Earth System Governance 3 (2020) 100043

Contents lists available at ScienceDirect

Earth System Governance

journal homepage: www.journals.elsevier.com/earth-system-governance

Review article

An earth system governance perspective on solar geoengineering

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A R T I C L E I N F O

Article history:
Received 21 November 2018
Received in revised form
27 January 2020
Accepted 4 February 2020
Available online 27 February 2020

Keywords:
Climate change
Geoengineering
Climate engineering
Earth system governance
Environmental governance
Environmental politics

A B S T R A C T

Solar geoengineering appears capable of reducing climate change and the associated risks. In part because it would be global in effect, the governance of solar geoengineering is a central concern. The Earth System Governance (ESG) Project includes many researchers who, to varying degrees, utilize a common vocabulary and research framework. Despite the clear mutual relevance of solar geoengineering and ESG, few ESG researchers have considered the topic in substantial depth. To stimulate its sustained uptake as a subject within the ESG research program, we identify significant contributions thus far by ESG scholars on the subject of solar geoengineering governance and survey the wider solar geoengineering governance literature from the perspective of the new ESG research framework. Based on this analysis, we also suggest specific potential lines of inquiry that we believe are ripe for research by ESG scholars: nonstate actors' roles, polycentricity, public engagement and participation, and the Anthropocene.

1. Introduction

In 2001, the leaders of four major international global change research programs agreed upon the Amsterdam Declaration on Earth System Science. Motivated by the rising risks of anthropogenic climate change, among other things, it argued that “An ethical framework for global stewardship and strategies for Earth System management are urgently needed,” and called for “deliberate strategies of good management that sustain the Earth's environment while meeting social and economic development objectives” (Moore et al., 2001).

Thereafter, one of the four – the International Human Dimensions Program on Global Environmental Change – established the Earth System Governance (ESG) Project, which investigates “political solutions and novel, more effective governance mechanisms to cope with the current transitions in the biogeochemical systems of the planet,” in the context of sustainable development, legitimacy, and justice (Earth System Governance, n.d.). Now entering its second decade, it has grown into “the largest social science research network in the area of governance and global environmental change” (Earth System Governance, n.d.). Its network of hundreds of researchers utilize, to varying degrees, a common vocabulary and research framework. This framework was gradually elaborated during the Project's first decade (Biermann et al., 2010) and has now been completely revised. This latest version “explores the innovations, opportunities and complexities emerging in earth system governance with the goal of stimulating a diverse, vibrant, and relevant research community [and] to guide and inspire the systematic study of how societies prepare for accelerated climate change and wider earth system change, as well as policy responses” (Burch et al., 2019:1–2) – and is centered on five paired “research lenses” bracketed by four “contextual conditions” (for details, see below).

Concurrent with these developments, the risks of expected anthropogenic climate change have become increasingly dire. In addition to cutting greenhouse gas emissions (“mitigation”), a wider spectrum of response options is now under consideration: adaptation, carbon dioxide removal (CDR), and solar geoengineering. The last of these would block or reflect a small portion of incoming sunlight in order to counter global warming. Solar geoengineering would constitute deliberate Earth system management and has received growing attention as a possible additional means to lessen climate change and its associated negative

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https://doi.org/10.1016/j.esg.2020.100043

impacts (Linnér and Wibeck, 2015). Evidence consistently suggests it would be effective at reducing climate change, technically feasible, relatively inexpensive, fast-acting, and reversible in its direct climatic effects (Irvine et al., 2019; National Research Councils, 2015; Smith and Wagner, 2018; Tilmes et al., 2018).

Despite the apparent relevance of solar geoengineering to ESG, researcher in the associated network have, for the most part, not applied their analytical approach to solar geoengineering and its governance. (For the few exceptions, see below.) Yet there are multiple opportunities for mutual learning: researchers of solar geoengineering governance from outside the ESG community could draw insights from the application of the ESG analytical framework to this emerging technology; ESG scholars could broaden their analysis of human-earth interactions and how best to govern them; and scholars of global environmental governance more generally could benefit from the knowledge generated by both research communities. In this paper, we promote a deeper and more sustained mutual engagement between the solar geoengineering research community and the broader ESG research program with the ultimate objective of enhancing global environmental governance including that of solar geoengineering. This entails first identifying significant contributions thus far by ESG scholars on this subject, then surveying the solar geoengineering governance literature from the perspective of the new ESG research framework, and finally deriving from these reviews a number of specific research questions pertaining to solar geoengineering that ESG scholars would be particularly well-suited to address. Before doing so, however, we offer a brief introduction to this emerging field.

2. Solar geoengineering

Solar geoengineering is a set of proposed technologies that could serve as an additional response option to climate change. It would block or reflect a small portion of incoming sunlight or otherwise directly alter the planet's energy balance, cooling the earth and reducing global warming without directly changing atmospheric greenhouse gas concentrations. The leading proposed method, which appears to be the most effective and feasible (Intergovernmental Panel on Climate Change, 2018; National Research Councils, 2015; Smith and Wagner, 2018; Tilmes et al., 2018), is inspired by large volcanoes, which temporarily cool the planet by emitting fine particles that linger in the atmosphere for months. Humans could mimic this by dispersing similar small particles into the upper atmosphere. This could use sulfur dioxide – which volcanoes naturally emit – or some other substance. This “stratospheric aerosol injection” technique would have substantial cooling capacity and seems technically and economically achievable. Other proposals include marine cloud brightening and cirrus cloud thinning.

Solar geoengineering, especially stratospheric aerosol injection, presently appears to be effective, technically feasible, inexpensive, rapid, reversible, and — importantly — imperfect. Models consistently show that it could *effectively* bring temperature and precipitation closer to preindustrial levels at the subregional scale (Irvine et al., 2019). Furthermore, the use of solar geoengineering – and especially stratospheric aerosol injection specifically – would necessarily be global in effect. Solar geoengineering's direct financial costs of implementation are presently estimated to be as low as 2.25 billion US dollars annually (Smith and Wagner, 2018). This is *inexpensive* compared to the costs of either aggressive mitigation or climate change damages, each of which could annually be trillions of US dollars (Nordhaus, 2018). It appears *technically feasible* in the sense that the technology necessary to deploy it appears comparatively simple and either already exists or could be developed in relatively short order by a number of industrialized countries and emerging powers (National Research Councils Committee on Geoengineering Climate, 2015:113). Its climatic effects would occur *rapidly* after deployment, on the order of months (National Research Councils, 2015, p. 5). Because of this, solar geoengineering could have a unique role in a portfolio of response options, reducing climate change risks in the short term. Likewise, its direct climatic effects would be largely *reversible* (National Research Councils, 2015, p. 48). Models indicate that, all things being equal, temperature and precipitation would re-equilibrate or return to previous conditions within months or a couple years following a reduction or cessation of solar geoengineering activity (Jones et al., 2013; Lee et al., 2019; Parker and Irvine, 2018). Finally, it would *imperfectly* compensate anthropogenic climate change. Anomalously warm, cool, wet, and dry areas would likely persist, depending on geography and the parameters of deployment (Intergovernmental Panel on Climate Change, 2018, p. 351; National Research Councils, 2015, pp. 34, 40).

Solar geoengineering is receiving increasing attention, and understandably so. Despite the Paris Agreement of 2015, mitigation and adaptation continue to be insufficient to avoid the impacts of dangerous climate change. Furthermore, there is growing awareness that scenarios of future greenhouse gas emissions and atmospheric concentrations that would be expected to keep warming within 1.5 or 2° above preindustrial levels, as agreed upon in the Paris Agreement, would require CDR technologies and practices at enormous – and likely unrealistic – scales (Intergovernmental Panel on Climate Change, 2018; Minx et al., 2018).

Solar geoengineering is controversial for a variety of reasons. Some of these relate to physical and environmental risks. As noted, climatic anomalies would remain, and some scientists are particularly concerned that precipitation patterns could substantially change (National Research Councils, 2015, p. 6). Furthermore, if sulfur dioxide aerosols – the most widely considered substance – were used they might slow the recovery of protective stratospheric ozone. Other concerns are more sociopolitical in nature. For example, solar geoengineering would need to be continuous; sudden and sustained termination would cause climate change to occur at a dangerously rapid rate (Jones et al., 2013; National Research Councils, 2015, p. 48; Parker and Irvine, 2018). It is also unclear how and whether the world's leaders would agree on the deployment parameters. There is justified concern that, due to solar geoengineering's effectiveness and low direct costs, its research and development could undermine efforts to reduce emissions by, for example, tempting decision-makers to substitute it for mitigation, fostering a general sense of complacency, and attracting a growing share of limited resources (Reynolds, 2015). Finally, some object – often on ethical grounds – to the notion of intentional, large-scale intervention in the natural world, which they argue would only increase humanity's environmental footprint and encourage an attitude of hubris (Corner et al., 2013).

3. Methods

In order to review the relevant literature on solar geoengineering from the ESG perspective, we used two databases. Harvard's Solar Geoengineering Research Program maintains a publicly accessible one (Harvard's Solar Geoengineering Research Program, n.d.). Within this, we searched for the phrase “earth system governance” in entries' titles and bodies, returning five results related to the ESG project (Curvelo, 2013; Dryzek, 2016; Hulme, 2008; Surprise, 2018; Talberg et al., 2018). We also searched this database for authors who are identified on the ESG website as lead faculty or senior research fellows, under the assumption that such individuals are relatively likely to employ an ESG approach. From these results, we removed grey literature, publications in which there were only one or two ESG scholars among fifteen or more total authors, and collections where the ESG scholar was the editor – and perhaps wrote an introductory piece – but is not the author of the contribution addressing solar geoengineering. This produced thirteen additional publications (Biermann and Möller, 2019; Burns, 2011; Burns and Flegal, 2015; Hamed et al., 2015; Jinnah, 2018; Jinnah et al., 2018; Jinnah and Bushey, 2017; McDonald et al., 2019; Nicholson et al., 2018; Petersen, 2018; Scholte et al., 2013; Steffen et al., 2011; Zelli et al., 2017).

The second academic literature database is maintained by the ESG international project office, which tracks publications by those within its network and tags entries with subjects, among which is "geoengineering." We applied the same removal criteria as above and also excluded publications that consider only CDR, which is often considered a form of geoengineering. This left seventeen publications (Asayama et al., 2019, 2017; Biermann and Möller, 2019; Bluemling et al., 2019; Conca, 2019; Flegal and Gupta, 2018; Galaz, 2014, 2012; Gupta and Möller, 2019; Horton et al., 2018; Kuokkanen and Yamineva, 2013; Nicholson et al., 2018; Rabitz, 2019, 2016; Reynolds, 2019a; Wibeck et al., 2017; Zelli et al., 2017), three of which were duplicates from the Harvard database. In total, these two data sources yielded 32 publications.

4. ESG engagements with solar geoengineering

This section highlights some ESG scholars' contributions to the solar geoengineering governance discourse. Among these publications, a small number substantively engage with solar geoengineering governance in ways that clearly draw upon an ESG approach, and only one – Talberg et al. (2018) – explicitly references the ESG research framework. They characterize the current "geoengineering" (including both solar geoengineering and CDR) governance landscape as "governance-by-default," in which academics are, in effect, steering collective decisions about geoengineering in the absence of state action. They attribute state inaction to a contradiction between norms of precaution (interpreted as discouraging deployment to prevent harm) and harm minimization (which promotes research). In their view, because the line between research and deployment is unclear, states are paralyzed by these competing impulses.

A related argument is made by Gupta and Möller (2019), who focus on the role of authoritative assessments made largely by academics. By constructing geoengineering (again conceived as both solar geoengineering and CDR) as an object of governance and by normalizing and institutionalizing research, they argue, high-level assessments "de facto" govern geoengineering. Such governance is neither formal nor widely recognized, but its effect is to organize and mold the field in ways that will heavily influence future decisions, including by affecting the discursive frames through which solar geoengineering is interpreted (see also Scholte et al., 2013).

Flegal and Gupta (2018) draw particular attention to so-called "vanguard experts" active in debates about solar geoengineering, whom they characterize as disingenuous in their claims to address justice concerns and as condescending in appearing to speak on behalf of vulnerable populations. By imposing their particular visions of equity on the emerging solar geoengineering discourse, these experts – Flegal and Gupta allege – may be reproducing the structural inequalities they cite as justification for more research.

In a similar vein, Biermann and Möller (2019) argue that solar geoengineering debates have been heavily dominated by individuals from industrialized countries, to the relative exclusion of voices from developing ones and especially the least developed countries. In support of this argument they document a pronounced underrepresentation of individuals from developing countries in international meetings on solar geoengineering as well as a neglect of issues particularly important to the global South in assessments and workshop reports. To correct this, Biermann and Möller urge developing countries to advocate more strongly for their interests in international institutions.

Several ESG scholars have asserted that the legal and regulatory framework for governing solar geoengineering is fragmented or incoherent (e.g. Galaz, 2012; Kuokkanen and Yamineva, 2013). For some, this is at least partly a function of the complexity that is likely to characterize solar geoengineering governance (Biermann, Pattberg, Van Asselt, and Zelli, 2009; Pattberg and Zelli, 2016). Many of these writers conclude or assume that such fragmented or incoherent governance would be ineffective. Dryzek describes the implications of this situation in stark terms: "The required institutions of geoengineering governance would need to be global, paramount and permanent: this means that the efficacy of the institutions and so the technology rests on a path dependency of a scope and strength unprecedented in human history, foreclosing other institutional options, and shutting down reflexivity" (Dryzek, 2016:951–952).

Nicholson et al. (2018) argue that polycentric governance – that is, decision-making that is dispersed but coordinated across multiple sectors and scales – may be particularly suited to governing such an emergent, complex policy space. They propose three specific interventions with polycentric attributes to help address key immediate governance needs: a transparency mechanism, a global forum for public engagement, and incorporating solar geoengineering in the Paris Agreement's global stocktake. Related to this, Jinnah et al. (2018) sketch a proposal for a "Commission on [Solar Geoengineering] Research Governance" to function in the near term at the US state level, with core functions including identifying key research questions and capacities, advising on social and ethical issues, and making recommendations regarding oversight and funding. (Similarly, McDonald and colleagues (2019) recommend an Australian national geoengineering governance framework to address field experiments in the Great Barrier Reef.) Elsewhere, Jinnah (2018) calls for careful consideration of the functional, strategic, and normative "demand rationales" for solar geoengineering in designing a more elaborate governance architecture with polycentric features.

At least two significant themes are apparent in these early contributions from the ESG community. First, in the absence of formal governance structures, ESG researchers underscore the seemingly powerful influence exercised by the solar geoengineering epistemic community in framing issues and setting the policy agenda. Second, in an effort to better understand the current, arguably fragmented governance architecture, they have advanced polycentricity and similar analytic frameworks as having potential both to shed light on contemporary developments in solar geoengineering governance and to suggest alternative institutional pathways.

5. Other engagements from an ESG perspective

Turning from a consideration of what ESG scholars have said about the governance of solar geoengineering, we now consider what has been written elsewhere – that is, not captured in our two-track methodology – on the topic. In doing so, we interpret these discourses from the perspective of the revised ESG research framework, which consists of two parts. First is a set of four empirical "contextual conditions": transformations, inequality, the Anthropocene, and diversity. Second is a set of five paired analytical "research lenses": agency and architecture, democracy and power, allocation and justice, anticipation and imagination, and adaptiveness and reflexivity. These together form the framework's "central element" (Burch et al., 2019). Here, we consider some of the solar geoengineering governance literature through each pair of research lenses in turn, paying particular attention to the presence of contextual conditions throughout.

5.1. Agency and architecture

Diverse agents (that is, political actors who “substantively participate in and/or set their own rules related to the interactions between humans and their natural environment” (Biermann et al., 2010, p. 282)) have been active in shaping the emerging fields of solar geoengineering and its governance. Scientists and other researchers have been at the forefront, and some scientific committees have been particularly influential in defining the field of solar geoengineering, including groups organized under the auspices of the UK Royal Society (Shepherd et al., 2009) and the US National Academies (National Research Councils, 2015). Some academics overtly seek to influence governance of solar geoengineering and have developed principles for geoengineering research and deployment (e.g. Burns and Nicholson, 2016). Of these, the Oxford Principles have had the greatest impact, including endorsement by the UK government (Rayner et al., 2013).

Nongovernmental organizations (NGOs) have also figured as important agents. Some moderate environmental groups, such as the Environmental Defense Fund (n.d.) and the Union of Concerned Scientists (2019), express qualified support for solar geoengineering research. The ETC Group, dedicated to opposing many emerging technologies, has been especially active in promoting hostility toward solar geoengineering through media campaigns and lobbying (ETC Group, 2013).

Perhaps surprisingly, states have been conspicuously absent from activities related to solar geoengineering governance (Reynolds, 2019a), despite a consensus that they will likely be the principal agents in future governance, at least when and if outdoor solar geoengineering activities are undertaken at large scales. Due to both its controversial nature and the lack of domestic constituencies that actively support solar geoengineering, elected and appointed decision-makers appear to have little to gain, and something to lose, by publicly and substantially engaging with these issues. Further, intergovernmental organizations embedded in international regimes – such as the Intergovernmental Panel on Climate Change (Intergovernmental Panel on Climate Change, 2018), Conferences of the Parties to the Convention on Biological Diversity, and Meetings of Contracting Parties to the London Protocol (for details, see below) – have also operated as agents in early efforts to establish governance over solar geoengineering.

Despite the lack of state involvement in solar geoengineering so far, most scholars have emphasized potential state-based governance architectures (Horton and Reynolds, 2016; Reynolds, 2019b). Given the apparently low direct financial cost and technical simplicity of solar geoengineering, a key function of governance is to prevent unilateral, premature, or excessive implementation. Researchers outside of the ESG orbit have thus begun to elaborate at least two main alternatives. First, a small number of states – particularly those with the capacity to implement solar geoengineering – could assert decision-making authority regarding solar geoengineering implementation, an arrangement that is sometimes referred to as a “club” (Benedick, 2011; Lloyd and Oppenheimer, 2014). Such a club would likely reflect existing distributions of state power. Second, broad multilateral governance would place decision-making authority with a larger number of states, including both major and minor powers (Zürn and Schäfer, 2013). As noted above and elaborated below, some ESG-affiliated scholars have recently begun to articulate another possible architecture for governance of solar geoengineering: polycentricity.

A key consideration in theorizing about alternative governance architectures for solar geoengineering is the formal status of institutions, and more broadly the role of international law (Reynolds, 2019a). For example, the Conferences of the Parties to the Convention on Biological Diversity (1992) have issued several decisions regarding geoengineering, including one of caution in 2010 (Decision X/33) and one calling for more research in 2016 (Decision XIII/14). Likewise, the Contracting Parties to the London Protocol to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (1996), approved an amendment (Resolution LP.4(8), not yet in force) to regulate marine geoengineering, which could include some forms of solar geoengineering.

5.2. Democracy and power

Democracy has featured prominently in at least two important debates about solar geoengineering. Many scholars emphasize the need to ensure that solar geoengineering activities are conducted in a way that is democratic. In this context, commentators stress some core procedural elements: public deliberation, engagement, and participation in decision making, as well as transparency in terms of procedural openness and access to information. Participatory mechanisms in particular are considered important means of increasing diversity in debates about solar geoengineering governance as well as empowering groups, countries, and regions that might otherwise be marginalized (Burns and Flegal, 2015; Carr et al., 2013; Rayner et al., 2013). Although all these components — sometimes collectively considered as procedural justice — are widely supported in general, the specifics of their implementation remain unclear and often contested, in part due to the technically complex subject matter (Craik and Moore, 2014).

At a broader level, a prominent debate has centered on the question of whether solar geoengineering is compatible with democracy in the first place. Some scholars have argued that they are fundamentally incompatible, based on claims including that democratic institutions would be incapable of settling disagreements over solar geoengineering, that the right to opt out of collective decisions would be nullified, that the degree of technocracy required would undermine democratic practices, and that solar geoengineering would necessitate a concentration of power resulting in authoritarianism (Szerszynski et al., 2013; see also Dryzek, 2016, p. 952). Others reject this argument, citing implicit technological determinism and an assumption of deliberative democracy as flaws in the assertion of incompatibility, and dispute each of the claims put forward (Horton et al., 2018). In contrast, Symons suggests that, by catalyzing requisite international discussions on a topic in which countries' relative power may substantially shift from the baseline, solar geoengineering may actually further global democracy (Symons, 2019).

Focusing on power, researchers have made assertions and counter-assertions regarding both how much technological, economic, and political power is required to develop solar geoengineering deployment capability and how much power it would endow on actors that possessed it. How these claims bear out will have significant implications for both democratic systems of government and efforts to democratize global governance. With regard to power requirements for solar geoengineering, although its key features including its apparent relative inexpensiveness and technological simplicity would seem to put the technology within reach of a large number of actors (Victor, 2008), broader infrastructure needs as well as the political and economic resources required to overcome sustained opposition suggest that only more powerful states would be in a position to implement it (Parson and Ernst, 2013; Rabitz, 2016). With regard to the power potential bestowed by solar geoengineering capability, some observers assert that it could give developing countries or middle powers greater relative power (Reynolds, 2019a; Symons, 2019), while others have speculated that solar geoengineering could be used as a tool of coercion or hostility (Adger et al., 2014, p. 777). Although the imprecision and uncertainty that would characterize any global climate intervention undercuts the plausibility of this proposition, more general consequences in terms of insecurity and heightened tensions may be outcomes of developed solar geoengineering capability (Corry, 2017).

Researchers have also grappled with how this technology might further extend humanity's power over nature. Activist-scholar Clive Hamilton describes solar geoengineering as a “Promethean” project characterized by dangerous hubris, a lack of respect for “natural” boundaries, and an alarming absence of humility (Hamilton, 2013). For many, the notion of people using high-leverage solar geoengineering technology to modify the climate epitomizes the Anthropocene (Baskin, 2015; Galaz, 2014, 2012; Jinnah and Bushey, 2017). Yet the line between nature and artifact is increasingly blurred in the present Earth system (Preston, 2018). Rather than representing a fundamental break with a prior ontological order, solar geoengineering may alternatively be viewed as a symbolically powerful but otherwise ordinary continuation of systemic transformations in the “age of the human."

5.3. Allocation and justice

Questions of distributive justice have dominated the discourse of solar geoengineering ethics (Preston, 2016). Yet the distributive effects of transformations caused by solar geoengineering would depend on the nature of a given deployment scheme. Variations in amount, duration, location, and other parameters could produce an array of regional and global aggregate welfare outcomes (MacMartin and Kravitz, 2019a).

The first generation of scholars of the politics and governance of solar geoengineering implicitly or explicitly assumed that it would be used to benefit developed countries to the detriment of developing ones (e.g. Zürn and Schäfer, 2013) in ways that would reinforce and potentially exacerbate existing patterns of inequality. But subsequent research has raised the possibility that the least well off may benefit disproportionately from solar geoengineering and hence implementation may have redistributive effects (Harding et al., 2020). Horton and Keith argue that “Taking principles of global distributive justice seriously entails a moral obligation to conduct research on solar geoengineering,” and further that “opposition to research on SRM threatens to violate principles of justice by effectively condemning developing countries to suffer the consequences of activities of which they have not been the primary beneficiaries” (Horton and Keith, 2016, p. 80; but see Flegal and Gupta, 2018).

Intergenerational justice, which seeks to fairly balance the benefits, obligations, and rights of multiple generations, is central to climate ethics. Solar geoengineering further complicates intergenerational justice. Specifically, some scholars argue that conducting research on solar geoengineering now would give knowledge and more options to future generations (Rayner, 2014). Others oppose such “arming the future” claiming that doing so would constitute an abdication of responsibility and exemplify moral corruption (Gardiner, 2010).

In this regard, one particularly worrying aspect of pursuing solar geoengineering is sometimes called “termination shock” (Jones et al., 2013; National Research Councils, 2015, p. 6). If solar geoengineering were undertaken at a substantial magnitude, suddenly ending the intervention without resuming it would, due to its reversibility, result in global warming at a fast rate. Thus, if the technology were deployed at a substantial magnitude of intervention, it would need to be maintained for a long time or slowly phased out. Some observers believe that imposing such a responsibility to maintain solar geoengineering would constitute an unjust burden on future generations (Burns, 2011). However, others argue that this risk is lower than it may initially appear (Parker and Irvine, 2018; Rabitz, 2019).

5.4. Anticipation and imagination

Solar geoengineering is contemplated as a response to the global transformations caused by climate change, and much research has sought to anticipate the additional transformations likely to result from deliberately intervening in the climate system (McCormack et al., 2016; Proctor et al., 2018; Yu et al., 2017). The solar geoengineering research community has employed a range of imaginative forecasting and scenario methods that blend disciplined thinking about causation, sequencing, and likelihoods with an appreciation for the possibility of abrupt change and disruptive events (Low, 2017). A key concern when seeking to anticipate the effects of solar geoengineering — whether or not such methods are employed — is that research, deployment, or even discussion of the technology might undermine already insufficient mitigation efforts. This so-called “moral hazard” concern has been subjected to substantial theoretical and, to some degree, empirical testing (Burns et al., 2016; Reynolds, 2015). The probability and magnitude of harm from mitigation obstruction are not self-evident. Nevertheless, a real or imagined future of solar geoengineering, if dominant, might crowd out possible those of radical mitigation and decarbonization through, for example, revolutionary technologies, emergent lifestyles and values, and economic degrowth.

Whereas foresight and scenario methods are concerned with plausible futures, formal modeling tends to be concerned with probable futures, at least given explicit starting assumptions (Parson, 2008). Researchers have frequently turned to global climate models to predict specific climatic effects of solar geoengineering under a range of scenarios (National Research Councils, 2015, pp. 6—7). Results from climate model simulations generally show that solar geoengineering would, at the regional scale, return both temperature and precipitation closer to pre-industrial values, but would somewhat overcompensate the latter relative to the former (Intergovernmental Panel on Climate Change, 2018, p. 351; National Research Councils, 2015, pp. 34, 40).

In the final analysis, it is the socioeconomic impacts of climate change that will be most important for future generations. To assess the probable scope and scale of impacts from climate change and solar geoengineering, economists and other researchers have incorporated outputs from global climate models into integrated assessment models (Heutel et al., 2018). Given the close association between higher temperatures and greater damages – for example, more heat stress tends to result in reduced agricultural output – these models generally show that solar geoengineering lessens the severity of impacts from climate change at low financial costs. At the same time, these modeling methods neglect other potential social and political consequences of solar geoengineering – such as potentially conflictual decision-making and the ethics of climatic interventions – and thus provide an incomplete evidence base for evaluating possible future use of the technology.

Anticipating a future with solar geoengineering, including in the context of a novel Anthropocene epoch, requires a healthy dose of imagination. Indeed, scholars from science and technology studies have referred to solar geoengineering as a “sociotechnical imaginary,” that is, a collective vision of the future premised on imagined complexes of science, technology, and social practice (Stilgoe, 2015). In a narrow, practical sense, solar geoengineering is imaginary, at least for the moment, in that it does not yet exist. At the same time, there is little doubt that a rudimentary version of solar geoengineering could be assembled quickly using existing components if an actor with sufficient resources so desired. The ultimate utility of the "sociotechnical imaginary" framing is consequently unclear.

5.5. Adaptiveness and reflexivity

The potential scale of the natural and social transformations that could accompany solar geoengineering have caused some commentators to emphasize the importance of building adaptiveness and reflexivity into any future governance. Particularly in the context of the Anthropocene, the possibility of unanticipated development pathways, policy consequences, and environmental and social effects with planetary impacts warrants a high degree of self-awareness and self-reflection on the part of those who would help steer solar geoengineering governance.

We identify three specific reasons why reflexivity should be embedded in solar geoengineering that have been advanced in the literature. The first relates to the "moral hazard" concern discussed above. At the very least, reflexivity in the governance of the various response options – mitigation, adaptation, CDR, and solar geoengineering – could help in efforts to dampen the possibility of "moral hazard."

Second, implementing solar geoengineering – as well as large-scale research – would involve great uncertainty. A significant level of technical uncertainty may simply be irreducible, and decision-making under uncertainty and adaptive management therefore will be essential to the governance of this set of technologies. There is also a growing line of research examining how implementation could be treated as a design problem and how feedback control could help manage uncertainty (MacMartin and Kravitz, 2019b). In addition, the public's preferences and understandings about solar geoengineering will most likely change. To reflect this, public participation and engagement should be central to solar geoengineering governance.

The third reason for the importance of adaptiveness and reflexivity is that some observers have expressed concern that the consideration, research, and development of solar geoengineering could cause future decision-making to be unduly biased toward programmatic expansion and ultimate operational implementation (Cairns 2014; McKinnon 2019). Such path dependence is sometimes called a "slippery slope" or "lock-in," and could occur through a number of mechanisms. Some of these could be more social in nature, in which early decisions empower certain actors, reinforce relationships, and normalize ways of thinking. Other pathways could be more economic, in which design choices could lead to network effects and increasing returns to scale for one path compared to other possibilities. Governance that keeps options open and is adaptive and reflexive to early evidence of lock-in would be salutary.

Opinions differ as to how reflexive the solar geoengineering endeavor has been thus far. At one end of the spectrum, Bellamy and colleagues conclude that major appraisals of geoengineering had "low levels of reflexivity," which leads to "closure around particular sets of hidden values or assumptions [and] produces variably limited ranges of decision options" (2012, pp. 609–610). Applying their theories of responsible research and innovation, however, Stilgoe and colleagues characterize a solar geoengineering research project as increasingly reflexive (Stilgoe et al., 2013, p. 1576). And a qualitative analysis of articles is more favorable in this regard: "Geoengineering proponents… [display] an unusual self-reflexivity, as they are well aware of and seriously consider all the technology's risks," which is "unusual when it comes to large-scale technologies" (Anshelm and Hansson, 2014, pp. 135, 141). Partly due to efforts to heighten reflexivity within the community, solar geoengineering researchers have recognized the lack of diversity within their ranks and the need to promote it in research and governance, both for moral reasons and to improve the quality and performance of research and governance.

6. Potential research questions

Solar geoengineering and ESG are clearly mutually related. After all, solar geoengineering itself would be a means to govern Earth systems. Yet ESG-affiliated scholars have, for the most part, not yet deeply engaged with solar geoengineering governance. In this section, we suggest a handful of specific lines of inquiry that appear to hold both academic and substantive potential. These research questions derive from our reviews in the previous two sections, which point toward a number of unresolved issues pertaining to solar geoengineering governance that the ESG research program is particularly well-suited to address.

6.1. Nonstate actors' roles

As noted, nonstate actors have been conspicuously active in the early discourse about — and arguably in the governance of (Gupta and Möller, 2019) — solar geoengineering. Scientific bodies, individual researchers, and NGOs have been particularly influential in framing issues and setting agendas. While this phenomenon has been widely observed, little effort has been made to connect the relative prominence of nonstate and state actors in solar geoengineering governance to the large literatures on nonstate, private, and transnational governance and regulation. Given ESG scholars' considerable prior work on the role and significance of intergovernmental institutions, transnational networks, and nonstate actors in global environmental governance (e.g. Biermann and Kim, forthcoming; Kuyper and Bäckstrand, 2016), they are well-positioned to describe, explain, and assess the emerging nonstate governance of solar geoengineering. One particular set of underexplored questions involves how nonstate actors in solar geoengineering governance are constituted, how they interact among themselves, and how they form and (re)create power relations and patterns of authority.

Specifically, some ESG scholars have constructed analytical frameworks for theorizing about how nonstate actors relate to state-based multilateral structures. Focusing on the climate change regime, Bäckstrand and colleagues (2017) characterize the climate governance system established under the Paris Agreement as a form of "hybrid multilateralism," in which national pledges to take climate action are monitored and reviewed by transnational actors operating within an international transparency framework. Green (2013) elaborates on how the ascendance of transnational governance creates spaces for "private authority" in which private actors make authoritative rules and set community-wide standards. Widerberg and Pattberg (2017) describe nonstate and substate actors as constituting a "transnational regime complex for climate change" that complements the traditional state-based regime. Reflecting current practices under the UN Framework Convention for Climate Change (UNFCCC), these and similar frameworks mostly emphasize the monitoring and evaluation roles of nonstate actors rather than the problem-framing and agenda-setting activities that have typified nonstate actions around solar geoengineering. This provides twin opportunities to employ such theoretical frameworks to better understand how nonstate actors are shaping early solar geoengineering initiatives and to refine existing frameworks in order to take account of nonstate actors' discursive effects.

In exploring the growing significance of transnational actors, ESG scholars have devoted special attention to the question of accountability. Indeed, in focus groups conducted by Asayama and colleagues, accountability of potential solar geoengineering decision-makers was a recurring theme (2017). In multilateral systems, intergovernmental institutions are — at least in principle — directly answerable to member governments and indirectly so to citizens represented by those governments. In transnational governance, however, it is unclear to whom nonstate actors are accountable. Are NGOs, for example, accountable to their memberships, to the human and nonhuman interests they claim to represent, to (corporate) donors, or to other actors? If their accountability is questionable, is their legitimacy also in doubt? The problem of accountability has been raised by various ESG researchers in the contexts of observer organizations and constituency groups in the UNFCCC (Kuyper and Bäckstrand, 2016), "cooperative initiatives" registered in the UNFCCC's Non-state Actor Zone for Climate Action (Widerberg and Pattberg, 2017), and nonstate actors involved in "multiactor environmental governance" (Newell et al., 2012). In light of the influence exercised by nonstate actors in early governance of solar geoengineering, ESG researchers could provide valuable insights into the nature of accountability and related concepts like representation and legitimacy as exhibited by NGOs.

6.2. Polycentricity

As described above, some ESG researchers have devoted considerable effort to developing and applying the concept of polycentricity. According to Ostrom (2010), polycentric governance is "characterized by multiple governing authorities at differing scales rather than a monocentric unit." Polycentric units engage in policy experimentation and learning to manage common problems, under an overarching system of rules (Aligica and Tarko, 2012). Indeed, a prominent instance of ESG scholars engaging with solar geoengineering has involved attempts to apply the polycentric model to early governance of this technology, as described above (Nicholson et al., 2018).

In these efforts, however, a first-order question has been overlooked: to what degree is polycentricity applicable to solar geoengineering? The model of polycentricity originated in studies of metropolitan governance (Ostrom et al., 1961), but has in the environmental policy context been used typically in the analysis of natural resources management. Efforts to bring polycentricity to bear on climate change have focused on emissions mitigation as the underlying problem, seeking to promote polycentric governance as a means to reduce carbon pollution (Jordan et al., 2015). The prototypical natural resource suitable for polycentric governance is the common-pool resource, defined as non-excludable but subtractive and subject to the twin problems of under-provision and overexploitation (Ostrom, 1990). From this perspective, mitigation can be conceived as a problem of either underprovided emissions reductions or overexploited absorptive capacity of earth systems.

The key problem underlying solar geoengineering, however, is one of overprovision requiring mutual restraint — the "free-driver" (Schelling, 1996; Weitzman, 2015). Insofar as polycentric governance is suited to maintaining stocks and regulating flows of common-pool resources and similar goods or services, its potential to constrain implementation of solar geoengineering is unclear. Scholars of polycentricity have identified and promoted a broad constellation of overlapping decision-making units working toward a shared goal of decarbonization as a potentially superior way to reduce emissions compared to multilateralism. But how could such a multiplicity of actors — ranging from local to international levels, confronting an ongoing challenge of coordination, and with power and authority fragmented and diffused among them — effectively check, block, deter, or otherwise inhibit strong states determined to deploy solar geoengineering? Indeed, this question should stimulate deeper reflection by ESG researchers on when polycentricity is and is not applicable to a governance problem.

6.3. Public engagement and participation

A common theme in solar geoengineering governance discussions is the need for robust public engagement and participatory mechanisms to promote democracy, procedural justice, and reflexivity. ESG scholars have explored such mechanisms and have much to say about the advantages and disadvantages of different processes. These include a number of innovative mechanisms, often enabled by new digital technologies, not previously considered in the solar geoengineering literature. For example, Rask and Worthington (2012) evaluate the World Wide Views on Global Warming multisite citizen consultation held prior to the Copenhagen Summit in 2009 ("the first global citizen deliberation in history"), while Gellers (2016) investigates the performance of a novel "crowdsourcing" technique using online surveys and discussions designed by the UN Development Program to shape the Sustainable Development Goals' content. Other ESG scholars have examined tools ranging from relatively narrow information disclosure systems (Mason, 2010) to comprehensive "open knowledge systems for sustainability" (Cornell et al., 2013).

A typical feature of these mechanisms is their emphasis on deliberation (e.g. see the workshops of Asayama et al., 2019). Indeed, deliberative democracy has been a central focus of ESG research, and participatory processes are frequently viewed as a key vehicle for promoting deliberation in global environmental governance (Baber and Bartlett, 2015). These scholars often see this as critical for both deepening democracy at the global level and improving the environmental performance of policies and governance structures (Bäckstrand et al., 2010; Dryzek and Stevenson, 2011). Underlying this is the key assumption that deliberative democracy is necessarily "green" because it cultivates ecological values and expands notions of citizenship (Arias-Maldonado, 2007).

While research on governance of solar geoengineering would benefit from ESG scholarship on deliberative engagement mechanisms, by considering them in the context of solar geoengineering, ESG scholarship might also be enriched, in at least two ways. First, some solar geoengineering governance researchers have underscored the variety of types of democracy beyond the deliberative model and cautioned against the uncritical privileging of one kind over another (Horton et al., 2018). From this perspective, ESG scholars might seek to explore and evaluate participatory processes inspired by other models of democracy, such as political mobilization. Second and related, the politics of solar geoengineering are characterized by sharp disagreements about the role of technology, the nature of risk, and other issues marked by deeply held values. It is not clear that the sort of communicative action at the heart of deliberative democracy is capable of reaching consensus on such contested questions. Instead, they may be resolvable only through the pluralistic, often conflictual form of politics frequently viewed as the antithesis of deliberation. Solar geoengineering, in other words, may challenge ESG researchers to make the case for deliberative democracy on terrain potentially more favorable to "difference democrats" (e.g. Mouffe, 2000). Success in this regard would demonstrate the value of deliberative democracy in helping overcome deep philosophical differences on issues of public policy to promote the (global) common good. Less than success would also be useful in helping define the practical limits of a deliberative model of democracy that is otherwise normatively appealing.

More generally, given its accumulated institutional knowledge about the politics of expertise (e.g. Bäckstrand, 2004) and the opportunities and challenges to democracy as nonstate actors take on more substantial governance roles (Betsill and Corell 2008), the

ESG community could provide insights into whether competent governance requires technocratic control of technologies like solar geoengineering, and, if that is the case, how this might be reconciled with democracy. Researchers largely outside of ESG have begun to consider this question (e.g. Horton et al., 2018). As demands for governance of solar geoengineering grow, and as debate continues over whether it could be democratically governed, the ESG research community can make critical contributions to discussions of what democracy is, can, and should be in an era of global environmental challenges such as solar geoengineering.

6.4. The Anthropocene

ESG and other scholars have been active in unpacking the sometimes-controversial concept of the Anthropocene, helping to reveal assumptions as to how we understand our relationship with an environment that is altering rapidly due to human influences. Many question the merits of alternative demarcations that have been proposed to delineate the beginning of a new Anthropocene geological epoch, for example, the detonation of the first atomic bomb in 1945 (Lewis and Maslin, 2015; Ruddiman et al., 2015). From a governance perspective, more important issues relate to the political implications of a revised geologic time scale. Malm and Hornborg (2014) criticize the Anthropocene discourse for its treatment of humanity as a monolithic, undifferentiated entity driving global environmental change, when in their view, in reality a particular subset of wealthy, powerful people issuing from specific places and a specific culture — the capitalist elite — has been chiefly responsible for promoting (and profiting from) global industrialization. This homogenization obscures the historically contingent nature of the Anthropocene and its integral connection to a particular social order; it also inhibits the application of social science to the Anthropocene *problematique*, which may prove crucial to successfully addressing contemporary socio-ecological challenges like climate change (Lövbrand et al., 2015).

The prospect of solar geoengineering is clearly related to the Anthropocene proposal. Galaz, a coauthor of the new ESG research framework, notes:

> Recognizing that humanity has moved into the Anthropocene has important repercussions, not only because it forces us to consider resilience at the planetary scale, but also because it forces us to discuss whether it is desirable to shift from unintentional modifications and experimentation with the Earth system to an approach where we intentionally try to modify the climate and associated biogeophysical systems to humanity's benefit. (Galaz, 2012, pp. 5–6; see also Galaz, 2014; Jinnah and Bushey, 2017, p. 505)

For some, the apolitical, systems-orientation typical of Anthropocene thinking leads to a distinctively managerial and technocratic approach to governing the world, for which technologies like solar geoengineering are especially appealing. As Baskin (2015) puts it, “Proponents of the Anthropocene almost always draw a link between the concept and the need for (or, at least, the need to research and consider) large-scale technological interventions, and, in particular, geo-engineering.” Such assertions are possibly bolstered by the fact that Nobel laureate Paul Crutzen both co-originated the concept of the Anthropocene (Crutzen and Stoermer, 2000) and was instrumental in breaking what had been a longstanding taboo on solar geoengineering research (Crutzen, 2006; Lawrence and Crutzen, 2017). For many, solar geoengineering, with its apparent potential to modify the global climate, epitomizes the concept of the Anthropocene.

The ESG community could help assess whether a specifically Anthropocenic governance mindset prevails, and if it does, whether it can be appropriately described as technocratic. Existing ESG scholarship on the Anthropocene has sought to open up the underlying concept while emphasizing how “the Anthropocene lens might suggest a redefinition of existing governance systems” (Biermann et al., 2016). Just as it would be a mistake to reify an Anthropocene version of nature, it would similarly be a mistake to assume a single form of Anthropocene governance. Given its accumulated institutional knowledge about the politics of expertise (e.g. Bäckstrand, 2004), the debate concerning the Anthropocene, solar geoengineering, and democracy would be enriched by the participation of ESG scholars.

7. Conclusion

This review and analysis make clear that researchers in the ESG network are poised to make significant contributions to the understanding of solar geoengineering and its governance. The community's research interests, methods, and normative commitments – as expressed through its research framework – predispose ESG researchers toward asking and developing answers to many of solar geoengineering's most challenging questions. Thus far, direct engagement with this topic by the ESG community has been relatively modest, yet the central thrust of ESG research–on the governance of the Earth system–speaks directly to many of the central questions about solar geoengineering governance already raised by those outside the community. If global society is to seriously contemplate deliberately modifying the planet's climate, then it is essential that decisions are guided and informed by knowledge produced by research communities with the appropriate subject matter expertise and explicitly committed to the study and promotion of democracy, justice, equality, and diversity. The ESG community is ideally placed to contribute in this capacity, and we hope this article encourages comprehensive engagement by its members with these difficult issues.

Declaration of competing interest

None.

Acknowledgements

The authors are grateful for the feedback of Sikina Jinnah, the participants of the 2018 Earth System Governance conference in Utrecht, and two anonymous reviewers, as well as for support from Harvard's Solar Geoengineering Research Program for J.R.'s 2018 visit and from the Open Philanthropy Project.

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