiation available for solar power and photosynthesis.[249] This could make cirrus thinning a good complement to stratospheric aerosol injection. Cirrus thinning has received less research attention than some other geoengineering interventions, and much more research would need to be conducted before it could be responsibly implemented. However, once implemented, its radiative forcing would be almost immediate, and its effects on temperatures would be felt within a year.[250]

4. CO_2 Removal

Afforestation, reforestation, forest preservation, and deforestation combine a localized effect on surface albedo (a positive or negative solar radiation management interference) with an atmospheric GHG concentration interference of uncertain

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[244] H. Muri, J.E. Kristjánsson, T. Storelvmo & M.A. Pfeffer, *The Climatic Effects of Modifying Cirrus Clouds in a Climate Engineering Framework*, 119 J. GEOPHYSICAL RSCH: ATMOSPHERES 4174, 4174 (2014).

[245] *Id.*

[246] Keith et al., *supra* note 164.

[247] *See, e.g.*, Blaž Gasparini et al., *To What Extent Can Cirrus Cloud Seeding Counteract Global Warming?*, 15 ENV'T RSCH. LETTERS No. 054002 (2019); Muri et al., *supra* note 244; J.A. Crook, L.S. Jackson, S.M. Osprey & P.M Forster, *A Comparison of Temperature and Precipitation Responses to Different Earth Radiation Management Geoengineering Schemes*, 120 J. GEOPHYSICAL RSCH: ATMOSPHERES 9352 (2015).

[248] Mitchell & Finnegan, *supra* note 69.

[249] *Id.*

[250] Keith et al., *supra* note 164; Mitchell & Finnegan, *supra* note 69.

duration. The net growth of forests and other land-based ecosystems absorbs 3 Gt of carbon every year, removing about 30% of the CO_2 emissions from fossil fuel burning.[251] The accumulated carbon stored in the world's forests is more than double that in the atmosphere.[252] At the same time, land use changes account for about 20% of all anthropogenic GHG emissions, mostly due to deforestation.[253] Tropical deforestation alone accounts for 1 GtC/yr (about 10% of global emissions) and is the fastest rising source of emissions.[254] Tropical deforestation is particularly problematic for the climate because the carbon cycle effects are not offset by albedo effects.[255] While tropical forests do tend to be replaced with brighter grasslands and shrublands (increasing surface albedo), tropical deforestation also reduces evapotranspiration and resulting cloud cover (reducing total albedo). These effects roughly cancel out, producing no net change in total albedo.[256] Boreal deforestation, by contrast, produces albedo increasing effects that more than cancel out the carbon cycle effects, resulting in net cooling.[257] And temperate deforestation is only mildly warming-inducing, with albedo effects offsetting most of the carbon cycle effects.[258]

Given the biodiversity benefits of tropical forests, preserving them is a clear environmental win. However, the demand for land for other uses, particularly agriculture, limits the potential scale of tropical forest preservation and afforestation.[259] Moreover, most tropical forests are located in low- to middle-income countries with inadequate incentive to invest in tropical forest preservation.[260] The manifold technical, political, and economic challenges associated with compensating those countries for the carbon sequestration services

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[251] THE ROYAL SOC'Y, *supra* note 10, at 10.

[252] *Id.*

[253] *Id.*

[254] *See generally* A. Baccini, S.J. Goetz, W.S. Walker, N.T. Laporte, M. Sun, D. Sulla-Menashe, J. Hackler, P.S.A. Beck, R. Dubaya, M.A. Friedl, S. Samanta & R.A. Houghton, *Estimated Carbon Dioxide Emissions from Tropical Deforestation Improved by Carbon-Density Maps*, 2 NATURE CLIMATE CHANGE 182 (2012).

[255] Bala et al., *supra* note 32, at 6552–53.

[256] *Id.*

[257] *Id.*

[258] *Id.*

[259] THE ROYAL SOC'Y, *supra* note 10, at 10.

[260] *See* Gabriel Weil, *Costs, Contributions, and Climate Change: How Important Are Universally Binding Emissions Commitments?*, 23 GEO. INT'L ENV'T L. REV. 319 (2011).

provided by their forests further limit the practically realizable climate change mitigation gains from tropical forestry.[261] To be sure, it is well worth continuing efforts to develop governance approaches to limit leakage and ensure permanence and additionality, but we should temper our expectations regarding what is likely to be achieved. Meanwhile, the offsetting albedo effects of temperate and boreal forests sharply limit the net cooling that can be achieved via preserving or expanding the land area covered by these forests. However, these albedo effects do not negate the role that forest carbon sequestration plays in mitigating ocean acidification, meaning that expanding boreal and temperate forest cover may have an important role to play in scenarios where cooling solar radiation management is deployed at significant scale.

Globally, the Intergovernmental Panel on Climate Change estimates that mechanisms aimed at reforestation and forest preservation could store (including new storage and avoided emissions) about 1–3 Gt of net CO_2 per year.[262] The role of forests as carbon sinks, however, is threatened by climate change itself, which increases the risk of forest fires, drought, biotic agents, and extreme weather events.[263] This decreases the expected duration of the impact of forestry-based climate interferences in a way that is positively correlated with overall climate risk. That is, forest-based carbon sinks are most likely to release carbon prematurely in scenarios where climate change is worse than expected, either due to failures of mitigation efforts or greater than expected climate sensitivity. While this does not imply that forestry-based interventions are not worth pursuing, it does reduce their role as a risk-management mechanism for avoiding catastrophic outcomes. Finally, large-scale efforts to increase forest cover would interfere with existing ecosystems, such as grasslands, which have their own biodiversity benefits.[264]

Enhanced mineral weathering is an effort to accelerate the natural process by which rocks absorb CO_2 to form bicarbonate ions and solid carbonate minerals. This happens naturally at a rate of less than 0.1 GtC/yr, around one hundredth of the rate

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[261] *Id.* at 339–41.

[262] *See* PETE SMITH ET AL., *Agriculture, Forestry and Other Land Use (AFOLU)*, *in* CLIMATE CHANGE 2014: MITIGATION OF CLIMATE CHANGE (2014).

[263] William R.L. Anderegg et al., *Climate-Driven Risks to the Climate Mitigation Potential of Forests*, 368 SCI. 7005 (2020).

[264] Wil Burns, Daniel Raimi & Elizabeth Wason, *Adding Subtraction to the Climate Toolkit: Discussing Carbon Dioxide Removal with Wil Burns*, RES. RADIO (June 2, 2020), https://www.resources.org/resources-radio/adding-subtraction-climate-toolkit-discussing-carbon-dioxide-removal-wil-burns/ [https://perma.cc/B3R9-PPYM].

at which carbon is currently being emitted.[265] Grinding up large amounts of silicate-containing rocks and spreading them over cropland could enhance the productivity of soils while accelerating carbon uptake by increasing the surface exposure of silicate minerals to the atmosphere.[266] This would remove one CO_2 molecule for each silicate molecule exposed to the atmosphere.[267] Using this method, about seven cubic kilometers of rock (roughly double the amount of coal mined each year) would have to be mined, ground up, and reacted with CO_2 each year to offset all anthropogenic emissions.[268] This would entail substantial energy requirements and could produce significant fine particulate pollution.[269] A variety of related techniques are possible, some using carbonate instead of silicate rocks and some involving direct ocean deposition, but broadly similar challenges apply.[270]

Weathering interventions would ultimately deposit bicarbonates and calcium or magnesium cations into the ocean, increasing its alkalinity.[271] This would have the benefit of combating ocean acidification, over and above its negative emissions effect. This means enhanced weathering might be a good complement to a solar radiation management intervention like stratospheric aerosol injection. However, it is possible that increasing the concentrations of bicarbonates and calcium/magnesium in the ocean could have adverse side effects for marine ecosystems.[272] Otherwise, enhanced weathering is largely free of adverse consequences. The only practical constraint on the scale of deployment is the cost and energy requirements of extracting, grinding, and transporting the minerals, but these costs are likely to sharply limit enhanced weathering's role.[273] A credible recent estimate is that between 0.5 and 2.0 gigatons of carbon could be removed annually at a cost of $80 to $180 per ton.[274] Deployment at scale would also require

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[265] THE ROYAL SOC'Y, *supra* note 10, at 13.

[266] *Id.*

[267] *Id.*

[268] *Id.* at 13–14.

[269] Burns et al., *supra* note 264.

[270] THE ROYAL SOC'Y, *supra* note 10, at 14.

[271] *Id.* at 13.

[272] *Id.* at 14.

[273] *Id.*; Burns et al., *supra* note 264.

[274] David J. Beerling et al., *Potential for Large-Scale CO_2 Removal Via Enhanced Rock Weathering with Croplands*, NATURE, July 2020, at 242, 242.

substantial infrastructure buildup, and effects on global temperatures would be substantially delayed, as with all carbon removal interventions.[275]

Ocean fertilization is another intervention designed to accelerate a natural carbon removal process. Phytoplankton in the earth's oceans are responsible for about half of all photosynthesis on earth.[276] A portion of the carbon absorbed by algal blooms settles into the deep ocean as organic matter and is consumed by bacteria and other organisms, which then release it back into the water as CO_2.[277] This process is responsible for the enormous stock of CO_2 in the deep ocean, about 35,000 GtC compared with about 750 GtC in the atmosphere.[278] The rate of carbon sequestration via this process is limited by the availability of specific micronutrients.[279] The scientific consensus is that nitrogen is the limiting nutrient over most of the open ocean.[280] In the Equatorial Pacific Ocean and the Southern Ocean, iron is the limiting nutrient.[281] Increasing the concentration of the limiting nutrient in a region would accelerate carbon uptake.[282] Attention has been focused primarily on iron, since it offers much greater leverage.[283] The ratio of nutrient elements in phytoplankton tissue for C:N:P:Fe is thought to be 106:16:1:0.001.[284] This means that, if fully effective, adding one nitrogen atom where it is the limited nutrient could sequester about 6 carbon atoms, whereas a phosphorus atom could induce the sequestration of about 100 carbon atoms and an iron atom could theoretically stimulate the sequestration of 100,000 carbon atoms.[285] However, stimulating carbon uptake by surface algae does not translate on a one-to-one basis to sequestration of carbon in the deep ocean, as there are many intervening and potential negative feedbacks.[286]

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[275] THE ROYAL SOC'Y, *supra* note 10, at 15.

[276] Burns et al., *supra* note 264.

[277] THE ROYAL SOC'Y, *supra* note 10, at 16–17.

[278] *Id.* at 16.

[279] *Id.* at 17.

[280] *Id.*

[281] *Id.*

[282] *Id.*

[283] *Id.*

[284] *Id.*

[285] *Id.*

[286] *Id.*

The precise yield from ocean iron fertilization is not well specified, but we do know that only a tiny fraction of carbon absorbed by phytoplankton is sequestered in the deep ocean, whereas most is rapidly returned to the atmosphere. There is likely a hard limit on the potential increase in long-duration sequestration well below 1 GtC/yr. As with other carbon removal interventions, the temperature response would be slow.[287]

The most straightforward side effect of ocean fertilization would be an increase in the acidity of the deep ocean.[288] However, by decreasing the CO_2 concentration in the atmosphere, it would also help mitigate ocean surface acidification.[289] Fertilization would also increase the quantity of oxygen used for respiration by deep ocean bacteria, potentially creating “dead zones” with no significant remaining oxygen supply.[290] More broadly, increasing the stock of phytoplankton is likely to alter marine ecosystems in unpredictable ways. While it is possible that this could lead to growth in the populations of fish consumed by humans, the limited evidence suggests otherwise.[291] Unlike some other carbon removal interventions, the risks generated from ocean fertilization are unlikely to be substantially contained within national borders or territorial waters.[292] This suggests that it may be desirable for the global climate governance regime to take a stronger hand in regulating this intervention.

Bioenergy with carbon capture and storage (“BECCS”) would entail converting organic material like wood or crop residues into heat, electricity, or fuels (liquid or gas) while capturing and storing the CO_2 emitted in the process.[293] This is a negative emissions technology because the organic materials capture carbon while they are growing, and the carbon released by burning or otherwise converting the organic materials is not released back into the atmosphere.[294] BECCS has the added benefit

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[287] *Id.* at 18.

[288] *Id.*

[289] *Id.*

[290] *Id.* at 17–18.

[291] *Id.* at 17.

[292] *Id.* at 51.

[293] *Carbon Removal Fact Sheet: Bioenergy with Carbon Capture and Storage*, AM. UNIV. INST. FOR CARBON REMOVAL L. & POL’Y (2018), https://www.american.edu/sis/centers/carbon-removal/upload/icrlp_fact_sheet_beCCS_181005.pdf [https://perma.cc/T5TH-TNHK].

[294] *Id.*

of producing a negative-carbon source of energy and fuels for difficult-to-decarbonize sectors like air travel.[295] However, it also produces a range of costs and risks. As with any carbon storage intervention, transporting and injecting CO_2 into geological reservoirs raises concerns about pipelines, CO_2 leakage, seismic activity, and water pollution.[296] Except for CO_2 leakage risks, however, these concerns are primarily localized in nature and so are of limited relevance to global climate governance. As with direct air capture and CCUS below, utilization of the captured CO_2 in synthetic fuels or materials is also an option.[297]

Costs and risks specific to BECCS include food security concerns associated with devoting fertile land to bioenergy, potential human displacement and biodiversity loss from land use changes, heavy use of water and fertilizer, conventional air pollution from biomass combustion, and potential soil carbon loss.[298] Any crediting scheme for negative emissions from BECCS would need to net out any induced emissions due to leakage or soil carbon loss. A global governance regime might also seek to account for potential biodiversity loss and human displacement, which could produce significant cross-border externalities. The other costs and risks of BECCS are largely either within the jurisdictions of national governments or internalized in market transactions. Nonetheless, these concerns will likely limit the scale of BECCS deployment.

The cost of carbon removal via BECCS is likely in the range of \$100–\$200 per ton CO_2, though estimates vary widely.[299] Limiting the global temperature rise to 2°C using BECCS alone would likely require crops to be planted solely for the purpose of CO_2 removal on a land area up to three times the size of India[300] Estimates of the maximum feasible sequestration in the year 2050 range from 0.5 to 5.0 billion metric tons per year, which could rise as high as 12.0 million metric tons per year by 2100.[301] This translates into a cumulative CO_2 removal potential of 50 and 150

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[295] *Id.*

[296] *Id.*

[297] *See id.*

[298] *Id.*

[299] *Id.*

[300] Renee Cho, *Can Removing Carbon from the Atmosphere Save Us from Climate Catastrophe?*, COLUM. CLIMATE SCH.: STATE OF THE PLANET (Nov. 27, 2018), https://news.climate.columbia.edu/2018/11/27/carbon-dioxide-removal-climate-change/ [https://perma.cc/TAT4-AYJT].

[301] *Id.*

ppm.[302] BECCS deployment to date has been limited to a handful of pilot projects.[303] Ramping up would primarily be limited by the availability of arable land.[304] Once deployed at scale, the impacts of BECCS on atmospheric GHG concentrations and temperatures would be slow and gradual.[305]

The last major carbon removal approach is direct air capture, an industrial process that captures CO_2 from ambient air to produce a pure CO_2 stream that is then used or stored.[306] There are a few potential industrial CO_2 capture processes, but the leading option involves passing ambient air across an alkaline solution of calcium or potassium hydroxide, which separates the CO_2 from other gases in the air.[307] There are currently only a few pilot direct air capture projects operating, and the potential for scaling up is disputed.[308] The most significant barrier to scaling up is direct cost, which currently runs between $94 and $232 per ton.[309] This is down considerably from an estimated $600 per ton in 2011, and there is hope for further cost reductions.[310] A major driver of the cost of direct air capture is high energy requirements, which is not a significant factor for BECCS.[311] These energy requirements, in turn, may limit the net carbon capture, depending on the source of the energy used.[312] Conversely, direct air capture has a comparatively small land use footprint. This means there is no hard limit on the amount of CO_2 that could be removed via direct air capture. As with all negative emissions technologies, however, any significant impact on temperatures would likely be delayed decades after

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[302] THE ROYAL SOC'Y, *supra* note 10, at 20.

[303] Burns et al., *supra* note 264.

[304] *Id.*

[305] THE ROYAL SOC'Y, *supra* note 10, at 12.

[306] *Id.*

[307] Burns et al., *supra* note 264.

[308] *Id.*

[309] Jeff Tollefson, *Sucking Carbon Dioxide from Air Is Cheaper Than Scientists Thought*, NATURE (June 14, 2018), https://www.nature.com/articles/d41586-018-05357-w [https://perma.cc/M87E-XDSN].

[310] *Id.*

[311] THE ROYAL SOC'Y, *supra* note 10, at 16.

[312] Mark Z. Jacobson, *The Health and Climate Impacts of Carbon Capture and Direct Air Capture*, 2019 ENERGY ENV'T SCI. 3567, 3567 (2019).

deployment at scale.[313] The same challenges, risks, and governance considerations associated with carbon storage for BECCS apply to direct air capture.

5. Emissions Abatement

Much has been written about measures to decarbonize the global economy. As I and many others have argued, the obstacles to decarbonization are more political than economic or technical.[314] The global benefits of decarbonization substantially exceed the global costs of decarbonization, at least at current margins.[315] However, the benefits of decarbonization interventions are diffuse in space and delayed in time, whereas the costs are much more concentrated in the present and on particular individuals, businesses, and countries.[316] Voluntary cooperation among the world's governments has so far proven incapable of generating sufficient investment in decarbonization.[317] Indeed, the absence of effective global governance on conventional mitigation has raised the salience and relevance of unconventional climate interventions. What follows is not intended to be an exhaustive analysis of optimal decarbonization strategies. Instead, this brief overview is meant to highlight the features that some emissions abatement interventions share with unconventional climate interventions, as well as the ways that they differ.

While it is somewhat unconventional and not yet deployed at scale, carbon capture, utilization, and storage ("CCUS") for power plants and industrial facilities is typically classified as a mitigation intervention.[318] Like other mitigation interventions, CCUS is intended to prevent new GHG emissions that occur as an unintended byproduct of beneficial economic activity. Unlike direct air capture,

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[313] THE ROYAL SOC'Y, *supra* note 10, at 16.

[314] Weil, *Beyond the Pledge*, *supra* note 3, at 927–33.

[315] *See generally* Tommi Ekholm, 154 *Climatic Cost-benefit Analysis Under Uncertainty and Learning on Climate Sensitivity and Damages*, 154 ECOLOGICAL ECON. 99, 103 (2018).

[316] Jesse Jenkins, *Why Carbon Pricing Falls Short*, UNIV. OF PENN. KLEINMAN CTR. FOR ENERGY POL'Y (Apr. 24, 2019), https://kleinmanenergy.upenn.edu/research/publications/why-carbon-pricing-falls-short-and-what-to-do-about-it/ [https://perma.cc/4LV7-6N52].

[317] Weil, *Beyond the Pledge*, *supra* note 3, at 927–33.

[318] *Carbon Capture, Use and Storage (CCUS)*, U.N. ECON. COMM'N FOR EUR., https://unece.org/sustainable-energy/cleaner-electricity-systems/carbon-capture-use-and-storage-ccus [https://perma.cc/5DV6-9E7B].

CCUS involves capture of CO_2 from flue gas where it is much more concentrated.[319] But separating the CO_2 from the other components of the flue gas and then compressing it for transportation and storage still consumes 25–40% of the energy produced at a coal-fired power plant.[320] This means that more fossil fuels need to be burned to generate the same net energy output, which increases localized health harms associated with conventional air and water pollution.[321] This energy cost represents 70–80% of the $70–$100 per ton total estimated cost of CCUS.[322] Breakthroughs in capture technology could bring this cost down considerably.[323]

Another concern with CCUS is that net capture rates can be as little as 10–20% of total emissions from a fossil fuel-fired facility, due to uncaptured upstream emissions and uncaptured emissions from the combustion of the fossil fuels used to power the carbon capture equipment.[324] Net capture can be increased by using wind or solar to power the capture equipment, but this may substantially increase the direct cost.[325] This suggests that cost-effective CCUS deployment may be limited to a few particularly difficult-to-decarbonize heavy industrial sectors, while playing a more minor role in the power sector.[326] In the United States, a carbon price is likely to drive existing coal-fired power plants into retirement before it is high enough to motivate CCUS deployment at scale.[327] The only application of CCUS that is economically viable at any significant scale without substantial policy support is

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[319] *What is CCUS?*, RSCH. COORDINATION NETWORK ON CARBON CAPTURE, UTILIZATION, & STORAGE, https://www.aiche.org/ccusnetwork/what-ccus#:~:text=Carbon%20Capture%2C%20Utilization%2C%20and%20Storage,safe%20and%20permanent%20storage%20options [https://perma.cc/N773-ZWKD].

[320] Jenny G. Vitillo, Berend Smit & Laura Gagliardi, *Introduction: Carbon Capture and Separation*, 117 CHEM. REV. 9521, 9521 (2017).

[321] Jacobson, *supra* note 312, at 3567.

[322] Vitello et al., *supra* note 320.

[323] *Id.*

[324] Jacobson, *supra* note 312, at 3569.

[325] *Id.*

[326] Max Åhman, *Unlocking the "Hard to Abate" Sectors*, WORLD RES. INST., https://www.wri.org/climate/expert-perspective/unlocking-hard-abate-sectors [https://perma.cc/U9CD-LJSY].

[327] Max Roser, *The Argument for a Carbon Price*, OUR WORLD IN DATA (June 1, 2021), https://ourworldindata.org/carbon-price [https://perma.cc/QG7M-G4N9].

enhanced oil recovery, which has questionable net environmental benefits.[328] Nonetheless, some scholars see CCUS playing a larger role, particularly in countries that are still building new coal-fired power plants.[329] Indeed, IPCC scenarios where temperature increases are limited to 1.5°C or 2.0°C typically involve substantial deployment of CCUS.[330] Even under more optimistic assumptions, however, the impact of CCUS in any particular jurisdiction is limited to reducing emissions from specific stationary sources like coal and natural-gas fired power plants and certain industrial facilities. Emissions from internal combustion engine-based transportation, home heating oil and gas, and agriculture cannot be meaningfully addressed using CCUS. These limits, along with deployment costs, rather than physical storage capacity, are likely to be the binding constraint on the scale of CCUS.

From a global governance perspective, it is crucial to note that the costs and risks associated with CCUS are primarily localized. Air pollution from ongoing coal combustion is a public health scourge, but the health costs are generally concentrated in the jurisdictions where power plants and industrial facilities are located and adjacent downwind jurisdictions.[331] Groundwater contamination, local ecosystem disruption, and earthquakes are also potentially significant, but largely localized risks.[332] The major exception to this is the risk of CO_2 leakage from underground

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[328] David Roberts, *Could Squeezing More Oil out of the Ground Help Fight Climate Change?*, VOX (Dec. 6, 2019, 7:56 AM), https://www.vox.com/energy-and-environment/2019/10/2/20838646/climate-change-carbon-capture-enhanced-oil-recovery-eor [https://perma.cc/R86R-P5W3].

[329] S. JULIO FRIEDMANN ET AL., NET-ZERO AND GEOSPHERIC RETURN: ACTIONS TODAY FOR 2030 AND BEYOND, COLUM. CTR. ON GLOB. ENERGY POL'Y 18 (Sept. 2020), https://www.globalccsinstitute.com/wp-content/uploads/2020/09/Net-Zero-Report-and-Geospheric-Returen-Actions-Today-for-2030-and-Beyond-1.pdf [https://perma.cc/C64A-TJGX].

[330] Ottmar Edenhofer et al., *Summary for Policymakers*, *in* CLIMATE CHANGE 2014: MITIGATION OF CLIMATE CHANGE 12–15 (2014), https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_summary-for-policymakers.pdf [https://perma.cc/SR94-2GD7].

[331] *See generally* Reid Johnson, Jacob LaRiviere & Hendrik Wolff, *Fracking, Coal, and Air Quality*, 6 J. ASS'N ENV'T & RES. ECONOMISTS 1001 (2019).

[332] EUR. ENV'T AGENCY, AIR POLLUTION IMPACTS FROM CARBON CAPTURE AND STORAGE (CCS) 24 (2011), https://www.eea.europa.eu/publications/carbon-capture-and-storage [https://perma.cc/NWN5-4Y9X] (EEA Technical Report No. 14/2011). *But see* Susan Hovorka, *Risks and Benefits of Geologic Sequestration of Carbon Dioxide—How Do the Pieces Fit?*, AAPG (Sept. 30, 2009), http://www.searchanddiscovery.com/documents/2009/80058hovorka/ndx_hovorka.pdf; S. Julio Friedmann, *Carbon Sequestration Risks and Hazards: What We Know and What We Don't Know*, NAT. RES. DEFENSE COUNCIL (Mar. 6, 2009), https://www.nrdc.org/sites/default/files/glo_10062101d.pdf [https://perma.cc/LKW9-9KR3].

reservoirs, which is shared by BECCS and direct air capture. According to the IPCC, however, the fraction of CO_2 retained in appropriately managed and selected storage sites is very likely (meaning a probability of 90%–99%) to exceed 99% after 100 years and likely to exceed 99% after 1000 years.[333] The risk of leakage is expected to decrease over time as deeper and more permanent forms of CO_2 trapping occur.[334] The most significant risk is leakage from well casings of abandoned wells.[335] Thus, while removal or avoided emissions via CCUS, BECCS, and direct air capture are not strictly permanent, storage of carbon in the geosphere is characterized by much longer durations than storage in the biosphere. Likewise, avoiding CO_2 emissions by leaving fossil fuels in the ground (another form of geosphere storage) does not prevent future actors from digging them up and burning them. Nonetheless, there is significant scope for global governance to set standards and certify CCUS projects that wish to be credited toward meeting emissions obligations. Otherwise, there could be a race to the bottom where countries and private actors seek out the cheapest, lowest quality storage opportunities that would present a substantial risk of physical leakage.[336]

Fuel switching from coal to natural gas reduces CO_2 emissions significantly and offers substantial local air quality benefits. These gains are driven by the fact that natural gas combustion inherently produces fewer GHGs and other pollutants than coal. However, natural gas extraction and transport produces a greater quantity of methane emissions than coal mining. This means that a climate governance regime that focused only on CO_2 and ignored other GHGs would likely lead to overinvestment in fuel switching from coal to gas.[337] Nonetheless, life-cycle analyses of energy generation from coal and natural gas find that fuel switching does significantly decrease GHG emissions in terms of total CO_{2e} based on a 100-year or 20-year integration period.[338] As you can see in Figure 4, switching from a 100-year

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[333] Howard Herzog, *Carbon Dioxide Capture and Storage*, THE ECONOMICS AND POLITICS OF CLIMATE CHANGE 263, 273–74 (Dieter Helm & Cameron Hepburn eds., Oxford Univ. Press 2009).

[334] *Id.*

[335] *Id.* at 277.

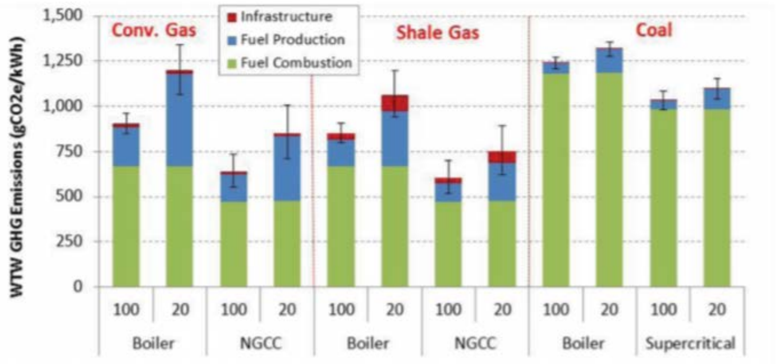
[336] *Id.* at 272.

[337] Sarah Zielinski, *Natural Gas Really Is Better than Coal*, SMITHSONIAN MAG. (Feb. 13, 2014), https://www.smithsonianmag.com/science-nature/natural-gas-really-better-coal-180949739/ [https://perma.cc/V7B8-LQDJ].

[338] *See* Andrew Burnham, Jeongwoo Han, Corrie E. Clark, Michael Wang, Jennifer B. Dunn & Ignasi Palou-Rivera, *Life-Cycle Greenhouse Gas Emissions of Shale Gas, Natural Gas, Coal, and Petroleum*, 46 ENV'T SCI. & TECH. 619 (2011); Paulina Jaramillo, W. Michael Griffin & H. Scott Matthews,

to a 20-year integration period narrows the gap between natural gas and coal significantly.[339]

Figure 4: Gas vs. Goal Climate Impact with 20-Year & 100-Year Time Horizons



This is because methane has an atmospheric lifetime of 8.4 years, compared to over 100 years for CO_2.[340] The instantaneous radiative forcing from a ton of methane is approximately 120 times that of CO_2, whereas the 100-year global warming potential of methane is only 21 times that of CO_2.[341]

While other interventions to reduce the emissions intensity of production and to reduce the consumption of emissions-intensive goods and services involve significant tradeoffs related to land use, mineral depletion, reliable electricity, air and water pollution, economic growth, nuclear waste disposal, etc., these tradeoffs are largely localized. To the extent that concerns about biodiversity preservation, nuclear proliferation, cross-border conventional air and water pollution, and other tradeoffs are a focus of international concern, they can be effectively addressed by instruments outside of the climate governance domain like the Convention on Biological Diversity, the Nuclear Non-Proliferation Treaty, and various bilateral and regional pollution control agreements.

Comparative Life-Cycle Air Emissions of Coal, Domestic Natural Gas, LNG, and SNG for Electricity Generation, 41 ENV'T SCI. & TECH. 6290 (2007).

[339] *Id.* at 619–27.

[340] *Id.*

[341] *Atmospheric Lifetime and Global Warming Potential Defined*, U.S. EPA: CTR. FOR CORP. CLIMATE LEADERSHIP, https://19january2017snapshot.epa.gov/climateleadership/atmospheric-lifetime-and-global-warming-potential-defined_.html [https://perma.cc/882K-MMXH].

6. Unabated GHG Emissions

Finally, it cannot be left unsaid that the most important climate interference of all is the ongoing emission of almost fifty billion tons of CO_{2e} every year.[342] While the range of activities that generate these emissions typically generate substantial benefits for those that engage in them and their immediate counterparties, we know that GHG emissions impose enormous costs on third parties around the world.[343] The cross-border negative externalities associated with continuing GHG emissions are much larger and better understood than for any of the other climate interferences discussed above.

Despite this reality, which has been well known for decades, the existing global climate governance regime imposes little to no meaningful constraint on the freedom of countries or private actors to emit GHGs.[344] To be sure, many national and subnational governments have imposed significant policies to reduce their own GHG emissions. 197 countries are parties to the United Nations Framework Convention on Climate Change.[345] 191 of those countries are parties to the Kyoto Protocol, which sets "binding" emissions limits for its 37 Annex I parties.[346] However, despite being formally legally binding, there was no enforcement mechanism for the Kyoto targets.[347] Indeed, Canada withdrew from the Kyoto Protocol and suffered no consequences for doing so, nor did the United States suffer consequences for its failure to ratify the Kyoto Protocol.[348] In any case, the Kyoto Protocol has run its course. Its second commitment period—in which fewer countries participated in—ended December 2020.[349] The Kyoto Protocol's successor, the Paris Agreement,

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[342] *See generally* Weil, *Beyond the Pledge*, *supra* note 3.

[343] *See id.*

[344] *See id.*

[345] *What is the United Nations Framework Convention on Climate Change?*, UNITED NATIONS CLIMATE CHANGE, https://unfccc.int/process-and-meetings/the-convention/what-is-the-united-nations-framework-convention-on-climate-change [https://perma.cc/Q4QU-LW9P].

[346] *The Kyoto Protocol—Status of Ratification*, UNITED NATIONS CLIMATE CHANGE, https://unfccc.int/process/the-kyoto-protocol/status-of-ratification [https://perma.cc/UDP6-BWD7].

[347] *See* Weil, *Beyond the Pledge*, *supra* note 3, at 927.

[348] *Canada's Withdrawal from Kyoto Protocol Regrettable—UN Climate Official*, UNITED NATIONS: UN NEWS (Dec. 13, 2011), https://news.un.org/en/story/2011/12/398142 [https://perma.cc/PM3M-HNJB]; *see also* Weil, *Beyond the Pledge*, *supra* note 3, at 957.

[349] *See The Kyoto Protocol—Status of Ratification*, *supra* note 346.

abandons any pretense of legally binding emissions limits.[350] Only emissions reporting obligations are legally binding, whereas the actual emissions targets are both self-selected and voluntary.[351] These voluntary targets fall far short of the emissions reductions needed to meet the headline goals of the agreement, and many countries are not even on track to meet their insufficient targets.[352] As with the Kyoto Protocol, the Paris Agreement offers no formal mechanism for imposing consequences on countries that either fail to meet their target or withdraw from the Agreement entirely, as the United States did.[353]

In evaluating the need for new global governance regimes to constrain other climate interferences, it is worth remembering this glaring omission in climate governance. As discussed in Section VI.C below, there are practical reasons why effective governance of other climate interferences is more feasible than for GHG emissions. Nonetheless, the fact remains that GHG emissions themselves represent the most significant externalization of cost and risk. Unconventional interventions like stratospheric aerosol injection are less familiar and represent intentional rather than byproduct interferences in the climate system. But these differences do not necessarily make them better candidates for strong restrictions at the global level. It is also worth considering whether certain governance approaches for unconventional climate interventions can offer leverage to improve global cooperation in reducing GHG emissions. This possibility is discussed further in Section IV.E.

IV. INTERACTIONS BETWEEN DIMENSIONS

Some governance challenges and opportunities arise from the interaction between the three dimensions analyzed above. In particular, stratospheric aerosol injection, which combines a solar radiation management mechanism of action with relatively short duration and extremely high leverage, raises some unique challenges, including termination shock (Section IV.A) and risk compensation (Section IV.D). The interaction between different dimensions also has implications for the optimal portfolio of climate interventions (Section IV.B), the susceptibility of different interventions to effective global governance (Section IV.C), and potential gains from a unified climate governance framework (Section IV.E).

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[350] Paris Agreement to the United Nations Framework Convention on Climate Change, Dec. 12, 2015, T.I.A.S. No. 16-1104, http://unfccc.int/paris_agreement/items/9485.php [https://perma.cc/QW8A-RG9P].

[351] *Id.*

[352] Weil, *Beyond the Pledge*, *supra* note 3, at 927–32.

[353] *Id.*

A. Termination Shock

The economic, social, and ecological consequences of climate change are not solely determined by the absolute amount of warming, sea level rise, and change in precipitation patterns. The rate of change also matters. Relatively slow warming allows time for individuals, communities, supply chains, and ecosystems to adapt and migrate. If climate change proceeds faster than people and wildlife can adapt, the human costs and biodiversity losses compound. One way that rapid warming could come about is if a short-duration climate intervention is implemented at scale and then suddenly halted. This prospect, known as termination shock, is most discussed in the context of stratospheric aerosol injection.[354]

A common argument against stratospheric aerosol injection is that once you start engaging in it, you have to continue it forever (or at least replace it with CO_2 removal) to avoid termination shock.[355] If this were true, the benefits of stratospheric aerosol injection would not only be temporary, but they would come at the expense of future welfare, locking humanity into a trap where it must continue stratospheric aerosol injection regardless of the negative consequences in order to avoid destructively rapid warming.[356] However, there are three reasons that termination shock is a manageable problem.

First, moderate amounts of stratospheric aerosol injection would not produce dangerously rapid warming if stratospheric aerosol injection were suddenly terminated.[357] The Intergovernmental Panel on Climate Change's Representative Concentration Pathway ("RCP") 2.6 is an optimistic scenario where fairly aggressive emissions abatement is combined with substantial negative emissions interventions before 2100 to limit net radiative forcing to 2.6 W/m^2 and prevent temperature rise from exceeding 2°C in most models.[358] In this relatively benign scenario, the rate of

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[354] *See* Scott R. Loarie, Philip B. Duffy, Healy Hamilton, Gregory P. Asner, Christopher B. Field & David D. Ackerly, *The Velocity of Climate Change*, 462 NATURE 1052 (2009).

[355] Andy Jones et al., *The Impact of Abrupt Suspension of Solar Radiation Management (Termination Effect) in Experiment G2 of the Geoengineering Model Intercomparison Project (GeoMIP)*, 188 J. GEOPHYSICAL RSCH. 9743, 9743 (2013); Brovkin et al., *supra* note 186, at 243.

[356] Brad Plumer, *One Problem with Geoengineering: Once You Start, You Can't Really Stop*, WASH. POST (Jan. 2, 2014), https://www.washingtonpost.com/news/wonk/wp/2014/01/02/one-problem-with-geoengineering-once-you-start-you-cant-ever-stop/ [https://perma.cc/M7HT-NHQ2].

[357] Andy Parker & Peter J. Irvine, *The Risk of Termination Shock from Solar Geoengineering*, 6 EARTH'S FUTURE 456, 458 (2018), https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2017EF000735.

[358] *Id.*

warming peaks at about 0.2°C per decade.[359] Thus, while a rise of 0.2°C per decade is certainly not harmless, it is well within the range of warming pace we can expect absent stratospheric aerosol injection.[360] Simulations of large instantaneous changes in radiative forcing indicate that about half of the equilibrium temperature response occurs in the first decade.[361] This suggests that the sudden termination of a stratospheric aerosol injection intervention large enough to produce 0.4°C of cooling would result in about a 0.2°C rise in temperature in the first decade after termination.[362] If the peak magnitude of stratospheric aerosol injection interventions were kept below this threshold, termination shock risk would be minimal.[363]

Second, stratospheric aerosol injection need not be terminated abruptly. A gradual phaseout could reduce the rate of warming substantially.[364] If the goal is to limit warming to 0.2°C per decade, then the length of the phaseout would need to be a maximum of fifty years per degree Celsius of stratospheric aerosol injection cooling.[365] Since stratospheric aerosol injection large enough to produce cooling greater than 0.4°C of cooling is only likely to be deployed in scenarios less benign than RCP 2.6—the phaseout needed to avoid inducing a greater maximum pace of warming than would occur absent stratospheric aerosol injection deployment—may be significantly shorter in practice. If stratospheric aerosol injection phaseout is combined with carbon removal and/or permanent abatement of short-lived GHG emissions, the net increase in radiative forcing could be further dampened.[366] Even if the only goal of climate policy was to minimize the maximum rate of warming, there could be a significant role for stratospheric aerosol injection in dampening the warming effects of increasing GHG concentrations.

Third, termination shock could be prevented by resuming stratospheric aerosol injection within a few months after termination. The half-life of aerosols injected

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[359] *Id.*

[360] *See id.*

[361] Ken Caldeira & Nathan P. Myrvold, *Projections of the Pace of Warming Following an Abrupt Increase in Atmospheric Carbon Dioxide Concentration*, 8 ENV'T RSCH. LETTERS No. 034039 (2013).

[362] Parker & Irvine, *supra* note 357, at 458.

[363] *Id.*

[364] Peter J. Irvine, Ryan L. Sriver & Klaus Keller, *Tension Between Reducing Sea-level Rise and Global Warming Through Solar-Radiation Management*, 2 NATURE CLIMATE CHANGE 97 (2012).

[365] Parker & Irvine, *supra* note 357, at 459.

[366] *Id.* at 466.

into the stratosphere is about eight months.[367] This means about 98% of injected aerosols would remain in the stratosphere after a week and about 92% would remain after a month.[368] The radiative forcing induced by stratospheric aerosol injection would decay slowly enough to allow a buffer before the effects begin to fade significantly. Recall that the earlier discussions of the pace of warming assumed an instantaneous reduction in radiative forcing. The pace would be much slower in the first few months after stratospheric aerosol injection termination since the equilibrium temperature implied by the instantaneous radiative forcing would still be close to the full stratospheric aerosol injection equilibrium.

Meanwhile, the low direct implementation cost of stratospheric aerosol injection and the very prospect of termination shock would create a strong incentive for other actors to step in to restart stratospheric aerosol injection if the actor or coalition that initiated stratospheric aerosol injection were to halt deployment.[369] The threat of termination shock would also encourage countries to build resilience and redundancy into their deployment infrastructure.[370] Even absent such advance planning, the relatively low cost and low-tech nature of some forms of stratospheric aerosol injection could enable new stratospheric aerosol injection delivery mechanisms to be developed and deployed fairly quickly.[371]

Andy Parker and Peter J. Irvine explore three potential pathways for solar radiation management termination. The first two are forced termination pathways: destruction of the solar radiation management deployment infrastructure, and destruction of the economic or political capacity to maintain solar radiation management.[372] The third pathway is elective termination of solar radiation management.[373] For each pathway, they show that multiple hurdles would have to be overcome to result in solar radiation management termination.

For destruction of solar radiation management deployment infrastructure to result in solar radiation management termination, the attack would have to overcome any defense system to disable a large fraction of the primary deployment capacity

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[367] *Id.* at 459.

[368] *Id.*

[369] *Id.* at 463.

[370] *Id.* at 464.

[371] *Id.* at 464–65.

[372] *Id.* at 460–61.

[373] *Id.* at 461–62.

and any backup capability would have to fail to be deployed either by the original solar radiation management sponsor or another party.[374] Hundreds of airplanes, likely operating out of distant airfields, would be needed to induce more than the 0.4°C of solar radiation management cooling to generate significant termination shock.[375] Given the potential costs of sudden termination, it would be worth investing in defenses, similar to those in place for nuclear power plants and military bases, to increase the robustness of solar radiation management deployment infrastructure.[376] This means that a physical attack would need to be extraordinarily well planned, coordinated, resourced, and executed to disrupt a large share of stratospheric aerosol injection deployment capacity.[377] However, it is plausible that a well-designed cyberattack could effectively paralyze an entire stratospheric aerosol injection deployment system at once.[378] Even if defenses failed, however, the buffer period discussed above would allow time for the original stratospheric aerosol injection sponsor to repair the primary deployment system or deploy a backup system or for another country or coalition to launch their own replacement solar radiation management effort.[379] Once again, the significant global costs of potential termination shock would give many actors adequate incentive to restart solar radiation management, particularly given the relatively low deployment costs.[380] Only if all these efforts were thwarted would termination shock come to pass.

A similar analysis applies to the second forced termination scenario. The same precautions that would increase the resilience of a stratospheric aerosol injection deployment system against human attack would also protect against local or regional disasters.[381] Redundant and/or geographically dispersed deployment capacity would be safe from a local or regional catastrophe. A global catastrophe, such as a pandemic, a large asteroid strike, an economic collapse, or a nuclear war could conceivably destroy the capacity of all potential solar radiation management

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[374] *Id.* at 460.

[375] *Id.*

[376] *Id.*

[377] *Id.* at 460–61.

[378] *Id.* at 460.

[379] *Id.* at 460–61.

[380] *Id.* at 463.

[381] *Id.* at 461.

sponsors.[382] However, such an event would have to be enormously destructive to effectively eliminate solar radiation management deployment capacity. For instance, an economic collapse would have to reduce global gross domestic product ("GDP") by over 90% for stratospheric aerosol injection maintenance costs to exceed 1% of the combined post-catastrophe GDP of the largest twenty economies.[383] Even if we assume the potential consequences of termination shock are insufficient to galvanize international cooperation, it would take a more than 70% reduction in U.S. or Chinese GDP for continued stratospheric aerosol injection deployment to cost more than 1% of their individual post catastrophe GDPs.[384] Such an economic collapse would far exceed the scale of World War I, the Spanish flu, the Great Depression, and World War II, each of which resulted in GDP loss in Europe ranging from 8% to 21%.[385]

Nonetheless, an unprecedented catastrophe such as a global nuclear war, large asteroid strike, or particularly severe engineered pandemic could result in termination shock. This sort of scenario is particularly worrisome inasmuch as it would produce a double catastrophe, with termination shock confronting a population that is already vulnerable due to the initial catastrophe.[386] Seth D. Baum, Timothy M. Maher Jr., and Jacob Haqq-Misra analyze these double catastrophe scenarios, concluding that they are highly unpredictable, but that plausible worst-case scenarios include human extinction.[387] Given that a human extinction event would represent an astronomical loss of potential value, such scenarios warrant substantial weight in any risk-benefit analysis even if the probability is quite low.[388]

Parker and Irvine note, however, that modern society is reliant on several other advanced sociotechnical systems like farming and healthcare that, if disrupted by some exogenous catastrophe, would greatly compound the resulting human

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[382] *Id.* For a thorough discussion of the economics of geoengineering, see Barrett, *supra* note 71.

[383] Parker & Irvine, *supra* note 357, at 461.

[384] *Id.*

[385] *Id.*

[386] *Id.* at 465.

[387] *See generally* Seth D. Baum, Timothy M. Maher Jr. & Jacob Haqq-Misra, *Double Catastrophe: Intermittent Stratospheric Geoengineering Induced by Societal Collapse*, 33 ENV'T SYS. & DECISIONS 168 (2013).

[388] *See generally* Nick Bostrom, *Existential Risk Prevention as Global Priority*, 4 GLOB. POL'Y 15 (2013).

suffering.[389] They conclude that more research on such double catastrophe scenarios is warranted as part of the broader existential risk research program.[390] It is plausible that a better understanding of such high-magnitude low-probability events would warrant setting a maximum limit on the cooling induced by short-duration anthropogenic solar radiation management, particularly stratospheric aerosol injection. John Halstead argues that the availability of stratospheric aerosol injection would produce a net reduction in existential risk, since it would eliminate the direct existential risk from climate change, which he estimates to be between 1.0% and 3.5%.[391] Halstead does not offer a numerical estimate of the existential risk from termination shock, but he concludes that it is much smaller, given the extremely low probability of the events that could realistically trigger termination shock.[392] This analysis suggests that existential risk minimization favors at least developing the capacity to deploy stratospheric aerosol injection quickly to offset a significant portion of truly catastrophic warming greater than 10°C.[393]

Parker and Irvine also discuss the potential for voluntary termination of solar radiation management. For this to produce termination shock, solar radiation management opponents would first have to gain political power in countries that are deploying solar radiation management.[394] Then they would have to refuse to ramp down solar radiation management slowly or replace one solar radiation management intervention that causes specific negative consequences with another relatively fast-acting solar radiation management or GHG intervention that minimizes those consequences.[395] Finally they would have to be sufficiently powerful to prevent other actors from launching new solar radiation management deployments.[396] Parker and Irvine suggest several solar radiation management deployment governance policies to mitigate the risk of elective termination.

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[389] Parker & Irvine, *supra* note 357, at 465.

[390] *Id.*

[391] Halstead, *supra* note 2, at 68.

[392] *Id.* at 69.

[393] *Id.* at 68.

[394] Parker & Irvine, *supra* note 357, at 461.

[395] *See id.* at 462.

[396] *Id.*

> In particular, decision-making mechanisms that reduced possible grievances over the impacts of [solar radiation management], or over the decision to deploy it in the first place, would reduce the level of antipathy to an ongoing geoengineering deployment. Making sure that deployment was agreed as widely as possible and was supported by strong support for adaptation and compensation regimes could help reduce injustices and perceptions of injustice. Slowly ramping up the [solar radiation management] cooling, with extensive environmental monitoring before and after deployment, could reduce the risks of damaging environmental effects being discovered only after the point where termination shock had become possible. The development of alternative [solar radiation management] techniques or deployment methods, which might maintain cooling while avoiding given environmental drawbacks, could allow the [solar radiation management system] to be modified to reduce undesired impacts. Finally, stopping [solar radiation management] need not involve termination shock, as parties pushing for an end to [solar radiation management] might be open to a gradual phase out of deployment, reducing the rate of temperature change and hence the impacts of termination.[397]

It is worth also considering to what extent stratospheric aerosol injection or other short-duration solar radiation management interventions pose a unique termination shock risk relative to other short-duration interventions. The most plausible basis for elevated termination shock risk from stratospheric aerosol injection is scale. That is, short-duration GHG interventions like abatement of short-lived GHG emissions could not induce net cooling on the scale needed to create the potential for termination shock, since these gases do not represent a large enough share of total radiative forcing. In theory, rapid warming could be induced by a sudden burst of emissions of highly potent GHGs, but prior abatement would only marginally increase this risk.

Another potentially relevant distinction is that stratospheric aerosol injection, as an affirmative intervention, is more likely to lapse suddenly in context of a catastrophe than a negative intervention like emissions abatement. Note, however, that this distinction does not apply to voluntary termination, which is just as plausible for negative interventions as for affirmative ones. Also, other interventions that are far less controversial, like reforestation and direct air capture, are similarly affirmative and subject to sudden termination. It is the interaction between duration, scale, and potential for sudden termination that makes termination shock most plausible. It is also worth noting that the sudden reversal of an intervention with relatively long expected duration could theoretically produce termination shock. For instance, if carbon storage were deployed at scale and then some catastrophic event

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[397] *Id.*

led to sudden release of a large fraction of the stored CO_2, the rapid increase in net radiative forcing could be comparable to a sudden termination of stratospheric aerosol injection. While a sudden CO_2 release large enough to match the change in radiative forcing from sudden termination of stratospheric aerosol injection may be significantly less likely, it would also be less quickly reversible. In the event of a sudden large carbon release, direct air capture or other negative emissions interventions could not be deployed fast enough to prevent termination shock. In fact, deployment of stratospheric aerosol injection may be the only viable means of avoiding rapid warming under such circumstances.

Lastly, the collateral risks associated with stratospheric aerosol injection may make sudden termination more necessary or desirable than it would be for other interventions. This may be a sound objection to immediate large-scale stratospheric aerosol injection deployment. Indeed, the uncertainty around the precise effects of stratospheric aerosol injection do justify caution in large-scale deployment. However, this uncertainty could be substantially reduced with further study, including field experiments and deployments below the termination shock threshold.

B. Optimal Climate Risk Management Portfolios

Given the multiple dimensions along which climate interferences vary, it is reasonable to ask how we might optimally allocate our efforts among them. After all, the world does not face a discrete choice between investing in conventional mitigation, carbon removal, adaptation, or solar radiation management but a continuous series of decisions about how to invest resources to manage climate risk.[398]

Consider a hypothetical world that was on track for an optimal climate response before anyone dreamed up the idea of solar radiation management. Policymakers had carefully considered appropriate discount rates, the costs of adaptation, and how to value tail risk scenarios and overcome all coordination problems to implement the best possible set of mitigation and adaptation policies, given the available tools. Had the world known about climate change at the time of the industrial revolution, it probably would have made sense then to invest some effort in mitigating the climate change we are now experiencing. However, our forebears would have been justified in reasoning that their much richer descendants could afford to adapt to the little bit of climate change that their fossil-fuel-powered factories were generating. Today, any plausible climate risk management portfolio would certainly involve substantial investment in GHG emissions abatement. On some margin, however, the least cost avoider of damage would cease to be the GHG emitter. Some continued GHG

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[398] NAT'L RSCH. COUNCIL, *supra* note 160, at 178.

emissions in difficult-to-decarbonize sectors (air travel, steel, and cement production) or essential services (backup generators for a hospital) would pass any reasonable cost-benefit test. Accordingly, even in an optimal climate risk portfolio, some effort would be dedicated to adapting to the climate change that does occur. Carbon removal would also play a role, to the extent that it can be deployed at a cost lower than the marginal cost of conventional emissions abatement and the risk-adjusted expected marginal damage from an incremental ton of CO_{2e}, which should be equal in an optimal climate risk portfolio.

With this optimal balance in place, now imagine that some of the world's top scientists, engineers, and economists say there is a cheaper way to achieve some of the policymakers' goals. Some reduction in mitigation effort under such circumstances would be appropriate. Reasonable people can disagree about whether an optimal climate intervention strategy, had it started to be executed decades ago, would have any role for solar radiation management. Perhaps the optimal approach would engage in sufficient decarbonization to all but eliminate the possibility of truly catastrophic warming. Under these conditions, the insurance offered by the availability of interventions like stratospheric aerosol injection might not be worth the cost.

Given the accumulated stock of GHGs in the atmosphere and the large capital investment in fossil fuel infrastructure, however, an optimal climate intervention portfolio going forward would likely involve substantial risk of catastrophic warming if restricted to conventional mitigation and adaptation. Indeed, even the most ambitious emissions pathways, involving extremely rapid decarbonization and deployment of negative emissions technologies, cannot guarantee that warming will be limited to 2°C.[399] This suggests that, even ignoring future geopolitical and other constraints on mitigation and adaptation, we should want to have the option to deploy fast-acting, highly leveraged interventions like stratospheric aerosol injection in tail risk scenarios. Once we account for the ongoing failure of our political institutions to implement sufficiently strong GHG emissions policies, the case for developing options for stratospheric aerosol injection-like interventions gets even stronger. The case for *near-term* deployment of stratospheric aerosol injection or similar interventions is weak, even after accounting for political constraints on decarbonization. However, the case for eventual deployment along with aggressive emissions abatement in likely (i.e., non-tail) scenarios to slow the pace of or shave the peak off otherwise unavoidable warming is considerably stronger.

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[399] Joseph E. Aldy & Richard Zeckhauser, *Three Prongs for Prudent Climate Policy* 24 (Harvard Kennedy Sch. Fac. Rsch. Working Paper Series No. RWP20-009, 2020).

The governance implication of this portfolio analysis is that we should adopt a strong presumption against efforts to stifle solar radiation management research or entirely prohibit its eventual deployment. This does not mean that there is no role for international coordination to resolve disagreements between countries regarding whether, when, and how much stratospheric aerosol injection or other high leverage interventions should be deployed. It does suggest that neither a ban nor a strong taboo against deployment of stratospheric aerosol injection and similar interventions would be desirable, even if it would be feasible. It is to the question of feasibility that we turn in Section IV.C.

C. Governance Tractability

Most of the foregoing analysis has focused on the factors that determine the desirability of strong global governance for various climate system interferences. The upshot of this analysis has been that GHG emissions themselves call out for strong global governance, while the case is more mixed for other interferences. However, there are strong reasons to believe that different climate interferences may be more and less amenable to global governance. Despite decades of concerted effort, there has been precious little progress on global governance of GHG emissions. This experience might incline one to think efforts to govern solar radiation management research and deployment would face similar challenges. Indeed, high-leverage solar radiation management interventions like stratospheric aerosol injection have been said to face a "free driver" problem analogous to the "free rider" problem faced by conventional mitigation.[400] That is, the low direct cost of stratospheric aerosol injection deployment suggests that unilateral deployment is likely, so long as its expected effects would be beneficial to the deploying country. Moreover, the scale of deployment is likely to exceed what is optimal for the world, and instead settle at what is optimal for the geoengineering-capable actor that benefits from the largest scale deployment. This would turn the "free rider" problem, under which conventional mitigation is underprovided, on its head.[401]

Even assuming this "free driver" story is correct, there is an important structural difference between the collective action problems posed by mitigation and high-leverage solar radiation management. In the mitigation context, divergent preferences about climate outcomes play a relatively minor role. If expected climate damages under different mitigation scenarios were spread evenly across countries,

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[400] Weitzman, *supra* note 14.

[401] *Id.* at 1060.

that would not make the global coordination problem all that much easier to solve. To be sure, some countries like Russia that are now relatively invulnerable to climate impacts would be more motivated to reduce their GHG emissions. But the fundamental problem would remain: Most of the damage caused by any particular country's GHG emissions occurs outside of its borders.[402] If countries also had the same risk tolerance and preferences regarding the tradeoff between near-term economic costs and long-term climate damages, they might be able to agree on a globally optimal level of mitigation effort. However, they would still face an enormous challenge in coordinating to engage in the amount of mitigation required to achieve that globally optimal climate outcome.[403]

In the high-leverage solar radiation management context, by contrast, equalizing countries' vulnerability to climate damages (including the deleterious effects of solar radiation management), risk tolerances, and relevant preferences would essentially eliminate the "free-driver" problem. Under such conditions, countries would all mostly agree about whether, when, and how much to deploy high-leverage solar radiation management. Any lingering disagreement would hinge on factual disagreement about the expected payoff from particular interventions, which would be relatively straightforward to resolve. If anything, this agreement regarding the desirability of high-leverage solar radiation management might dissuade any particular country from engaging in it, since it might expect to be able to free ride off the interventions of others. This would reduce the governance challenge for high-leverage solar radiation management to a watered-down version of the free rider problem that could easily be overcome, given the dramatically lower direct implementation costs compared to emissions abatement and carbon removal. In such a circumstance, there might still be a marginal role for global governance in coordinating solar radiation management research and deployment, but the governance challenges would be modest.

Of course, we do not live in a world where countries are equally vulnerable to climate impacts. Estimates of the domestic social cost of carbon vary substantially between countries.[404] For low-lying island states, the stakes in avoiding warming

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[402] Weil, *Beyond the Pledge*, *supra* note 3, at 954.

[403] *Id.* at 933.

[404] Katharine Ricke et al., *Country-level Social Cost of Carbon*, 8 NATURE CLIMATE CHANGE 895, 897 (2018).

beyond a certain level are existential.[405] For other countries, the expected damages are modest.[406] Likewise, countries are not equally vulnerable to different kinds of climate impacts—some would be disproportionately harmed by the negative consequences of high-leverage solar radiation management.[407] In the mitigation context, compensating relatively invulnerable countries for their mitigation efforts is a promising mechanism for addressing differential vulnerability.[408] While this approach could run into problems associated with the opacity of countries' vulnerability, risk tolerance, and preferences, it is hard to know how significant these barriers are while collective action is thwarted by the much more daunting commons problem. In the high-leverage solar radiation management context, this commons problem is greatly muted, so differential vulnerability, risk tolerance, and other relevant beliefs and preferences are front and center as a challenge for global governance. Countries also have stronger incentives to be transparent about their vulnerabilities and preferences in this context to influence high-leverage solar radiation management deployment decisions. Since the active cooperation of all countries would not be needed for effective solar radiation management deployment, the incentives to hold out for a better deal and mislead other countries about one's own vulnerability are also significantly dampened in this context.

The foregoing analysis would seem to suggest that excessive or premature unilateral deployment of high-leverage solar radiation management interventions like stratospheric aerosol injection is the most likely failure mode for governance of unconventional climate interventions. Given the heterogeneous vulnerability of different countries to both the likely impacts of unabated climate change and the likely impacts of high-leverage solar radiation management, there are likely to be one or more powerful countries that prefer much more solar radiation management deployment than would be globally optimal. Given the low direct implementation costs, the standard analysis goes, unilateral deployment is likely.[409]

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[405] Nemat Sadat, *Small Islands, Rising Seas*, UNITED NATIONS: UN CHRONICLE, https://www.un.org/en/chronicle/article/small-islands-rising-seas [https://perma.cc/SSM7-8579].

[406] *Rankings*, NOTRE DAME GLOB. ADAPTATION INITIATIVE, https://gain.nd.edu/our-work/country-index/rankings/ [https://perma.cc/9EVS-6SZZ].

[407] *See id.*

[408] *See generally* Matthew J. Kotchen, *On the Scope of Climate Finance to Facilitate International Agreement on Climate Change*, 190 ECON. LETTERS No. 109070 (2020).

[409] Barrett, *supra* note 71, at 46.

There are, however, strong reasons to doubt the likelihood of unilateral high-leverage solar radiation management deployment. First, the direct implementation costs for controversial unilateral deployment would be significantly higher than for consensus multilateral deployment. This is because the defensive measures needed to effectively secure deployment infrastructure would be significantly greater if other major powers oppose deployment at the chosen scale.[410] This, combined with the necessity of sustained effort to effect a lasting climate impact via high-leverage solar radiation management, limits the number of actors capable of meaningful deployments to a handful of powerful countries.[411]

Second, unilateral deployment runs the risk of destructive interference with other countries' unconventional climate interventions. Multiple uncoordinated stratospheric aerosol injection deployments by different countries at different latitudes could work at cross-purposes.[412] For instance, one country might pursue high-latitude aerosol dispersal to stabilize the arctic climate and protect the Greenland ice sheet. Preliminary modeling suggests that isolated aerosol injection in the arctic would combine with the increased poleward water vapor transport induced by climate change to increase regional snowfall.[413] However, simultaneous stratospheric aerosol injection carried out at lower latitudes would likely reduce water vapor transport, leading to less arctic precipitation and undermining the snowpack gains sought by high-latitude stratospheric aerosol injection deployment.[414]

Another potential source of destructive interference involves aerosol chemistry. The most commonly proposed stratospheric aerosol injection method entails dispersing gas-phase precursors to sulfate aerosols.[415] The process of oxidation and aerosol formation from these precursors is complex. Potential pitfalls include coagulation, which would produce excessively large sulfate particles that sediment out of the atmosphere.[416] Multiple independent and uncoordinated injections would exacerbate the risk of undesirable particulate interactions, reducing the prospects for

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[410] Horton, *supra* note 75, at 59.

[411] Parson & Ernst, *supra* note 70, at 333.

[412] Horton, *supra* note 75, at 60.

[413] *Id.*

[414] *Id.*

[415] *Id.*

[416] *Id.*

successful deployment.[417] Unilateral stratospheric aerosol injection deployment could also interfere destructively with other solar radiation management and carbon removal interventions.[418] Marine cloud brightening, ocean iron fertilization, and land surface-based solar radiation management interventions could each distort the outcome of stratospheric aerosol injection deployment in difficult-to-predict ways, including by altering regional albedo, disrupting circulation patterns, and modifying atmospheric chemistry.[419] These multiple potential sources of destructive interference diminish the expected benefits of unilateral deployment and increase the incentive for countries to coordinate any deployment activities.[420]

Third, any country that initiated a large-scale high-leverage short-duration solar radiation management deployment would confront the so-called termination problem.[421] If solar radiation management deployment were not paired with global emissions reductions, termination would result in rapid temperature increases that might be more damaging than those avoided by initial deployment.[422] This could effectively commit a country that initiates unilateral solar radiation management deployment to continue funding deployment indefinitely.[423] As discussed in Section A above, this termination problem would only arise in the context of short-duration solar radiation management that decreased global average temperatures by more than 0.4°C.[424] Likewise, any termination shock could be mitigated by phasing out deployment slowly.[425] However, if deployment is not coordinated with a strong global program of emissions reductions, the accelerated warming induced by phaseout would be layered on top of the underlying rate of warming driven by increasing atmospheric GHG concentrations.[426] A unilateral solar radiation management deployer might also bank on other countries stepping up to restart

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[417] *Id.*

[418] *Id.* at 61.

[419] *Id.*

[420] *Id.*

[421] *Id.*

[422] *Id.* at 61–62.

[423] *Id.*

[424] Parker & Irvine, *supra* note 357, at 458.

[425] *Id.* at 459.

[426] *See* Horton, *supra* note 75, at 61–62.

deployment when the initial deployer ceases. However, it is hard to imagine this strategy reducing net risk relative to coordinating multilateral deployment in the first place. Also, any country that engaged in such reckless unilateral deployment and cessation of high-leverage solar radiation management would be likely to suffer substantial diplomatic fallout. In any case, while the effective commitment to indefinite solar radiation management deployment may not be sufficient on its own to deter unilateral deployment for certain, it contributes to the interlocking set of forces that make such unilateral action unattractive. [427]

Fourth, governments that strongly oppose a unilateral geoengineering deployment have a number of options for offsetting its effects.[428] These include efforts to *decrease* surface albedo, such as via intentional black carbon deposition,[429] as well as timely emission of highly potent, short-lived GHGs like hydrofluorocarbons.[430] Both of these measures would imperfectly offset stratospheric aerosol injection. Black carbon emissions would directly offset the total albedo effects of solar radiation management but would struggle to match its geographic scope due to the localized nature of black carbon deposition. Fluorinated gas emissions would more closely match the geographic scope of stratospheric aerosol injection but would operate via the atmospheric GHG concentration channel rather than the solar radiation management channel. In either case, the prospect of countermeasures from countries strongly opposed to high-leverage solar radiation management deployment further reduces the expected payoff from unilateral deployment.[431]

Finally, any country that embarks on unilateral solar radiation management deployment would risk retaliation in the form of trade sanctions, diplomatic isolation, less favorable treatment in other policy domains, and possibly even use of force.[432] This means that the total expected cost of unilateral deployment, including these indirect costs, could greatly exceed the direct implementation costs. In combination with the foregoing factors that increase the implementation costs and

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[427] *Id.* at 62.

[428] *Id.*

[429] James Hansen & Larissa Nazarenko, *Soot Climate Forcing via Snow and Ice Albedos*, 101 PNAS 423, 424 (2004).

[430] Horton, *supra* note 75, at 61–62.

[431] *Id.* at 62.

[432] *Id.* at 59.

reduce the expected benefits of unilateral deployment, these indirect costs greatly reduce the likelihood that any country would determine that its interests are best served by unilateral deployment.[433]

One might reasonably ask why, if the potential retaliatory options against unilateral high-leverage solar radiation management deployment are so potent, they cannot be successfully deployed to compel countries to decarbonize their economies. While I strongly support efforts at mutually coercive climate diplomacy, the challenge in the mitigation domain is far greater.[434] In deterring unilateral solar radiation management deployment, governments need only target their punitive measures at a single outlier country. This means they can use coercive tools that would not make sense if applied against the many countries that are not taking sufficient steps to decarbonize their economies. Every country in the world continues to emit GHGs and the vast majority continue to do so at rates that are not consistent with meeting the goal of avoiding 2°C of warming, let alone 1.5°C.[435] GHG emitting activities are deeply woven into the fabric of the modern industrial economy and will take sustained effort to eliminate.[436] In this context, the use or threatened use of retaliatory measures to induce greater mitigation effort is a much more daunting task.

The upshot of this analysis is that high-leverage solar radiation management presents a substantially *easier* governance problem than mitigation. Provided the divergence of interest regarding high-leverage solar radiation management deployment among major powers is not too wide, multilateral agreement regarding large-scale deployment is likely. Note also that such an agreement could be further facilitated by establishing a basic framework of neutral governance principles while scientific uncertainty still places political leaders behind a partial veil of ignorance regarding their nations' interests.[437] The precise content of that agreement will depend on the findings of further research on the costs and benefits of particular interventions. But the basic structure of that governance should be mindful of the three distinct dimensions on which climate interferences vary. A key priority for this governance framework would be determining under what circumstances risky, high-leverage, short-duration solar radiation management may be deployed. Perhaps it should be reserved for genuine emergencies where it is needed to prevent

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[433] *Id.*

[434] *See generally* Weil, *Beyond the Pledge*, *supra* note 3.

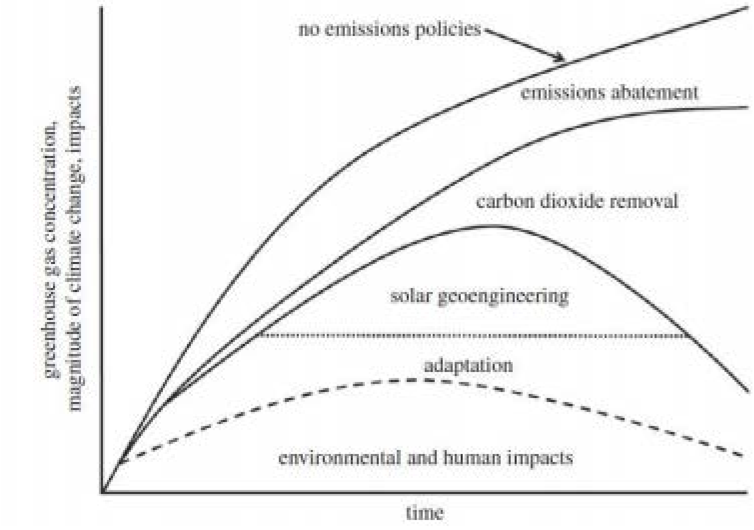
[435] *See Countries*, CLIMATE ACTION TRACKER, https://climateactiontracker.org/countries/ [https://perma.cc/F56K-M99Q].

[436] *Id.*

[437] *See* RAWLS, *supra* note 146.

catastrophic climate outcomes, but there is also a case for limited usage in non-emergency situations to shave the peak off warming, in concert with heavy deployment of emissions abatement and carbon removal interventions.

Figure 5: Peak-Shaving Deployment Scenario



[438]

A key implication of the relative feasibility of high-leverage solar radiation management governance is that influence over the nature, timing, and extent of multilateral solar radiation management deployment could be leveraged to induce greater mitigation effort. That is, a clear signal could be sent that countries that sharply reduce their emissions will be rewarded with a greater voice in setting the terms under which high-leverage solar radiation management interventions might be deployed. Indeed, this is one of the stronger arguments for early action to reach agreement on a basic framework of global governance for high-leverage solar radiation management deployment. The sooner that countries understand that mitigation efforts will be rewarded with influence over high-leverage solar radiation management deployment, the greater the cumulative effect that such incentives could have on atmospheric GHG concentrations. Options for reaping potential gains from a unified climate governance framework will be discussed further in Section IV.E.

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[438] Jesse L. Reynolds, *Solar Geoengineering to Reduce Climate Change: A Review of Governance Proposals*, 475 PROC. ROYAL SOC'Y A, Sept. 4, 2019, at 5 fig.3.

D. Risk Compensation

Another common concern regarding high-leverage interventions like stratospheric aerosol injection is that the availability of a cheaper or easier intervention than conventional mitigation would reduce investment in mitigation.[439] This concern is often referred to as "moral hazard." However, the economic concept of moral hazard is typically understood to involve adverse incentives arising from the interaction between two or more parties.[440] This has led some to prefer describing this problem in terms of crowding out or obstructing mitigation effort.[441] Regardless of the terminology used, scholars generally agree that the mechanism by which the prospect of high-leverage solar radiation management might hinder mitigation efforts is by offering an (apparently) easier, cheaper, or less painful alternative.[442]

Of course, if high-leverage solar radiation management really did offer a cheaper, easier, and less painful alternative that could produce an outcome at least as good as conventional mitigation, then a reduction in mitigation effort would be appropriate. In this sense, concerns about the prospect of solar radiation management obstructing progress on mitigation cannot stand on their own; they only matter if the other critiques of solar radiation management hold. As we know from Part III, however, unconventional climate interventions are not perfect substitutes for conventional mitigation. In Section III.A, we saw how solar radiation management cannot perfectly offset the temperature and precipitation effects of CO_2 emissions. In Section III.B, we saw how interferences vary by several orders of magnitude in terms of duration. In Section III.C, we saw how different interferences operate at widely varying scales and present a qualitatively different set of costs, risks, and uncertainties. Stratospheric aerosol injection, as a high-leverage, short-duration, solar radiation management intervention, differs starkly from CO_2 emissions abatement across all three dimensions.

As discussed in IV.B, these differences do not mean there is no role for stratospheric aerosol injection in an optimal portfolio of climate interventions. Many climate system interventions, like cool roofs and methane emissions abatement, differ from conventional CO_2 emissions abatement interventions along one or two dimensions while remaining uncontroversial components of an overall climate

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[439] Wagner & Merk, *supra* note 90. For example, when one party provides insurance to another against a specific risk, the insured party may take less care to mitigate the risk. *Id.* at 136.

[440] *Id.* at 136.

[441] Halstead, *supra* note 2; David Morrow, *Ethical Aspects of the Mitigation Obstruction Argument Against Climate Engineering Research*, 372 PHIL. TRANSACTIONS ROYAL SOC'Y A, Dec. 28, 2014, at 2.

[442] *See generally* sources cited *supra* notes 438–40.

intervention portfolio. Given its low direct cost and capacity for relatively rapid climate effects, stratospheric aerosol injection has an important potential role in insuring against catastrophic warming. Moreover, given the geopolitical and other barriers to decarbonization, stratospheric aerosol injection's practical role may be much larger than its role in optimal global climate response with no coordination failures. That is, to the extent that the world underinvests in mitigation, the importance of having stratospheric aerosol injection or other high-leverage solar radiation management interventions available grows.

For mitigation obstruction to be a persuasive argument against high-leverage solar radiation management, it would have to induce sufficient incremental reduction in mitigation effort so as to not only exceed the optimal portfolio adjustment to the addition of the high-leverage solar radiation management option, but to exceed it by enough to outweigh the benefits provided by that option. Consider an investor with a portfolio of 100% bonds, because that is the only investment available. If more lucrative, but riskier, equity investment options become available, it would be rational for her to shift some of her investments into that asset class. However, she might err and put too much of her savings into equities, given her risk tolerance. Say her optimal portfolio is a fifty-fifty bond/equity split, but she puts 60% of her savings in equities. This would be an overreaction to the availability of equity investments but might still leave her better off than she was with an all-bonds portfolio. The same could well be true for high-leverage solar radiation management; its availability as an option could induce the world to reduce mitigation investment too much, but still leave us better off.

To be sure, the world already suffers from chronic underinvestment in mitigation for reasons that have little to do with the prospect of high-leverage solar radiation management. Any reduction in mitigation effort induced by the perceived availability of high-leverage solar radiation management would thus be an adjustment in the wrong direction. This could be true even if the magnitude of the reduction is precisely what is warranted by the introduction of the high-leverage solar radiation management option. However, this would not imply that the world is worse off than it would be if high-leverage solar radiation management was somehow permanently ruled out. A modest overadjustment in mitigation effort could leave us better off, so long as the costs of that overadjustment do not exceed the climate risk management benefits of having high-leverage solar radiation management available.

Are there strong reasons to expect that declining to rule out high-leverage solar radiation management would cause a large overreaction in terms of reduced mitigation effort? The phenomenon of risk compensation is well documented.[443] People drive more dangerously as cars get safer and they are required to wear seatbelts.[444] But the basic theory of risk compensation holds that compensation will rationally restore the level of risk to the level implied by the decisionmaker's underlying risk preferences.[445] For overcompensation to occur, the public or policymakers would have to either misjudge the risks of solar radiation management or shift their preferences to become more risk tolerant. Albert Lin, relying on the cognitive science literature on heuristics and biases, argues that optimism bias, overconfidence bias, and hyperbolic discounting may lead people to downplay the risks of geoengineering.[446] He also argues that geoengineering may offer a psychologically attractive sense of control, reinforcing "the belief that humans have the technological capacity to control their environmental future."[447] Lin further suggests that if geoengineering is framed as a solution to climate change, the affect heuristic may cause people to discount its risks.[448] Finally, he worries that high-leverage solar radiation management may be especially appealing to politicians seeking to provide voters a relatively painless and sacrifice-free solution to climate change, while shifting its risks and uncertainties onto future generations that are unrepresented in today's political decisions.[449]

Lin's analysis is speculative, however, and there are equally plausible reasons to expect people to underrate the net benefits of high-leverage solar radiation management. For instance, Lin also notes that "people perceive familiar, voluntary, and natural risks as less threatening than quantitatively equivalent risks that are unfamiliar, involuntary, and man-made."[450] But the risks from high-leverage solar radiation management are even more unfamiliar, involuntary (to all except those who

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[443] Morrow, *supra* note 441, at 1–2.

[444] Sam Peltzman, *The Effects of Automobile Safety Regulation*, 83 J. POL. ECON. 677, 707 (1975); Russell S. Sobel & Todd M. Nesbit, *Automobile Safety Regulation and the Incentive to Drive Recklessly: Evidence from NASCAR*, 74 S. ECON. J. 71, 71 (2007); Adrian K. Lund & Paul Zador, *Mandatory Belt Use and Driver Risk Taking*, 4 RISK ANALYSIS 41 (1984).

[445] Gerald J.S. Wilde, *Risk Homeostasis Theory: An Overview*, 4 INJURY PREVENTION 89, 89–91 (1998), https://injuryprevention.bmj.com/content/4/2/89 [https://perma.cc/6PEJ-7C94].

[446] *See* Lin, *supra* note 89.

[447] *Id.* at 697.

[448] *See id.* at 698–99.

[449] *See id.* at 707.

[450] *Id.* at 694–95.

decide to implement the interventions) and man-made than the risks from climate change. The comparison between public attitudes toward nuclear power and coal-fired power is instructive in this context. Public hostility toward nuclear power in the United States far outstrips the objective health risk, precisely because the risk is exotic and perceived as catastrophic.[451] The ongoing drip of public health harms and accumulating carbon emissions from coal-fired power plants draws comparatively little public concern. Geoengineering strikes many observers as akin to "playing God" and is certainly exotic and open to perceptions of catastrophic risk. It is likewise easy to see the affect heuristic cutting against high-leverage solar radiation management, with the public seeing it as just another risky intervention in the earth's climate system, not unlike GHG emissions themselves. While Lin is correct that short-term political incentives are poorly aligned to support the sort of near-term sacrifice for long-delayed benefits required for decarbonization, it is less clear that the presence of high-leverage solar radiation management as an option significantly exacerbates this problem.

Joseph Aldy and Richard Zeckhauser argue that the prospect of high-leverage solar radiation management deployment might even spur additional mitigation efforts by serving as an "awful action alert."[452] If, as Lin argues, the public does not fully appreciate the risks posed by climate change, policymakers' willingness to consider an extreme option like high-leverage solar radiation management deployment might wake people up to the danger of unabated GHG emissions.[453] To be sure, Aldy and Zeckhauser's analysis is similarly speculative; it is fundamentally hard to know with any confidence whether, how much, and in what direction the public and policymakers' reactions to the possibility of high-leverage solar radiation management will deviate from rational risk compensation. Given the large overreaction needed for risk compensation to make the world worse off, however, our prior should be that this is an unlikely outcome. Indeed, empirical public opinion studies generally do not even support the conclusion that the availability of geoengineering reduces emissions abatement.[454]

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[451] Wolfgang Kröger, Didier Sornette & Ali Ayoub, *Towards Safer and More Sustainable Ways for Exploiting Nuclear Power*, 10 WORLD J. NUCLEAR SCI. & TECH., July 2020, at 91.

[452] Aldy & Zeckhauser, *supra* note 399, at 25.

[453] *Id.*; Lin, *supra* note 89, at 696.

[454] *See* THE ROYAL SOC'Y, *supra* note 10, at 43; Dan Kahan et al., *Geoengineering and Climate Change Polarization: Testing a Two-Channel Model of Science Communication*, 658 AM. ACAD. POL. SOC. SCI. 192 (2015).

It is also worth considering whether high-leverage solar radiation management can effectively be taken off the table in a way that substantially eliminates risk compensation. David Keith, Edward Parson, and M. Granger Morgan argue that, since the possibility of solar radiation management is widely recognized, "failing to subject it to serious research and risk assessment may well pose the greater threat to mitigation efforts, by allowing implicit reliance on solar radiation management without scrutiny of its actual requirements, limitations and risks."[455] No governance regime can fully bind future policymakers from solar radiation management deployment; much less completely banish the belief that solar radiation management is available as an option. If the risks of solar radiation management deployment are as grave as its opponents suspect, further research will illuminate this. A preemptive effort to permanently bar solar radiation management deployment is likely to hinder such research and may be counterproductive in combating excessive risk compensation.[456]

Finally, game theory offers some reason to believe that the availability of risky geoengineering could increase the likelihood of an ambitious climate change mitigation agreement. Adrien Fabre and Gernot Wagner analyze global climate negotiations as a weakest-link game.[457] If some countries prefer high to low mitigation and others prefer low to high, low mitigation is the outcome. Introducing risky geoengineering into the option set may scramble this outcome. Countries that are particularly vulnerable to climate impact might prefer risky geoengineering to low mitigation, with preference ranking high mitigation > geoengineering > low mitigation. Countries that are relatively invulnerable to the impacts of climate change, but stand to suffer significant expected harm from geoengineering, might prefer to bear the costs of high mitigation rather than be exposed to the risks of geoengineering. Their preference order would be low mitigation > high mitigation > geoengineering. Both of these types of players prefer high mitigation to geoengineering, suggesting that the threat of geoengineering by relatively vulnerable countries might induce less vulnerable countries to agree to more ambitious mitigation.[458] Options for leveraging the prospect of high-leverage solar radiation management to promote mitigation are considered in the next section.

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[455] Keith et al., *supra* note 81, at 427.

[456] BODANSKY, *supra* note 79.

[457] Adrien Fabre & Gernot Wagner, *Availability of Risky Geoengineering Can Make an Ambitious Climate Mitigation Agreement More Likely*, 7 HUMANS. & SOC. SCI. COMMS. 1 (2020), https://www.nature.com/articles/s41599-020-0492-6#citeas [https://perma.cc/WD89-XNWK].

[458] *Id.*

E. Linkage

One key advantage of early action to formalize the governance of unconventional climate interventions is that this would enable influence over eventual deployment of high-leverage solar radiation management to be used as an incentive to motivate stronger global cooperation on decarbonization. Control over the terms of solar radiation management deployment could serve as an excludable benefit that could be directed to countries that adopt strong domestic emissions policies, thereby producing non-excludable climate change mitigation benefits for the world. This could help close the gap between emissions policies that pass a strictly domestic cost-benefit test and the more ambitious policies that would be best for the world. Linking solar radiation management deployment governance with emissions policies would require a mechanism for comparing jurisdictions with qualitatively different mitigation regimes. In prior work, I introduced and defended a carbon price equivalent metric that would enable such a comparison—summarizing countries' total mitigation effort in terms of what economy-wide carbon price would have been required to achieve their observed emissions performance.[459] One way to link solar radiation management governance to progress on mitigation would be to make countries' influence over multilateral solar radiation management deployment proportional to their average carbon price equivalent over the period between when the linkage is agreed upon and time when solar radiation management deployment is being considered.

There are, however, obvious limits to how much influence over high-leverage solar radiation management deployment can depend on prior mitigation effort or emissions performance. Large powerful countries expect to have more influence over major global decisions than smaller, poorer, and weaker countries. Multilateral institutions tend to accommodate these countries' greater hard power by affording them greater influence in formal governance processes. The UN Security Council is a good example of this. Any attempt to exclude a powerful country like China or the United States from exerting substantial influence over solar radiation management deployment decisions is unlikely to be accepted by the excluded great power, which would have substantial capacity to act outside formal global governance channels to exert its will. Nonetheless, an advance agreement that the major powers sign onto and view as legitimate may be able to tilt the balance of influence toward countries that make greater mitigation efforts without tempting countries with poorer emissions performance to defect from the solar radiation management governance

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[459] Weil, *Individual Preferences*, *supra* note 189.

framework. What is crucial is that the commitment to reward strong GHG emissions policies with later influence is credible, so that countries have a meaningful incentive to increase their mitigation effort.

Edward Parson offers four options for linking high-leverage solar radiation management governance with conventional mitigation: Plan B Linkage, Reverse Linkage, Real-Time Linkage, and Pay to Play Linkage.[460] In Plan B Linkage, states would pursue decarbonization while building the capacity to deploy high-leverage solar radiation management, with the understanding that it will be used as needed to avoid severe climate impacts.[461] For Plan B Linkage to produce enhanced decarbonization effort, something like the logic of Fabre and Wagner's game theory logic would have to hold. Parson's account does not explicitly depend on a divergence of interests between countries regarding high-leverage solar radiation management deployment. Instead, his account relies on the prospect that the salience of high-leverage solar radiation management's risks will motivate action in a way that expected damage from climate change has not.[462] This is closer to Aldy and Zeckhauser's notion of an "awful action alert."[463] In any case, Plan B Linkage would not be that significant a departure from the status quo, under which states are free to pursue high-leverage solar radiation management research and preparations for deployment. Making this more explicit might indeed raise the salience of the high-leverage options, but it is unclear whether this would have a significant impact on mitigation effort, or what the direction of the effect would be. Plan B linkage would not do anything to overcome the global commons problem that stands as a major barrier to stronger action on mitigation.

Reverse Linkage follows the opposite logic, with states jointly agreeing to refrain from deploying high-leverage solar radiation management no matter how catastrophic the expected impacts of climate change become.[464] This approach relies on the fear of negative climate change impacts, with no hope of high-leverage solar radiation management coming to the rescue, to motivate mitigation. Plan B Linkage and Reverse Linkage rely on mutually incompatible beliefs about the likely effect on

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[460] Edward A. Parson, *Climate Engineering in Global Climate Governance: Implications for Participation and Linkage*, 3 TRANSNAT'L ENV'T L. 89, 105–08 (2013).

[461] *Id.* at 105.

[462] *Id.*

[463] Aldy & Zeckhauser, *supra* note 399.

[464] Parson, *supra* note 460, at 105.

mitigation efforts of raising or lowering the availability of high-leverage solar radiation management deployment as a backstop.[465] As argued in the previous section, we should not be confident that there would be a strong net effect in either direction. Reverse Linkage faces a higher bar since it would have to produce large enough benefits in terms of increased mitigation effort to outweigh the loss of high-leverage solar radiation management as a fallback option. This seems implausible for the reasons outlined in the previous section. Parson, for his part, views credible commitment as the main obstacle to Reverse Linkage.[466] He is right to worry that the permanence of any commitment to forego high-leverage solar radiation management would always be in doubt, meaning that even an outright ban could not completely eliminate risk compensation. Like Plan B Linkage, Reverse Linkage would not help overcome the global commons problem.[467] In fact, it is somewhat misleading to describe the option as a form of linkage at all. It really just represents an attempt to permanently rule out at least some forms of geoengineering, with the hope that this spurs further mitigation action. As indicated in the preceding sections, I believe this extreme approach is inadvisable.

Real-time Linkage seeks to address the intertemporal disconnect that Parson sees as the main problem with Reverse Linkage by linking actions on mitigation and high-leverage solar radiation management concurrently.[468] Instead of reserving high-leverage solar radiation management for situations where it is needed to prevent catastrophic outcomes, a small deployment of solar radiation management would be paired with steep emissions cuts in real-time to shave the peak off of near-term warming or address regional issues like hurricane formation and arctic sea ice loss. On Parson's account, this would make mitigation easier by enabling it to be tied to immediate benefits.[469] But if all policymakers care about is immediate benefits, there is nothing to stop them from just deploying high-leverage solar radiation management interventions and leaving the long-term issues to their successors. Real-time Linkage avoids a separation in time between aggressive decarbonization and high-leverage solar radiation management deployment, but it does not solve the basic problem that policymakers and their constituents are insufficiently willing to bear near-term costs to reap long-term benefits. Perhaps Parson is right that the immediate

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[465] *Id.* at 105–06.

[466] *Id.*

[467] *Id.* at 106.

[468] *Id.*

[469] *Id.* at 106–07.

benefits offered by a modest dose of high-leverage solar radiation management will act as the spoonful of sugar needed to make the medicine of decarbonization go down, but this still requires leaders that are motivated to make their publics swallow the medicine at all.

Real-time Linkage also entails a high likelihood of high-leverage solar radiation management deployment, potentially under circumstances where its risks outweigh its benefits. Parson spins this as a benefit, namely that the scale of needed high-leverage solar radiation management deployment would be reduced.[470] Of course, this is only true if the linkage is successful in bringing about rapid decarbonization. To the extent that risk compensation is a real problem, high-leverage solar radiation management deployment that starts out ostensibly linked to emissions cuts could quickly become a substitute for them if it produces the cheap and rapid results that are desired. Like Plan B Linkage and Reverse Linkage, Real-time Linkage does not directly address the commons problem. However, Parson suggests that the problem of up-front costs and delayed benefits under mitigation alone, which Real-time Linkage is supposed to address, may be the more significant obstacle to conventional mitigation progress.[471]

Parson's final proposal, Pay to Play Linkage, is the only one that addresses the commons problem head on. Pay to Play Linkage works like Real-time Linkage, except that it "also provides individual incentives to deter free-riding, by making each state's mitigation performance a condition for its participation in decision-making" on high-leverage solar radiation management deployment.[472] Parson also considers a weaker version, where exclusion only means that "non-performing states and their citizens and enterprises may not participate in implementing" high-leverage solar radiation management deployment.[473] In both cases, Parson imagines a sharp cutoff between inclusion and exclusion, rather than a sliding scale based on a country's level of mitigation effort.[474] He correctly surmises that the weak form of exclusion is unlikely to offer a meaningful incentive and that the potency of strong exclusion will depend on the expected degree of divergence in national interests and

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[470] Parson, *supra* note 460, at 107.

[471] *Id.*

[472] *Id.* at 107–08.

[473] *Id.* at 108.

[474] *Id.* at 107–08.

preferences regarding high-leverage solar radiation management deployment.[475] If countries largely agree on the circumstances under which it would be appropriate to deploy specific unconventional climate interventions and at what scale to do so, exclusion from decision-making would not be much of a punishment for lagging mitigation performance.

Parson also considers whether the threat to exclude countries from deployment decisions would be credible. He correctly notes that credibility would rise with the size and power of the cooperative coalition.[476] Parson also observes that heterogeneity of national interests and preferences regarding high-leverage solar radiation management deployment would tend to undercut credibility of exclusion, meaning there is a tradeoff between the credibility of the threat to exclude and the incentive effects of a credible threat.[477] He argues that the real-time nature of high-leverage solar radiation management interventions in this scenario would ease these tensions somewhat, "allowing a balance between the disagreeability of exclusion and the credibility of threatening it."[478] It does seem like the efficacy of Pay to Play Linkage would depend on something like the product of the magnitude and the credibility of the threat to exclude from decision making, such that moderate levels of interest divergence would offer optimal leverage. However, Parson offers no compelling reason to think that contracting the decision space to only consider limited, near-term high-leverage solar radiation management deployment would move the magnitude of disagreement toward the optimal level. Moreover, this scenario assumes that the commitment to a limited decision space itself is credible. If powerful countries, whether they be mitigation cooperators or not, strongly prefer to hold high-leverage solar radiation management deployment in reserve to protect against catastrophic climate outcomes, why would they agree to exclude that option from the decision space, let alone hold to that commitment?

If some mechanism for reducing the stakes of exclusion is needed, a better alternative is to abandon the binary inclusion/exclusion structure of Parson's formulation. Instead, as suggested above, influence (perhaps in the form of voting shares) could be made to scale with mitigation effort. Since Parson is correct that large and powerful countries would be difficult to credibly exclude from decision-making entirely, they should instead be sent a clear signal that the magnitude of their

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[475] *Id.* at 108.

[476] *Id.*

[477] *Id.*

[478] *Id.*

influence will vary, within reasonable bounds based on their underlying national power, with their level of mitigation effort. Again, the carbon price equivalent metric I developed in prior work could be used to compare mitigation effort in jurisdictions with qualitatively different GHG emissions policy regimes.[479] This approach would have the advantage of not prematurely eliminating any options for unconventional climate interventions that may later prove attractive. We do not know enough about the risks and benefits of various unconventional climate interventions to rule out the option of keeping deployment capacity in reserve to reduce the risk of catastrophic climate outcomes, for instance.

Keeping the decision space regarding the substantive content of unconventional climate intervention governance as large as possible could also support the goal of locking in a decision framework early. After all, the scholarly opponents of early formalization of geoengineering governance are not wrong to argue that scientific uncertainty should prevent us from committing in advance to specific substantive outcomes. Nonetheless, there are two substantial benefits that could be realized via early action to establish a durable governance framework that includes unconventional climate interventions. First, as soon as the decision framework is in place, it can begin offering governments incentives to increase their mitigation effort. Second, the decision framework can be agreed upon under a partial veil of ignorance, where countries lack full knowledge regarding their ultimate interests and preferences regarding deployment of unconventional climate interventions.[480] This negotiation environment should facilitate agreement on neutral principles for governing high-leverage solar radiation management deployment.

To be sure, this vision for linkage is not a panacea. There are fundamental limits on how much pressure global governance institutions can bring to bear on large and powerful countries. It is unlikely that, on its own, linking governance of unconventional climate interventions with traditional mitigation governance will solve the global commons problems. Credibly committing to substantially reduce the influence of countries with weak emissions policies will be difficult. The basic tradeoff that Parson identifies between strong incentives and credible commitments can only be managed, not avoided. In my proposed framework, that tradeoff would be optimized via agreement over the degree to which decision-making power regarding high-leverage solar radiation management deployment depends on mitigation performance. This would also require some mutually acceptable accounting of the relative power of different parties, which would determine the baseline distribution of influence if all countries were to make equivalent mitigation

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[479] *See generally* Weil, *Individual Preferences*, *supra* note 189.

[480] *See* RAWLS, *supra* note 146.

efforts. None of this will be easy. But linkage can serve as one tool to help the world move toward incentive compatible climate change mitigation, while also enabling effective and legitimate governance of unconventional climate interventions.

V. CONCLUSION

This Article has made the case for a unified framework for climate governance. This conclusion rests on two key premises. First, there is no sharp distinction to be drawn between conventional mitigation and geoengineering. Instead, climate interferences differ across at least three distinct dimensions, each of which are relevant to global governance. Second, linking governance of risky high-leverage solar radiation management with lower risk and higher direct cost GHG interventions can help solve the free rider problem facing efforts to decarbonize. This linkage will require distinguishing between benign climate interventions that we want to fully credit, intermediate interventions that will merely be permitted or partially credited, and riskier interventions that will be the subject of multilateral choice regarding deployment. This distinction must account for the location of interventions along all three dimensions: mechanism of action, characteristic duration, and leverage. Some interventions, like small scale localized solar radiation management (e.g., cool roofs), may not pose great enough risks to require prescriptive regulation at the global level, but also might not warrant being credited in the same way as low leverage, long duration interventions that operate by reducing atmospheric GHG concentrations. Likewise, there is room for reasonable disagreement regarding how to credit GHG interventions of short or uncertain duration. In any case, global climate governance would benefit from a unified approach to all interferences that significantly affect the global climate. This will require abandoning the binary distinction between mitigation and geoengineering and instead applying the principles of climate governance to each dimension along which interferences differ.

The framework laid out here cannot prejudge the disposition of some climate interventions, which will depend on both a negotiation between parties with different interests and priorities and further research that could improve our understanding of the risks and benefits. But it should provide a structure for analyzing those risks and benefits and reaching an accommodation between actors with different preferences and interests. The current state of high scientific uncertainty, which places countries behind a partial veil of ignorance regarding their interests, should be viewed as an opportunity to reach agreement on neutral geoengineering governance principles.