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Solar Geoengineering: Social Science, Legal, Ethical, and Economic Frameworks

Jane A. Flegal,[1] Anna-Maria Hubert,[2,3] David R. Morrow,[4,5] and Juan B. Moreno-Cruz[6]

[1]School for the Future of Innovation in Society, Arizona State University, Tempe, Arizona 85287, USA

[2]Faculty of Law, University of Calgary, Calgary, Alberta T2N 1N4, Canada

[3]Institute for Science, Innovation and Society, University of Oxford, Oxford OX2 6PN, United Kingdom

[4]Forum for Climate Engineering Assessment, American University, Washington, DC 20016, USA

[5]Institute for Philosophy and Public Policy, George Mason University, Fairfax, Virginia 22030, USA

[6]School of Environment, Enterprise and Development, University of Waterloo, Waterloo, Ontario N2L 3G1, Canada; email: juan.moreno-cruz@uwaterloo.ca

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Abstract

Solar geoengineering research in the social sciences and humanities has largely evolved in parallel with research in the natural sciences. In this article, we review the current state of the literature on the ethical, legal, economic, and social science aspects of this emerging area. We discuss issues regarding the framing and futures of solar geoengineering, empirical social science on public views and public engagement, the evolution of ethical concerns regarding research and deployment, and the current legal and economic frameworks and emerging proposals for the regulation and governance of solar geoengineering.

Contents

1. INTRODUCTION

In 2010, a group of scientists met in Asilomar, California, where 30 years earlier another group of scientists had met to discuss the risks of research on genetic engineering. This time, however, the scientists were concerned with a different type of engineering: climate geoengineering (1). Climate geoengineering is a broad concept, and most of its techniques remain highly speculative. The concept of geoengineering itself is much disputed, partly because how it is defined has implications for its study and governance. In 2009, the Royal Society defined geoengineering as large-scale intervention in the climate for the purpose of reducing climate change (2). Under this broad umbrella are a suite of proposed technologies that aim to influence different aspects of the carbon–climate system. One category of proposals seeks to enhance the natural carbon absorption capacity of the planet (carbon geoengineering), while another looks to enhance the reflectivity of the planet to reduce incoming solar radiation (solar geoengineering).

Nontechnical considerations have figured prominently in the geoengineering debate and literature over the last 10 years. There are several possible explanations for this upstream inclusion. For example, proposals to address climate change through deliberate interventions in Earth systems represent, for some, a marked shift in humanity's relationship with nature, and one that challenges current conceptions of environmental ethics, law, and governance. In addition, the rise of geoengineering as a "matter of concern" (3) has coincided with growing demands for the greater social accountability of science and technology in modern societies (4). Recent and persistent public controversies over the societal implications of technologies, as well as broader debates over the distribution of the benefits and costs of innovation, can be read as an implicit acknowledgment of the complex linkages between—indeed, the coproduction of (5, 6)—science and society (7). The seminal 2009 Royal Society report on geoengineering (2, p. 9) reflects this interest in the political foundations of innovation in its conclusion that "[t]he acceptability of geoengineering will be determined as much by social, legal, and political issues as by scientific and technical factors" and in its recommendation to develop and implement governance frameworks for research and development (R&D), as well as potential deployment. Early interest in questions of the governance of geoengineering underscores the perceived need to better understand the ethical, political, and legal issues associated with these ideas.

Solar geoengineering: a set of techniques designed to limit the amount of sunlight entering the atmosphere or increase the amount of heat that leaves the atmosphere

Since the (re)emergence of the topic in the early 2000s, the scholarly literature on geoengineering has included an array of disciplinary perspectives from the natural sciences, social sciences, and humanities. Several recent reviews have covered carbon and solar geoengineering. These reviews have developed frameworks for comparing technologies (8) and have placed them in context with other conventional approaches to combating climate impacts (9). Some have emphasized physical modeling studies (10) and impacts assessment (11). Others have taken the form of consensus reports with the goal of interfacing with policy makers and identifying research priorities (2, 12–16). Here, we review the ethical, legal, economic, and social scientific literature. This article focuses primarily on solar geoengineering, although, depending on the matter, the discussion and analysis may be salient for carbon geoengineering as well.

2. SOCIAL SCIENCE AND GEOENGINEERING

The inclusion of social sciences and humanities early in the geoengineering research process has raised concern among some researchers that such scholarship may have an outsized role in shaping the future of the field of geoengineering, for example, by either prematurely stabilizing geoengineering as a policy option (4, 17) or inhibiting valuable scientific research by giving decision makers and scientists the impression that social scientists, ethicists, and legal experts must sort out the governance issues before any research can or should move forward (18). There are, of course, other explanations, including that upstream inclusion of social scientific and humanities perspectives has not significantly affected decisions by research funders regarding the pursuit of climate geoengineering research, or that it has altered trajectories in more complex ways. Nevertheless, as Rayner (18, p. 113) has argued, these conditions—including a "research impasse"—mean that "the values underlying debates about novel technology are unusually transparent." To be certain, many of the issues raised with respect to geoengineering could just as easily apply to other issues, including climate change more generally. Nevertheless, in this section we review social scientific studies of solar geoengineering, particularly those informed by insights from science and technology studies (STS).

2.1. From the Governance of Risk to the Governance of Innovation

One approach to addressing the social dimensions of science and technology broadly has been to support inquiry into the ethical, legal, and social consequences of large scientific initiatives. However, the treatment of these issues in domains from biotechnology to nanotechnology has been met with some critique. Some researchers have argued that this approach to technological governance is often not well integrated into research itself early enough to steer innovation in meaningful ways (19). Moreover, efforts to understand and evaluate the consequences of research are often expert driven, in which "science proposes, society disposes," and broader societal engagement is limited to scientists informing society about how to respond to the consequences of innovation (7). This has often resulted in formal risk-based regulation, which sometimes fails to anticipate matters of concern early on (20), ignores them, or captures only certain risks as relevant (21). For these reasons, STS-inflected research on geoengineering has sought to account for more than the downstream consequences of a self-governing scientific enterprise. Doing so has involved shifting scholarly attention from the governance of risk to the governance of innovation itself, and addressing questions such as: "[W]hat is the purpose; who will be hurt; who benefits; and how can we know" (22, p. 240)? While these questions apply well beyond solar geoengineering, this section describes efforts to address them in the geoengineering domain.

An important contribution of STS broadly has been to question technological determinism, or the idea that innovation is natural, inevitable, or uncontrollable—although there is some debate about the degree of indeterminacy of particular technologies. Some researchers argue that technologies, including geoengineering, have particular forms of political life inscribed in them from the very beginning, while others believe that political effects are a matter of design choice, and still others afford more interpretive flexibility to the political life of technologies (20, 23, 24). Funtowicz & Ravetz (25) have argued that when facts are uncertain, values are in dispute, stakes are high, and decisions are urgent, society is firmly operating in the context of "postnormal science." By these criteria, many of today's societal problems are postnormal. In such contexts, the traditional mechanisms of peer review are likely to be insufficient to resolve controversies and compel policy action.

These findings raise at least three relevant points for conceiving of governance for geoengineering innovation. First, technologies are not politically neutral, hinting at the imperative to steer technological development toward socially desirable ends upstream in the innovation process itself. Second, because the political life of technologies can become locked in as technologies develop, societies seeking to govern emerging techno-scientific developments are faced with what has come to be known as the Collingridge dilemma: How can technologies be deliberately governed when they are flexible but too inchoate in early stages and too locked in to existing economic and social interests further downstream (20)? Third, the emergent and uncertain nature of geoengineering research implies the need to include broader perspectives upstream in the innovation process.

STS research on the governability of geoengineering has grappled with these issues in several ways. Some scholars have debated whether geoengineering, as it is being constituted, is amenable to democratic governance (26, 27), while others have suggested that it is simply too early to know how this sociotechnical system—which does not yet exist—is likely to develop (4). These understandings imply different prescriptions. If (some forms of) geoengineering are inherently undemocratic, an extremely precautionary position, then perhaps a ban on innovation in this domain might be desirable; if geoengineering is politically undetermined, then governance arrangements might be imagined which steer innovation in more socially robust directions.

STS analysts have examined and proposed formal institutional approaches to governance—including in recommendations for high-level principles informed by STS insights (28), advisory commissions for overseeing research (29), and responsible innovation (21). Many of these efforts draw on lessons learned from historical cases, such as nuclear power, biotechnology, and nanotechnology. In addition to these formal approaches, STS researchers look for the governance of innovation in unexpected places, including in the patent system (30), in analyses of the structuring power of knowledge production in geoengineering research (31), and in how authoritative assessments construct geoengineering as an object of governance (32).

2.2. Framing

An interest in framing, a central matter of inquiry in coproductionist accounts of STS, including research on "sociotechnical imaginaries" (33), has generated a diverse body of literature on framings of geoengineering in media (34, 35), in academic literature (36, 37), in public discourse (38), in key texts and policy documents (37, 39), and at various formative moments in ongoing geoengineering activities and discussions (1). Despite methodological and epistemological diversity, some common themes and points of tension have emerged, not least of which is an understanding that "representations matter as much as whatever we may choose to call reality in shaping social behaviors" (6, p. 25). There has been much discussion of whether framings of geoengineering are narrowing or opening up over time (35, 36, 40, 41); the importance of, and issues with, climate emergency as a framing device (42–45); cross-national comparison of policy framings (37); the emergent narrative around climate geoengineering in contrast to narratives around other emerging technologies (1, 4); analyses of frames/framings as discursive phenomena, actively constructed and negotiated by a range of actors (46); and the need to attend to the power of framing, including in empirical social science on public views of geoengineering (36, 47).

The climate emergency frame has received significant attention. Markusson et al. (45) examine the "preemptive, emergency frame" of geoengineering, arguing that it tends to close down the possibilities for deliberation, that climate emergencies are poorly defined, that it can justify action in the present on the basis of unpredictable futures, and that it needs to be actively defused. Several scholars have noted that this frame can bolster technocratic approaches to environmental management (48). Others have argued that declarations of emergencies can foster a "state of exception" (49, 50) that carries inherent risks (51, cited in 52). Moreover, as Hulme (53, p. 134) has argued, "[c]limate emergencies are made, not discovered, and what matters most is who announces them and for what purpose." Nerlich & Jaspal (42) examine the use of metaphors in promotional discourse related to geoengineering and argue that the catastrophe frame is used to sell geoengineering to the public, which contributes to closing down debates about geoengineering. Luokkanen et al. (54, p. 973) widen the scope of analysis, pointing to diversity in the use of metaphors beyond those that support the climate emergency/catastrophe argument. Their research traces "how geoengineering metaphors are used in a variety of contexts with implications for both positive and negative views and perceptions of geoengineering."

Another central theme is whether framings of geoengineering "in mass media, public engagements, and elsewhere" have been opening up (i.e., becoming more wide-ranging and diverse) (40) or closing down. Scholte et al. (35) map the framing of geoengineering in English-language newspapers from 2006 to 2011, arguing that framings have widened, not narrowed, in recent years. In contrast, in a review of geoengineering appraisals, Bellamy et al. (36, p. 597) argue that geoengineering has often been evaluated in isolation of broader contextual information and that appraisals have been dominated by technical expertise and, therefore, close down "upon particular sets of problem definition, values, assumptions, and courses of action." Concerns about this narrowing can also be found in the literature and practical experience with public engagement on geoengineering (see Section 2.4, below). Sikka (43, p. 173), in her critical discourse analysis of geoengineering advocacy, argues that particular institutions and actors advocating for geoengineering research have strategically framed geoengineering to "limit, shape and mold the current debate surrounding geoengineering." Cairns & Stirling (46) warn of the dangers of co-option via strategic framing devices that can be used to garner support for a particular view.

2.3. Futures

A smaller body of literature, building on research in sociology and STS (33, 55, 56), has examined the politics and sociology of expectations, including how appeals to the future shape near-term geoengineering-related activities (for a brief review, see Reference 57). Some of this research has focused on the role of climate modeling in producing visions of solar geoengineering (58, 59) as well as credibility contests (60) around global climate models for geoengineering purposes (4, 61). Flegal & Gupta (62) analyze how particular visions of equity are embedded in the discourse and practices of advocates of solar geoengineering research or "sociotechnical vanguards" (Hilgartner 2015), which potentially narrow the set of concerns and actors deemed relevant and/or authoritative. Beck & Mahony (63) analyze the politics of anticipation at the Intergovernmental Panel on Climate Change, arguing that pathways for achieving temperature targets are more than technical artifacts, and in fact may work to hasten particular futures into being—futures with wide-ranging political and societal implications, as well as scientific and technical ones. Rayner (64), in his anthropological account of the 2°C goal agreed to at the Paris climate conference, argues that the inclusion of an imaginary technology (in this case, carbon geoengineering) to meet politically negotiated expressive goals, without instrumental commitment to achieving them, constitutes magical thinking.

Stilgoe (65, p. 851) has called into question the stabilization of geoengineering as an object of governance, arguing that it "has been naturalised by its researchers, treated as a thing in the world to be understood rather than a highly controversial, highly speculative set of technological fix proposals." He advocates, instead, for engaging with the collective experimental nature of geoengineering research and its governance—including, perhaps, by adopting interdisciplinary research approaches in the realm of field experiments. Stilgoe (4, p. 35) points to the dynamics of hype that often accompany emerging technologies, while noting that geoengineering would seem distinct from other domains, like nuclear power and genetics, in that "[f]ew people interested in geoengineering imagine that it will be an unalloyed good." Nevertheless, he argues that narrow promising on the basis of predictions of the future should be supplanted with a more inclusive practice of anticipation, which aims to "think through various possibilities" and responsibilities related to innovation (4). Rayner (66) has warned of the "novelty trap" for emerging technologies, which can lure researchers into overselling the newness of their innovations to attract research funds, and downplay those same dimensions as mundane when they attract the eye of regulators.

2.4. Inclusion and Public Engagement

Identifying and promoting tools for enhancing democratic decision making in technical domains have been a central concern of many scientists researching geoengineering. However, analysis of the cultural, ethical, political, and social dimensions of geoengineering have sometimes been divorced from scientific and technical considerations, even though studies of protracted technical controversies and cross-cultural risk assessment have shown that attempts to draw sharp delineations between science and society are likely to make controversies in uncertain and politically contested domains worse. Moreover, research suggests that acknowledging science's political entanglements upstream in the innovation process can enhance the substance and democratic legitimacy of science itself.

Research has analyzed how social, political, ethical, and cultural assumptions are interwoven with technical work, including in the production of knowledge about geoengineering (61, 67). Such research suggests that appeals to the universality and objectivity of science are unlikely to quell concerns about the legitimacy and credibility of geoengineering research, and that there is a risk that even ethical experts may miss some salient issues for diverse publics. Winickoff et al. (61), on the basis of an engagement exercise with environmental practitioners from the Global South, argue for the importance of inclusion and representativeness in knowledge production, as well as governance institutions. Carr & Preston (68) draw on in-depth interviews with vulnerable populations to examine ethical concerns about geoengineering, finding that issues linked to "legacies of colonialism and imperialism" and concerns with self-determination—often missed in existing ethics literature on geoengineering—represent an overarching concern for vulnerable populations. Frumhoff & Stephens (69) argue for the coproduction of research priorities and standards for governance through a process that involves a wide range of potential stakeholders—including civil society organizations from regions of the world that are particularly vulnerable to climate risks.

In the last 10 years, more than 30 studies investigating public views of geoengineering have been undertaken, mostly in the Global North (70), even as natural and physical scientific research on geoengineering has largely been confined to indoor modeling studies. This empirical social scientific research can be interpreted as a response to the recognition of broad public interest in anticipatory governance of geoengineering research (71). Such interest has been articulated by scientific and policy advisory bodies, as well as by natural scientists, social scientists, ethicists, legal experts, and even members of various publics. For example, the 2009 Royal Society report (2, p. 42) argued that "geoengineering research [...] should not proceed in the absence of a wider dialogue between scientists, policymakers, the public and civil society groups."

Anticipatory governance: a broad-based capacity extended through society that can act on a variety of inputs to manage emerging knowledge-based technologies while such management is still possible

As described above, the rationales for greater public engagement with science and technology, and geoengineering in particular, vary widely. These rationales are sometimes considered in three categories: normative, instrumental, and substantive (40, 72). The normative rationale holds that, because geoengineering has the potential to affect the entire planet, wider publics should have a say in whether and how such research moves forward. The instrumental rationale assumes that early engagement might help stave off public controversy. Finally, the substantive rationale is based on the view that researchers do not have a monopoly on the kinds of expertise relevant to science and technology, and that input from nonexperts can enhance the quality of research itself and the utility of technologies. Public engagement can take many forms. It can be a part of more formal processes of technology assessment and/or informal processes, such as protests against emerging technologies. As there are different rationales for engaging publics on geoengineering, so, too, there are different formats for eliciting and analyzing public views. Scholars have warned of treating these approaches similarly, given their different aims and epistemologies (73). For example, the aims of public opinion polling are often distinct from those of public deliberation. For a review of empirical social science on solar geoengineering, see Reference 70.

While the trend toward adoption of public engagement policies within innovation policy—and in geoengineering in particular—suggests that it may be perceived by some countries as beneficial, its effective implementation faces some challenges. First, previous engagement efforts and scholarly research suggest that engagements are most effective at achieving stated objectives when policy makers do not view the public as having deficient knowledge with respect to science and technology (74). In addition, constructing representative publics through such exercises can prove difficult. Some public engagement processes are viewed as legitimate only for those publics directly engaged in them. This has been termed a "fundamental problem of scale" (75, 76) and points to the need to consider engagement exercises as only one element of more responsible innovation policy. There is also the challenge of cross-national differences in civic epistemologies (5). Another issue involves making geoengineering-related decisions responsive to the outputs of public engagement efforts. There is some risk that weak public engagements do not facilitate true deliberation and, instead, serve to legitimate existing policies, especially if these activities adopt a managerial discourse (77). Moreover, these mechanisms of engagement are most likely to have an impact when technologies are further upstream, or before they are locked in (20). This means that, while especially effective in cases of emerging technologies, public engagements can be more challenging for technologies that are already deeply entrenched. It also means that it can be difficult—though certainly not impossible—to engage publics on technologies that are at early stages of development, and therefore inchoate (78).

Critical reviews of the first round of public engagement efforts on geoengineering argue that the topic was perhaps too narrowly construed (36, 79), and as a result more recent efforts have attempted to open up dialogues. Corner et al. (79, p. 14) articulate two issues related to this concern. First, early engagements often introduced geoengineering as a response to a climate emergency, which potentially "artificially enhanced the acceptability of conduct research," and favored proposals that could be fast-acting and operate at the global scale (17). Second, characterizing certain proposals as natural resulted in some publics favoring those techniques (80). Moreover, reliance on expert assessment of the potential risks and benefits of specific technologies potentially limited the ability of participants to consider a broader range of issues about geoengineering, including those potentially missed by technical experts (79). The issue of presenting climate engineering in isolation of other approaches to addressing climate change has also been raised as potentially closing down policy options, or stabilizing geoengineering as a policy option (17, 40).

More recent engagement exercises have attempted to tackle these issues by, for example, changing the inputs provided to the assembled minipublics. This included a weaker role for STEM (science, technology, engineering, and mathematics) experts in facilitating discussions during public engagements (17), expert self-restraint in answering questions, and an attempt to shift geoengineering from noun to verb (e.g., referring to approaches as ideas or proposals and not technologies; see also Reference 65). Recent engagements have tried to take a broader approach in an attempt to situate climate geoengineering in broader discursive fields. Bellamy & Lezaun (17) trace a few specific strategies employed by more recent engagements: The workshops conducted by the Integrated Assessment of Geoengineering Proposals introduced geoengineering in the context of climate change more broadly, rather than as a separate object of discussion (81); the Deliberative Mapping project forced consideration of geoengineering symmetrically alongside mitigation and adaptation (82); and solar geoengineering focus groups decoupled geoengineering from climate change entirely (38). In 2017, Bellamy & Lezaun (17), rather than seeking to unframe geoengineering per se, engaged in self-reflective experimental manipulation of deliberative exercises—both its participants and its rules for deliberation—in an attempt to generate insights into whether and how cultural worldviews affect public views on geoengineering and its governance.

While the aims of public engagement efforts are not to derive generalizable conclusions, a few key themes have emerged across some activities: general unfamiliarity with geoengineering among many publics; the importance of framing; nuanced views of research and deployment; the importance of risk, uncertainty, and controllability; and complicated concerns related to the moral hazard hypothesis. The basic idea of moral hazard in this context is that discussion of either solar or carbon geoengineering might weaken various actors' resolve to cut greenhouse gas emissions.

When it comes to public engagement, several issues warrant further attention. The first is a relative lack of diversity in existing public engagement work along geographical and cultural lines, the kinds of publics (e.g., a focus on lay publics and not experts, policy makers), and other dimensions. Greater attention should be paid to the specific epistemic gaps that researchers and decision makers are seeking to fill. Notably, calls for broad public consultation and/or engagement frequently refer to the need to incorporate the views of vulnerable populations (83), but there has been a paucity of efforts to include these perspectives to date (for exceptions, see References 61 and 68). Existing engagements have tended to focus on understanding publics' general views, but have not focused more narrowly on issues such as concrete research governance options (Reference 17 is one exception, as is forthcoming work from D. Sarewitz). Scholars have pointed out that engagements have revealed the need for climate engineering to be governed responsibly, but very few engagements have considered climate engineering governance, and none have considered how such governance could or should be designed (82). Relatedly, there is a question as to whether existing engagement work has been disconnected from ongoing decision making in ways that fail to fulfill the dimension of responsiveness in responsible innovation (21). Moving forward, there are interesting changes in the context of geoengineering experimentation (and, of course, the broader sociopolitical context) that require continued consideration and scrutiny, including the role of private funding.

3. ETHICAL FRAMEWORK

Scholarship on the ethics of geoengineering reveals the range of ethical issues that arise or would arise at different stages of the process from research through deployment. Key questions surrounding the motivation for R&D include the implications of a precautionary approach and normative questions about the potential benefits and risk–risk trade-offs that would be involved in deployment. Salient concerns surrounding research and its governance include worries about the moral hazard problem, the potentially slippery slope from research to deployment, and the need for transparency and democratic decision making. Any deployment of solar geoengineering would raise profound questions about procedural justice and global governance, distributive concerns, and restitution for loss and damage. The ethical significance of intentionally intervening in or trying to control the climate system also appears as a consistent theme throughout the literature. Many of the ethical issues raised above also apply, in one form or another, to negative emissions technologies.

While ethical issues arise frequently across the many disciplines in the geoengineering literature, they have received the most sustained attention in the philosophical literature, beginning with Jamieson's (83) early effort to lay out some basic ethical arguments for and against geoengineering, along with some conditions necessary for ethical deployment.

The next phase of the ethics literature emerges about a decade later, lasting until approximately 2013. In this phase, ethicists sketch out the main normative issues surrounding geoengineering in more detail, paying special attention to concerns about research and deployment. Betz & Cacean (84) and Preston (85) capture the contours of this debate, and Preston's (86) first edited volume on geoengineering encapsulates many of the concerns expressed during this period. Preston (85) categorizes the normative issues temporally: Some issues arise simply from discussions of geoengineering, some from R&D, some from deployment, and some from the aftermath of any deployment.

Simply discussing geoengineering raises various ethical worries. Chief among these is the so-called moral hazard or mitigation obstruction problem, as defined in Section 2.4, above (i.e., the notion that geoengineering distracts from mitigation efforts). This issue arises, at least in passing, in almost every early discussion of the ethics of climate engineering and receives sustained attention in a few publications (39, 87, 88).

Further issues arise with research into geoengineering technologies. The general discussion, which occurs across disciplines, concerns whether and how to research geoengineering at all. An important part of the early debate concerned the argument that R&D was a way of arming the future with geoengineering technologies in case of a climate emergency. While popular among some scientists, this argument was generally met with skepticism among ethicists (89, 90). If R&D does proceed, an issue arises concerning whether such research calls for special governance principles. The most prominent attempt to articulate such principles, first developed in 2009, became known as the Oxford Principles (28). Another concern, often mentioned but rarely explored in the early literature, is that R&D might put us on a slippery slope toward deployment, even if deployment seems to be unwise (90). A third concern is that such R&D might proceed (or not) without the input of vulnerable populations, including indigenous peoples, even though their fates may depend on whether and how geoengineering is implemented (86).

Some of the weightiest issues would not arise until implementation. The first issue at that stage would be procedural: How could decisions about whether and how to deploy geoengineering be made in an ethically defensible way? Much of the scholarly research on that question has been done in other disciplines, such as law and politics, but ethicists have discussed the ethical challenges of creating decision-making mechanisms that can achieve procedural justice (91), global political legitimacy (92), and the consent of indigenous peoples (93). The second obvious issue, raised frequently in the literature, concerns the impacts of geoengineering. Early discussions focused on downside risks and the potential injustice of harming or dominating vulnerable populations and future generations (91, 94). The third objection is that attempting to control the global climate amounts to hubris, which either is objectionable in itself or courts catastrophe (88). A final concern, which is mentioned frequently but not discussed in detail in the ethics literature, is the risk of a so-called termination effect, in which abrupt cessation of solar geoengineering against a background of rising greenhouse gas concentrations leads to very rapid warming (85).

This first phase of the literature sometimes invokes the precautionary principle, which is usually understood in the philosophical literature to say, roughly, that grave risks justify taking special precautions, especially in the context of deep uncertainty [note the divergence between this understanding and the conventional formulation in international law, as found in the Rio Declaration and the UN Framework Convention on Climate Change (FCCC)]. With respect to solar geoengineering, the precautionary principle can cut both ways, depending on how it is specified (95). Researching or even deploying solar geoengineering might be regarded as a precautionary response to the threat of catastrophic climate change, but because it carries its own risks of serious adverse consequences, precaution could also militate against possible harms from research and deployment (96).

The second phase of the ethical literature in geoengineering begins around 2013 and continues through the present. Heyward's (48) effort to situate different kinds of geoengineering within a complete menu of climate policy options symbolizes the turn from thinking about geoengineering in isolation to thinking about it in the broader context of climate policy and climate justice. In this second phase, ethicists develop earlier strands of thought in more detail and tie them more securely to both the burgeoning climate ethics literature and the growing interdisciplinary literature on geoengineering governance. They also dive more deeply into issues associated with particular geoengineering technologies.

Two collections of papers exemplify most of the key aspects of this phase: Preston's (97) second anthology and a special issue of *Environmental Values* (e.g., 98). The papers in these collections take up key questions about how various kinds of geoengineering might (or might not) fit into a morally acceptable portfolio of climate responses. Taken together, they address one of the central questions about geoengineering: Given the likely options for coping with climate change without geoengineering, could a climate policy portfolio that includes geoengineering be acceptable or even desirable?

The literature of this second phase also deepens the study of particular ethical questions. For instance, studies of the moral hazard problem attempt to integrate recent empirical research and to consider this problem in the context of climate change more broadly (99, 100, 102). Studies of procedural justice consider the requirements for just decision making about geoengineering, including the capacity to stop solar geoengineering if deployment were to begin (101, 103, 104). Other scholars explore questions about compensation for damages from geoengineering (105), the hubris-related objection that geoengineering constitutes playing God (106), and the slippery slope argument (107, 108).

This phase also explores a morally important contrast between geoengineering and climate change: Only geoengineering involves deliberately modifying the climate. Intentions clearly matter in ethics, but the implications of this contrast remain contested (109, 110).

Another trend emerging in this phase is an emphasis on kinds of justice beyond distributive and procedural justice. Morrow (111) and Svoboda (104) focus on nonideal justice, which concerns questions about what to do when ideally just actions are infeasible. Most of the arguments for geoengineering rest, in some way, on the assumption that although it would be ideal for society to address climate change through emissions abatement, given the slow progress on abatement, it might be justifiable to complement abatement with some kind(s) of geoengineering. Hourdequin (112), McLaren (113), and Preston & Carr (114) all address recognitional justice, which requires respectful engagement with persons, including their differences, and scrutiny of exclusion in geoengineering discourses and decisions.

Most of the ethics literature on geoengineering has focused on solar geoengineering. More recently, ethicists have begun to explore the ethical complexity of carbon geoengineering, which only partially overlaps with the ethical issues confronting solar geoengineering. Early research in this area has focused on carbon geoengineering in certain kinds of scenarios (111, 115) or on specific technologies (116–118).

4. LEGAL FRAMEWORK

Early scholarly analysis of geoengineering highlights the significant gaps in existing laws and legal processes to regulate the field. The bulk of this initial work focuses on the potential applicability of existing international environmental regimes and legal norms to geoengineering. It also tracks and describes key legal and institutional developments at the international level. Since then, there have been notable developments in the legal literature in this field, including (*a*) an expansion of the scope of analysis from environmental law to cover other legal subject areas of relevance to geoengineering; (*b*) a broader and more nuanced analysis of the different levels (international, national, transnational) and actors (states, intergovernmental and nongovernmental organizations, companies, and scientific institutions and experts) beyond the traditional sphere of international law that are likely to play a role in the future regulatory and governance landscape; and (*c*) a focus on the near-term regulation and governance of geoengineering R&D, as well as the specific legal issues that arise in this context.

This section focuses narrowly on legal scholarship on geoengineering, and not on governance writ large. Specifically, it reviews the current body of legal literature, including the applicability of existing laws and processes to geoengineering, key legal and institutional developments related to law and governance of geoengineering, and the prospects for regulating and governing different geoengineering methods in the future.

4.1. Current Legal Landscape

Questions related to the regulation of deliberate, large-scale interventions in the natural environment touch upon many subject areas of law. For obvious reasons, much of the legal literature has focused on the interpretation and application of environmental law to geoengineering, which is the focus of the remainder of this section (119–121). More recently, legal scholars have turned their attention to the intersection of international human rights law and geoengineering. For example, Burns (122, p. 1) argues that the adoption of a human rights approach within the context of the climate regime, and the Paris Agreement specifically, "may help to ensure that any potential negative ramifications of climate geoengineering options on the human rights interests of the world's most vulnerable peoples are taken into account and minimized." Further expanding the field of discussion, Reynolds et al. (123) examine law and policies on intellectual property and data access, and how these may shape the behavior of private commercial actors and regulate access to data and technologies concerning solar geoengineering. Looking ahead, as geoengineering proposals mature, further legal analysis of the implications for other subject areas of law—including international trade, food security, international and peace security, and international development—and their interrelationships will be required.

Much of the legal scholarship on geoengineering targets the international level. The main sources of international law that are relevant to the regulation of geoengineering are customary international law and treaty law. Customary international law provides a legally binding set of norms that apply to virtually all countries. As such, it can be conceived of as providing a floor, reflecting a minimum standard that all countries must meet in order to satisfy their international obligations with respect to geoengineering. Specifically, under the foundational no-harm rule, States have the responsibility to ensure that activities within their jurisdiction or control do not cause damage to the environment of other States or of areas beyond the limits of national jurisdiction. This customary norm requires not only that States adopt appropriate laws and measures with respect to their own conduct but also that they carry out "a certain level of vigilance in their enforcement and the exercise of administrative control applicable to public and private operators" under their jurisdiction and control (124). The no-harm rule imposes an obligation of conduct on states to prevent a significant risk of transboundary harm and, thus, would apply to any type of geoengineering activity that triggers this threshold (125). The due diligence standard also incorporates a series of procedural obligations, including duties to exchange information on transboundary risks, to consult and negotiate, and to conduct an environmental impact assessment (EIA). However, although customary international norms, such as the no-harm rule, are "significant in providing a general frame of reference" (119), they are regarded as too general and vague to provide an adequate standard of conduct with respect to specific geoengineering interventions, and it may be difficult to prove elements to make out a breach (e.g., proving the causal link between the climate intervention and specific damage) depending on the circumstances (125, 126). For example, Craik (127) points out the limitations of the customary law requirement to conduct a transboundary EIA as a mechanism for regulating geoengineering, noting, inter alia, that the process narrowly focuses on the assessment of direct, physical impacts and does not provide for analysis of downstream environmental and social risks associated with uncertain and controversial technological developments.

In contrast to customary international law, treaty sources are more specific and typically establish institutions and decision-making processes that allow them to evolve to respond to new issues. Deliberate, large-scale interventions in environmental systems may fall within the regulatory and geographic scope of several treaties. A well-developed body of literature analyzes the interpretation and application of different treaties to geoengineering, including the 1992 UN Convention on Biological Diversity (CBD); the 1992 FCCC and its associated instruments, including the 2015 Paris Agreement; the 1977 Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques; the 1985 Vienna Convention on the Protection of the Ozone Layer (Ozone Convention) and its 1987 Montreal Protocol on Substances that Deplete the Ozone Layer; the 1979 Convention on Long-range Transboundary Air Pollution; the 1967 Outer Space Treaty and related agreements; and the 1982 UN Convention on the Law of the Sea and related international and regional agreements on the protection and preservation of the marine environment. However, Armeni & Redgwell (128, p. 21) point out the limits of this methodology to understanding how different treaties may be relevant to geoengineering governance, arguing that "although useful, this approach overlooks the assessment of how these treaties" and related bodies "perform their functions and objectives in practice and in their wider political context." Instead, these authors analyze the different treaty regimes according to a set of indicators with a view to assessing the key features that contribute to the success of a treaty in achieving its mandate and functions. The advantage of the indicators approach is that it provides "a more realistic picture of pros and cons of governing geoengineering techniques under any given framework (if any) and place existing mechanisms in relation to each other in a more coherent and transparent way" (128, p. 23).

Although many treaty instruments are relevant, few address the topic of geoengineering expressly. There are two important exceptions in the field of international environmental law (129). First, the countries party to the CBD have adopted a series of legally nonbinding decisions of the Conference of the Parties (COP), beginning with the decision in 2008 on ocean fertilization activities. In 2010, States Parties recommended in decision X/33 that, "in absence of science-based, global, transparent and effective control mechanisms for geoengineering," no geoengineering activities should take place except small-scale research subject to specific requirements such as environmental assessment (130). A more recent 2016 COP decision implies a modest policy shift from the strongly precautionary language of previous CBD decisions, noting that "more transdisciplinary research and sharing of knowledge among appropriate institutions is needed in order to better understand the impacts of climate-related geoengineering on biodiversity and ecosystem functions and services, socio-economic, cultural and ethical issues and regulatory options" (131).

Second, the Contracting Parties to the 1972 London Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (LC) and its 1996 London Protocol (LP) have taken steps to address marine geoengineering in the context of the law of the sea. In 2007, private activities involving ocean fertilization prompted the Contracting Parties to the LC/LP to issue a statement of concern and led to further study of the scientific and legal issues within this family of treaties (132, 133). In 2008, they adopted a legally nonbinding resolution stating that ocean fertilization activities other than "legitimate scientific research" should not be allowed (134). This determination was to be made in accordance with a 2010 resolution adopting an Assessment Framework for Scientific Research Involving Ocean Fertilization, which was designed to evaluate whether research proposals for ocean fertilization exhibit "proper scientific attributes," and provides "detailed steps for completion of an environmental assessment, including risk management and monitoring" (135). In 2012, a prominent UK newspaper broke the story that a major ocean fertilization project had been conducted beyond 200 nautical miles of Canada's western coastline, an incident that further strengthened the resolve of the LC/LP to regulate such activities (136). In 2013, countries adopted an amendment to the LP that aims to provide a legally binding framework to regulate marine geoengineering, and ocean fertilization specifically (137; see also 138). The amendment defines geoengineering as "a deliberate intervention in the marine environment to manipulate natural processes, including to counteract anthropogenic climate change and/or its impacts, and that has the potential to result in deleterious effects, especially where those effects may be widespread, long-lasting or severe" (137). However, this definition alone does not determine whether particular activities are subject to binding regulation under the LP. Although currently the only technique addressed in the regulation is ocean fertilization, the amendment adopts a "positive-listing approach," which allows for the regulation of other marine geoengineering placement activities on a case-by-case basis. This "future-proofing" approach provides the Contracting Parties with the flexibility to address new marine geoengineering activities with deleterious effects on the marine environment in the context of a secure, legally binding framework. The amendment also incorporates a general assessment framework and establishes an independent international advisory group of experts to provide guidance on marine geoengineering proposals. The LP amendment is not yet in force, with only two Contracting Parties having deposited their instruments of acceptance to date. This situation provides a vivid illustration of the limits of reliance on treaty-based approaches for regulating geoengineering going forward.

Future evolution of environmental treaty regimes in response to geoengineering is anticipated. Notably, the 1992 FCCC and its associated agreements are all wholly silent on the matter. Despite the present state of affairs, the international climate regime is still arguably one of the most important for the future regulation of geoengineering in light of its object and purpose, declaration of general legal and equitable principles for addressing human-induced climate change, and near-universal participation. Specifically, article 2(1)(a) of the 2015 Paris Agreement (139) adopts a temperature goal that aims at "holding the increase in the global average temperature to well below 2°C above preindustrial levels and to pursue efforts to limit the temperature to increase 1.5°C." Current analysis suggests that this goal is unlikely to be achieved without large-scale implementation of carbon geoengineering methods, and possibly solar geoengineering as well (140, 141). Craik & Burns (142, p. 1) have analyzed the potential applicability of the Paris Agreement to geoengineering, broadly concluding that the "[i]nclusion of CDR [carbon dioxide removal] technologies as part of a State's nationally determined contributions (NDCs) is permissible under article 4 of the Paris Agreement, but will likely trigger concerns respecting technological readiness and equity. SRM [solar radiation management] technologies would appear to have little entry room within the Paris Agreement, but the process mechanism of the agreement provides opportunities to satisfy SRM research governance demands for transparency and public deliberation." Further analysis of the interpretation and application of the Paris Agreement to geoengineering is necessary, particularly as the regulatory and policy framework is elaborated through the ongoing work of the COP.

With regard to enforcement, legal scholars have also examined questions of state responsibility and liability in international law. This analysis shows the limitations of existing legal rules and principles for ensuring legal accountability for environmental harms arising from large-scale geoengineering interventions. Thorny issues arise with respect to definitions of damage, the burden and standard of proof, causation, legal standing, and the availability of appropriate remedies (126, 143).

Scholarly analysis also sheds light on the potential application of domestic law to geoengineering. However, legal research in the area is currently limited to the laws of a handful of developed countries, including Canada (144), Germany (129), the United Kingdom (128), and the United States (145). This area is ripe for additional research that maps out the interpretation, application, and comparison of domestic laws in different jurisdictions to geoengineering.

There are some major caveats to the usefulness of the present body of legal scholarship in clarifying the lawfulness of geoengineering activities. Analysis of the interpretation and application of law to geoengineering is highly fact sensitive and will ultimately turn on the particular circumstances of the case. Moreover, the scientific and technical immaturity of most geoengineering proposals, combined with lack of explicit political and public input on questions of law and governance, means that the existing legal scholarship is inherently limited. Nonetheless, the overall contribution of the current body of scholarship is that it provides a map of the different issues, actors, institutions, and norms relevant to the regulation and governance of geoengineering. In some circumstances, existing laws may apply directly to constrain actors' conduct. Overall, however, significant gaps remain in the coverage of existing international and domestic legal frameworks with respect to geoengineering techniques. Legal analysis shows how existing legal norms provide an important frame of reference and set the terms of debate for the establishment of new instruments or the dynamic evolution of existing ones to address lacunae (119, 132, 146). In addition, given the diverse technical characteristics of proposed geoengineering methods and their effects, the emerging governance picture is one resembling a "patchwork quilt" (128). Legal analysis has only tangentially addressed concerns of legal and institutional fragmentation, which may become more pronounced as regulation and governance develop across different regimes and at different levels.

4.2. Prospects and Proposals

Recent scholarship has focused on developing frameworks to address regulatory and governance gaps. As a starting point, Bodansky (147) usefully describes some fundamental governance issues raised by geoengineering and lays out the possible functions, forms, objects and agents of governance within this context (see also 129). This analysis frames a wider discussion of the different levels, instruments, and actors that are likely to play a role in geoengineering regulation and governance beyond the descriptive mapping approaches adopted in early scholarship.

In addition, there is a growing literature describing the possible scope and contents of geoengineering regulation and governance. Drawing upon existing norms and mechanisms, this research examines general principles and rules (e.g., prevention of environmental harm and precaution) (146), environmental assessment (127), transparency and disclosure mechanisms (148), scientific advisory bodies (149), and public participation (73).

The near-term governance of geoengineering research and innovation constitutes a distinct issue area subject to special considerations that do not come into play in the regulation of established activities (146, 150), such as uncertainty and novelty associated with R&D and the different aims and objectives of research governance in comparison to deployment, as discussed in Section 2.1, above. In its seminal report on geoengineering, the Royal Society (2, p. 61) recommended a program of work on "the development and implementation of governance frameworks to guide both research and development in the short term, and possible deployment in the longer term," including the development of a code of practice for geoengineering research that will "provide recommendations to the international scientific community for a voluntary research governance framework." Taking up this recommendation as a scholarly endeavor, Hubert & Reichwein (146) provide a comprehensive analysis of the various legal norms, mechanisms, and processes that could contribute to the elaboration governance specifically for geoengineering R&D. They also present an in-depth analysis of the role of soft-law instruments such as codes of conduct to provide a flexible, intermediate form of governance to address the conduct of outdoor geoengineering experiments (146, 151). The articulation of standards is only one piece of the governance puzzle, however. Institutional decision-making processes will also play an important role in the regulation and governance of geoengineering research. For example, drawing on different theoretical insights, Jinnah et al. (152) advocate the creation of advisory commissions to oversee and review the governance of solar geoengineering research at the US substate level.

Overall, although legal and other scholarly analysis provides insight, generally speaking, direct political input to define the aims and objectives of geoengineering regulation and governance is lacking or absent. As mentioned in Section 2, geoengineering proposals fall within the category of complex, uncertain, politically contested areas of emerging science and technology. In such cases, upstream regulatory and governance processes must also be designed to consider the normative side of the debate and include of a wider diversity of expert and nonexpert views. International and domestic legal systems often guarantee a right of public participation in environmental decision making, which entails a right of access to information; public participation in decision making; and effective access to judicial and administrative proceedings, including remedies and redress (153, principle 10). In order to provide for greater democratic legitimacy and accountability, the development of regulatory and governance frameworks for geoengineering should coincide with opportunities for public engagement and transparency in decision making about the development of geoengineering proposals (see Section 2.4 for a description of current efforts and further analysis).

5. ECONOMIC FRAMEWORK

Recent reviews have distilled the contributions of economics to the study of solar geoengineering (154–156). Unlike these earlier reviews, this section deals with aspects related to the governance of geoengineering: optimal policy design, or the normative view of the world and the creation of futures; uncertainty and the risks involved in dealing with new technologies; and inequality and fairness, the study of how heterogeneous outcomes affect decisions by interested parties, with particular attention to the role of the free driver.

The starting point of any economic analysis is the understanding of the optimal climate policy that maximizes human welfare. While there have been theoretical contributions to the topic, most of these analyses are done using integrated assessment models. These models suggest future scenarios that offer, from the constraints of the model assumptions, the best way to maximize economic outcomes while minimizing the impacts of climate change. The common threads that emerge from these studies are that solar geoengineering can, at most, be a complement to traditional mitigation techniques (157), that there are welfare benefits from introducing geoengineering in the policy mix, and that there needs to be a more robust research program addressing geoengineering challenges (158, 159). When uncertainty is introduced, the conclusions remain the same, but with an added caveat that, in a world with climate uncertainties, geoengineering can add a new layer of interactions that complicate the policy descriptions (160). Chief among these complications is the risk created by what is now termed the termination effect. This issue has been addressed in the economic literature, but no consensus has emerged from this discussion, and further analysis is required (161, 162). Moreover, this literature has been dominated by traditional cost–benefit analyses that leave out fundamental issues regarding regional disparities and strategic interactions.

A separate strand of the literature analyzes the role of solar geoengineering in changing international relations. This literature starts with the seminal paper by Schelling (163) that presents solar geoengineering as a low-implementation-cost alternative to mitigation with large social implications. In particular, these technologies offer the capability of some countries to impose their preferred climate on others, thus creating the possibility of conflict. Of course, these technologies can also help increase cooperation in the international community regarding climate change. This possible alternative was introduced by Barrett (164), who argues that the reduced costs and high leverage of solar geoengineering technologies could help reduce the problem of climate mitigation, something akin to global poverty remediation, to one of coordination, something more akin to the funding of the International Space Station. In two independent papers, Moreno-Cruz (165) and Millard-Ball (166) go a step further and introduce the concept of geoengineering threat (see also Reference 167 for a dynamic-game setting). These authors argue that once the assumption of symmetry from Barrett's paper is abandoned, a richer set of results appear whereby the presence of solar geoengineering not only reduces the costs of climate change but also increases the contribution of mitigation by all countries. This view of the world relies on the assumption that countries will not retaliate using other forms of force. In order to circumvent this issue, Ricke et al. (168) consider the formation of coalitions that are powerful enough to sustain any attempt to deviate from their preferred climate. The resulting coalitions have an incentive to exclude countries for participating, suggesting that future geoengineering climates will approach the preferences of the most powerful countries.

The issue of exclusion and power in the international arena is best captured by Weitzman's (169) definition of the free driver. Free driving is defined as the capacity of a single agent, such as a country or a very rich individual, to impose its desires on other countries by implementing a larger-than-optimal amount of a particular public good, thus transforming it into a "public bad." The free-riding externality arises with solar geoengineering because it has low technical implementation costs and high leverage on the climate. The free-driving externality has presented the economics community with one of the most challenging governance problems. A large literature in climate economics deals with the issues of lack of cooperation and underprovision of global public goods (170). The free driver presents new challenges because the regulatory framework is meant to stop a country, or a small coalition of countries, from implementing too much solar geoengineering. Weitzman (169) defines a voting architecture such that the amount of geoengineering implemented is decided by a global government with the goal of limiting the side effects of solar geoengineering. Others have introduced free driving in more traditional economic frameworks (165, 171).

The problem with solar geoengineering is that it could be individually incentive compatible to deviate from some global optimal, and in fact there is no international agency able to rein in a free driver, if one were to appear. All international governance proposals to date tacitly assume that some international agency will police and punish those who deviate from their promised strategy. Two recent working papers (172, 173) introduce counter-geoengineering as a deterring mechanism to the overprovision of solar geoengineering. Counter-geoengineering can be implemented at low cost to counterbalance the climate effects of solar geoengineering either by neutralizing solar geoengineering or by increasing warming in equal proportion to the overcooling created by the free driver (172). The framework in Reference 173 shows that counter-geoengineering can endogenously generate a moratorium equilibrium but can also lead to costly tit-for-tat outcomes where all countries are made worse off. Thus, regulating the free driver remains the most difficult issue in the international economics of solar geoengineering.

Finally, geoengineering plays a role in redistributing the impacts of climate change. Because solar geoengineering imperfectly compensates for climate change, countries that gain the most from geoengineering are not necessarily those that would suffer the most from climate change. There has been little economic analysis of the distributive issues regarding solar geoengineering. One of the few papers addressing heterogeneity in the welfare response to solar geoengineering is that by Moreno-Cruz et al. (160), who devise a Pareto-optimal policy. Using the climate model simulation results in Reference 174, they propose a "residual angle model" and find that there is an amount of solar geoengineering that significantly reduces climate damages without making any single country worse off. In a follow-up paper (175), the authors applied the same methodology to a host of alternative scenarios defined in the Geoengineering Model Intercomparison Project, finding similar results.

The residual angle model approach has two limitations. First, it assumes that all countries would want to return to preindustrial temperatures (59). Clearly, if given the opportunity, countries would prefer temperatures that match their economies today, not more than 200 years ago. Second, the approach assumes that damages are proportional to deviations from the optimal temperature and precipitation. A recent publication (176) has attempted to address this issue by incorporating new econometric techniques to estimate the damages from climate change for each country and the possible benefits from solar geoengineering. As the field matures, however, there is evidence of growing cracks and fissures in expert discussions about the research, deployment, and governance of geoengineering along disciplinary lines. The power asymmetries in the context of interdisciplinary work remain.

6. CONCLUSIONS

The idea of solar geoengineering remains on the fringes of climate policy. Assertions that solar geoengineering is cheap and easy are true only if one does not examine its full costs, including the ethical, legal, and economic issues it raises. Meanwhile, carbon geoengineering is making its way onto the climate policy agenda and seems poised to attract increasing attention from social scientists.

Solar geoengineering remains a highly speculative set of ideas for addressing climate change risks. In fact, as research has illustrated, there is almost no engineering in geoengineering. To date, research—where it has been funded—has tended to focus on computer simulations and speculation about ethics and effects. This may change, particularly as researchers turn to private funding for experimentation.

The field of geoengineering is noteworthy for having emerged in a uniquely interdisciplinary context. As the field matures, however, there is evidence of growing cracks and fissures in expert discussions about the research, deployment, and governance of geoengineering along disciplinary lines. These divergences are evident in the various approaches to this topic taken in this review. Yet geoengineering, as a response to human-induced climate change, embodies all of the features of a wicked problem—it is extremely complex and deeply uncertain, entails profound ethical issues and trade-offs, and even raises fundamental disagreements about the nature and framing of the problem itself. Looking ahead, institutional processes will have an important role to play to ensure that "multiple, diverse, perhaps incompatible, perspectives are brought to bear, resulting in a settlement that is inelegant from any single perspective, but robust because it relies on more than one epistemological and ethical foundation" (177, p. 123).

SUMMARY POINTS

1. Solar geoengineering, as a sociotechnical system capable of delivering geoengineering outcomes, does not yet exist. There are significant methodological challenges associated with studying an imaginary technology using traditional social scientific tools. As a result, some social scientific research has examined attempts by a small set of actors to get the topic on the public agenda (or keep it off).
2. Social scientific scholarship has tended to focus on imagined scenarios of deployment and, to a lesser extent, near-term questions regarding the governance of research.
3. Public engagement is widely regarded as important for geoengineering governance, largely for normative and instrumental reasons. The substantive rationale—that public engagement can improve the content of geoengineering research itself—is underappreciated in the literature. Public engagement on geoengineering has often been geographically limited, disconnected from policy making, and difficult, given low familiarity with geoengineering.
4. The ethics literature is evolving from a narrow focus on distributive and procedural concerns about solar geoengineering to a broader assessment of solar geoengineering and carbon geoengineering in the context of climate justice.
5. Regulation and governance of geoengineering will develop in reference to existing legal norms and processes at the international and domestic levels. Legal and institutional gaps exist at the international and domestic levels. The regulation and governance of geoengineering will have to develop in reference to existing legal norms and processes, while also taking into account the more novel features of geoengineering proposals. Cooperation and coordination across different levels and regimes will be important to address concerns of fragmentation and normative incoherence.
6. The legal literature provides rich insights into how geoengineering should be regulated along the the near- and long-term horizons. However, direct political input is currently lacking, and it is important that other stakeholders and the general public be included in upstream development and governance of geoengineering proposals.
7. Estimating the impacts of climate change and solar geoengineering is fundamental to understanding of geoengineering proposals. More research is needed in this area.
8. The free-driver problem is the most nuanced and complex issue that arises from the economic analysis of solar geoengineering.

FUTURE ISSUES

1. Field experiments with solar geoengineering technologies could become a reality in the near future, including proposals that are privately funded. Social, political, and legal systems will be challenged to respond to these pressures.

2. There will be campaigns to shape the views of the general public. Inclusion of all countries and all peoples and publics will be paramount.
3. While carbon geoengineering has started to emerge in mainstream climate law and policy, solar geoengineering has not yet taken hold. This topic remains highly controversial and raises significant challenges for multilateral processes and politics.
4. Given that solar geoengineering does not address the root cause of the climate problem, it is unclear whether (and, if so, how) it will be integrated into the international climate regime, recently elaborated under the Paris Agreement and its rule book. Concern remains that, instead of serving as an adjunct to decarbonization efforts, solar geoengineering will be used to circumvent mitigation commitments and maintain a business-as-usual scenario.

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