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ADVANCED REVIEW

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The politics and governance of research into solar geoengineering

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Abstract

Research into solar geoengineering, far from being societally neutral, is already highly intertwined with its emerging politics. This review outlines ways in which research conditions or constructs solar geoengineering in diverse ways, including the forms of possible *material technologies* of solar geoengineering; the *criteria and targets* for their assessment; the *scenarios* in which they might be deployed; the *publics* which may support or oppose them; their *political implications* for other climate responses, and the *international relations*, *governance mechanisms*, and *configurations of power* that are presumed in order to regulate them. The review also examines proposals for governance of research, including suggested frameworks, principles, procedures, and institutions. It critically assesses these proposals, revealing their limitations given the context of the conditioning effects of current research. The review particularly highlights problems of the reproduction of Northern norms, instrumental approaches to public engagement, a weak embrace of precaution, and a persistent—but questionable—separation of research from deployment. It details complexities inherent in effective research governance which contribute to making the pursuit of solar geoengineering risky, controversial, and ethically contentious. In conclusion, it suggests a case for an explicit, reflexive research governance regime developed with international participation. It suggests that such a regime should encompass modeling and social science, as well as field experimentation, and must address not only technical and environmental, but also the emergent social and political, implications of research.

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1 | INTRODUCTION

The politics of climate change has gained urgency in recent years, with climate emergencies declared, and net-zero targets announced by many countries, cities, and companies (Climate Emergency Declaration, 2020; Williams, 2019). This has brought proposals for large-scale carbon removal (carbon geoengineering) center stage, but research into related proposals to ameliorate global warming by reducing incoming solar radiation (solar geoengineering), although less prominent, has also grown substantially since Paul Crutzen's call for its consideration in 2006 (Crutzen, 2006). Solar geoengineering at a global scale carries high stakes: it may be rapid but has deep implications for climate policy, justice, security, and international relations and is controversial with publics. Yet solar geoengineering can be expected to gain more prominence as temperatures continue to rise. It is therefore timely to review both how solar geoengineering research may be influencing climate politics, and how such research might be appropriately governed. In this respect we hope to complement recent review work that has focused on other aspects of solar geoengineering such as ethics, law, economics and social science (Flegal et al., 2019), the governance of deployment (Reynolds, 2019a), or the role of responsible research and innovation (RRI) in geoengineering of all types (Low & Buck, 2020).

Interest in governance for geoengineering—both regarding deployment and research—also grew rapidly in the late 2000s. By 2011, calls for research governance had been made from both within and outside of the geoengineering research community—including from science institutions (Royal Society, 2009), climate scientists (Asilomar Scientific Organizing Committee [ASOC], 2010), politicians in the United Kingdom and United States (House of Commons Science and Technology Committee, 2010; US Government Accountability Office, 2010), influential think-tanks (Long et al., 2012), and new dedicated groups (Solar Radiation Management Governance Initiative, 2011). Contemporaneously parties to the Convention on Biological Diversity called for a moratorium on geoengineering activities that might affect biodiversity, with the exception of small-scale research in controlled settings. And the London Protocol adopted a framework on ocean fertilization (Ginzky & Frost, 2014) providing for assessment of both whether a proposed activity has genuine scientific attributes and of its potential environmental impacts.

Research governance proposals (reviewed in Section 3) range from light-touch self-regulation by scientists to strong international frameworks to constrain or enable such research. The mechanisms suggested include: codes of ethical and legal principles; the application of frameworks such as anticipatory governance, responsible innovation, and mission driven research; novel institutions and formal procedures involving moratoria, thresholds, transparency registers, and public consent. However, currently there is no widely recognized code, standard, or institution governing solar geoengineering research. Rather, there remains a palimpsest of different ideas, patchily applied in desk and laboratory research (with few field experiments attempted, but increasing amounts of public and stakeholder engagement). In the absence of consistent governance, research is conditioning and constructing particular social and technical manifestations of solar geoengineering in ways that may inappropriately prejudice[1] the politics of future global climate action.

The ways in which ongoing *research* may affect the emerging politics of solar geoengineering extend far beyond the direct contribution of research findings to rational debate and policy-making. In Section 2 we summarize key aspects of the politics of research, including work indicating that research activities can condition or construct the *material technologies* that may emerge, the *criteria and targets* against which they might be assessed, the *scenarios* in which their deployment might be considered, the *publics* which may support or oppose them, the *political implications* they might have for other climate responses or for international relations, and the *international relations*, *governance mechanisms*, and *configurations of power* that are presumed in order to regulate them. If we consider potential *deployment* of solar geoengineering to merit governance in the public interest (Reynolds, 2019b), then all these effects make governance of *research* equally important. And by "research" we do not mean only natural science, experimentation, and engineering (the focus of most research governance proposals), but also modeling, public engagement, ethics, and critical social and political science. Like Low and Schäfer (2019), we understand research that constructs "futures" as necessarily political, and capable of structuring expectations and foreclosing alternatives.

The paper then proceeds by critically reviewing proposals for governance for solar geoengineering research (Section 3) revealing their limitations in the face of the conditioning effects of current solar geoengineering research, and developing a novel critique of research governance proposals on that basis. In selecting material we defined "governance" broadly as the intentional exercise of power to influence other actors to behave in ways reflecting some conception of a wider public interest, while noting that in the absence of effective international governance, "de-facto governance" (Gupta & Möller, 2019) may be constituted through existing power relations. In Section 4 we briefly consider some examples of research governance in practice for solar geoengineering experiments. In Section 5 we seek to synthesize learning from the review, highlighting shortcomings in the extant proposals. Finally in Section 6 we draw conclusions and make suggestions for future research governance.[2]

2 | HOW RESEARCH CONDITIONS POLITICS AND PRACTICE

In response to a threat such as climate change, most research is seen as inherently "policy-relevant," generating knowledge that can better inform those making decisions and designing tools to mitigate the threat or its impacts. Practicing researchers often understand policy relevance in terms of a linear or "technocratic" model (Hulme, 2009, p. 102) of science-policy interaction. In this idealized model, policy-makers are rational actors, responding (however imperfectly) to the public interest, informed by objective evaluations of problems and possible responses. Scientific research is independent and objective, enabling better policy-making.

However, for climate science in general, and solar geoengineering research in particular, the situation is rather more complicated. We need not rehearse the extent to which climate science is contested, politicized, and "post-normal" (Funtowicz & Ravetz, 1993; Hulme, 2009). Nor the deep complications and injustices introduced by histories of colonial and post-colonial (resource) exploitation (Ghosh, 2016; Mitchell, 2011; Moore, 2015), and by the ongoing social contestation of climate policy through continued disinformation by vested interests (Oreskes & Conway, 2011). Yet solar geoengineering is further complicated by being primarily a "technological imaginary" (Jasanoff, 2015), which is produced through research, regulation, and opinion (Stilgoe, 2015) and which in turn co-produces (future) societies and international orders.

Almost all scholars writing about geoengineering appear to support some form of research governance, although the extent recommended is highly variable. Many acknowledge, for instance, that geoengineering research may touch on "sensitive questions of sovereignty … inter-generational rights and responsibilities … [and] tensions between the private and public sector" (Carlarne, 2011). Others highlight issues such as distrust in experts and researchers and their motives, lack of control over the symbolic significance of research, and systemic concerns such as lock-in, moral hazard, and even military conflict (Lin, 2016). We argue here that effective and extensive research governance is essential: rather than simply informing policy, geoengineering research is already conditioning and potentially prejudicing future climate politics.

We draw on relevant debates and literature spanning climate science, environmental humanities, politics, science and technology studies, ethics and international relations to identify four major—and interconnected—ways in which solar geoengineering research might prejudice climate politics. In each we suggest that decisions over how research is conceived, funded and performed are excluding, promoting, or locking in outcomes more properly considered the territory of democratic and/or intergovernmental debate and negotiation. We consider politically performative and not only constative effects of research; that is, rather than simply producing true (or false) statements on solar geoengineering, research—as "speech acts" (Austin, 1959; Searle, 1969), or as part of the co-production of science, technology, and society (Jasanoff, 2015)—inevitably also "does things" in the world. First, research performatively imagines and in a very real sense enables the construction of particular configurations of material technologies. Second, research helps evoke and assemble epistemic communities, stakeholder groupings and even publics with particular orientations towards the topic. Third, research helps construct de facto forms of governance, normalizing and institutionalizing research, adding to climate pathways in which the deployment of solar geoengineering appears desirable or even inevitable. Fourth, research implies or creates capacities and expectations that condition international relations in the climate sphere. These four routes are not unique to geoengineering among novel high-risk technologies, but in combination raise potent risks.

2.1 | Technological imaginaries

The dominant mode of solar geoengineering research uses Earth system models to project the effects of particular interventions (Irvine et al., 2016), but in doing so, modelers imagine particular technical constructions and possibilities most of which do not (yet) exist in the material world. The commonly modeled imaginaries of SRM changed from those of "turning down the sun" with space mirrors to distributed veils of stratospheric particulates, not because the former was seen as technologically infeasible, but because modeling the latter became practical as modeling capabilities developed

(Stilgoe, 2015). Carefully targeted and modulated stratospheric deployments are still widely modeled while effectively presuming their technological (and political) feasibility (McLaren, 2018).

In models, these technical imaginaries have not only particular defined parameters, but also presumed purposes and political forms (Bellamy, 2016; Lin, 2016; Szerszynski et al., 2013). These presumed purposes (typically climate risk reduction via global optimization of SRM through intergovernmental agreement) may be equally infeasible. Yet they reflect the ways research anticipates or establishes criteria, concepts, and scenarios for the assessment of geoengineering (Bellamy, 2016; Bellamy & Palmer, 2019; Flegal & Gupta, 2018; McLaren, 2018; Sugiyama et al., 2018; Talberg et al., 2018; Wiertz, 2015). For instance, to run models to obtain clear results tends to imply a presumption of global planning (Corry, 2017); or to assess the relative desirability of different outcomes, modelers need to assume that all people have the same climatic interests, rather than ones which vary nationally, or even between groups or localities (McLaren, 2018; Wiertz, 2015). Moreover, the scenarios evaluated are typically based on those included in the Geoengineering Model Intercomparison Project (Kravitz et al., 2011), which are designed primarily for modeling convenience rather than as a reflection of reality (Sugiyama et al., 2018).

These processes can be self-reinforcing. Stratospheric aerosol injection in part became "locked-in" as the most widely modeled form of solar geoengineering and the presumptive technological configuration because of a combination of simple assumptions and a growing body of work, despite performing badly when experts and stakeholders were enabled to set and weight criteria in a multi-criteria assessment (Bellamy et al., 2013). This effect has subsequently been reinforced by growing interest in fast-acting responses to climate impacts and developing technical understanding of the options for solar geoengineering (MacMartin et al., 2018).

The snowball effect of such research prioritization applies also to critical social and political science, and research questioning the ethics of geoengineering. Following Nordmann (2007) and Rip (2012), Science and Technology Studies scholars (Flegal, 2018; Stilgoe, 2015) have highlighted that analysis of the ethics of particular socio-technical formations of geoengineering could help solidify and establish those imaginaries, increasing their salience, and increasing the likelihood that they might be further examined scientifically, or even grasped at politically, in the face of an apparent "climate emergency." As Flegal et al. (2019) suggest, social science more generally, including engagement studies, might be as complicit in "naturalizing geoengineering" as natural science research, prematurely stabilizing it as a policy option.

2.2 | Publics and communities

Unevenly empowered epistemic communities (Haas, 1992) of networked researchers and experts play important roles in defining problems and developing responses. Dominant ones also establish and spread norms and presumptions regarding research topics and practices. The geoengineering epistemic community has been notoriously narrow (Kintisch, 2010) and despite growth in numbers in the last decade remains predominantly white, male, wealthy, and Northern—even in contrast with broader climate change networks (Biermann & Möller, 2019; Buck et al., 2014; Stephens & Surprise, 2020). Deliberate efforts to broaden the community include the Solar Radiation Management Governance Initiative (SRMGI) (2011), which has actively sought to engage scientific and policy audiences in the global South, and in recent years has provided funding in the DECIMALS program for SRM modeling research based in the global South.[3] Unfortunately while the topics of investigation have been defined by Southern partners, the models, norms, and practices applied in DECIMALS remain primarily those of the dominant Northern research community. For Victor (2008, p. 325), such a process is part of a desirable governance effort to spread scientific norms through international collaboration, and to enable research by "socializing" scientists even in countries skeptical about geoengineering research.

Research into technological imaginaries not only helps construct the epistemic communities, it also assembles particular publics, including through engagement seeking to assess public opinion (Bellamy & Lezaun, 2017; Chilvers & Kearnes, 2019). In introducing the technologies to its subjects, such research also inevitably frames them. Such publics may be supportive, but research may also fuel geoengineering conspiracy thinking (Cairns, 2016). Similarly, stakeholder engagement exercises by researchers can serve to *create* stakeholder interests as much as they identify pre-existing ones (Turnhout et al., 2010), contributing to a process whereby policy-making regarding such novel issues reconfigures the polity (Hajer, 2003). Such stakeholder exercises have been undertaken primarily in the global North, indicating conditional support for more research (Asayama et al., 2017; Burns et al., 2016; Flegal et al., 2019). Those directly engaging global Southern interests suggest more desperate concern about climate impacts, and in some studies, more—although still cautious—openness to geoengineering (Carr & Yung, 2018; Sugiyama et al., 2020) but in others deep reluctance to engage with geoengineering outside of the context of colonial and imperial legacies (Flegal et al., 2019; McLaren & Corry, 2021). Such findings suggest a critical need for future geoengineering research to be better rooted in Southern theory and epistemology, rather than predominantly reflecting Northern research norms.

By contrast, for some researchers, geoengineering is an aspect of an "ecomodernist" ideology, which posits that past environmentalism has failed, and that new approaches, more positive towards technologies such as nuclear power and geoengineering are desirable. Ecomodernists (Asafu-Adjaye et al., 2015; Grinspoon, 2016) tend to actively seek to build public support for such interventions, whereas some prominent geoengineering researchers echo similar themes (Keith, 2013). Such a framing of geoengineering both reflects and shapes research agendas. Critics of the ecomodernist approach point to the convenient coincidence between the solutions it advocates, and sustained growth in consumption, avoiding redistributive economics, or lifestyle change (Gardiner, 2011). Although publics show grave concern about the role of financial interests in geoengineering (and geoengineering research) (Bellamy et al., 2017; McLaren et al., 2016), they may respond to the ecomodernist framing. Hence, along with interest groups and media, research helps to create publics.

2.3 | De facto governance

Geoengineering research also helps to construct de facto forms of governance. In particular, high-level "authoritative assessments" undertaken by panels of elite scientists construct geoengineering as an object of governance by demarcating and categorizing the field (Gupta & Möller, 2019). Such assessments also normalize and institutionalize geoengineering research (and specific epistemic communities). Such emergent, de facto sources of governance "are unacknowledged and unrecognized as seeking to govern, even as they exercise governance effects" (Gupta & Möller, 2019, p. 48) both directly steering research and indirectly establishing patterns and expectations for subsequent formal governance.

For example, IPCC assessments (Beck & Mahony, 2018; Gupta & Möller, 2019) legitimize model-based findings (regardless of the limitations of such methods), which in turn establish particular pathways. Previously these have included, for example, pathways heavily reliant on forms of carbon geoengineering (Carton et al., 2020; Fuss et al., 2014). Now, research sector incentives (such as publication and funding), and political encouragement to emphasize findings commensurate with the political targets that inform IPCC report cycles, combine to prompt researchers to construct climate scenarios and pathways in which the deployment of solar geoengineering becomes—if not indispensible—at least desirable.

The reframing of the objectives of climate policy towards temperature suppression (McLaren & Markusson, 2020) brings solar geoengineering firmly into the remit of the IPCC, making it the site of (permissive) de facto governance for this technology also. These dynamics are facilitated by the relatively narrow range of political and economic variables and presumptions that have long been embedded in the overarching baseline scenarios used by the IPCC. With limited room in those scenarios for radical political and economic change, options for climate policy are artificially narrowed towards tools that allow for a slower decline in emissions (currently dominated by carbon removal promises, but potentially also including solar geoengineering). While the latest incarnation of IPCC scenarios, the shared socioeconomic pathways (SSPs), involve welcome efforts to broaden the range of possible futures considered, they do not escape from this dynamic. In the current political context the SSPs may be used as frameworks by modelers seeking to explore the role of solar geoengineering within climate policy, in another emanation of de facto governance.

Enthusiasm for consideration of solar geoengineering may also be increased by the common perception that 1.5 or 2.0°C targets may not be met without such tools in the face of economic inertia and the slow pace of mitigation. Yet such assumptions can be self-reinforcing (McLaren & Markusson, 2020), and thus geoengineering research might contribute to mitigation deterrence or moral hazard, discouraging accelerated effort in emissions reduction (Currie, 2018; Lin, 2013; McLaren, 2016). Even initially tough regulation could lead to moral hazard, lapsing into self-regulation due to regulatory capture and complacency (Wolff, 2019). More generally, worries of a "slippery slope" or "lock-in" effects whereby investment in research would bias decisions towards deployment also remain valid (Gardiner & Fragnière, 2018; Lin, 2016; McKinnon, 2019).

Technology assessment also risks a rebound effect through public and stakeholder engagement in which the limitations and configuration of the technology structure the assessment practices themselves (Bellamy & Lezaun, 2017; Chilvers & Kearnes, 2019). Public engagement in assessments seeks to "open up" debate about the potential technologies but can be seen as legitimating a particular form of governance. Even the open and responsive public engagement emphasized in "responsible research and innovation" may act as "efforts to shape 'de-facto governance', the informal but forceful norms of scientific conduct" (Low & Buck, 2020, p. 8). This promises legitimation, judged against social and ethical concerns rather than technical ones, explored through deliberation rather than modeling, but such forms of governance remain unaccountable.

Experiments also constitute sites of public contestation, establishing parameters of de facto governance. Stilgoe (2016) describes the potential for research to give political meaning to particular uncertainties, noting the consensus in most geoengineering research to presume certain technologies, and to seek to establish their implications and public acceptability. Stilgoe instead recommends reframing geoengineering research as a space for collective experimentation with methods and approaches that facilitate its democratization.

2.4 | International relations

Finally, even without steps to deployment, research helps condition international political relations in the climate sphere. Research which presumes a global planner (or forms of governance that aggregate or ignore diverse interests and perspectives) either serves to down-play the stark multiplicity of the international, or renders as plausible a global governance system capable of disciplining "rogues" or overruling recalcitrant anti-geoengineering actors. And otherwise, solar geoengineering research typically puts forward simplified and ahistorical representations of the international system. For example, rationalist international relations (Lloyd & Oppenheimer, 2014) including game theoretical approaches (Heyen et al., 2019; Ricke et al., 2013; Weitzman, 2015) assume a limited set of unitary rational actors with predetermined interests, and thus help construct simplified and partial expectations of both geopolitics and governance (McLaren & Corry, 2021). Assumptions recognized as unrealistic in methods sections nevertheless generate findings that are interpreted as valid or pertaining to the real world. Empirical research into international dynamics around solar geoengineering suggests that, in practice, rival epistemologies and visions of political and technological futures, within as well as between countries, will make multilateral governance hard to achieve (McLaren & Corry, 2021).

Solar geoengineering research also posits certain international identities (e.g., the [illegitimate] "rogue" nation or agent vs. [legitimate] technology leaders or coalitions), with states usually considered the principal actors. Simultaneously "global governance" or world governmental authority features as a logical necessity alongside targeted and calibrated geoengineering scenarios. The specific target of such governance is often a moot point. When countries have been named, for example in scenario exercises, India, Saudi Arabia, and Nigeria have been portrayed as potential unilateralists as well as the super-powers China and the United States (Barrett, 2014; Bodansky, 2011; Boettcher et al., 2016; Lockyer & Symons, 2019; Victor, 2011).

When research effectively underplays the complex inequities and histories of the international, this inflates feasibility and risks reinforcing inequality in climate politics. Even *indoor* solar geoengineering research can exacerbate inequalities in power relations between countries and domination cannot be prevented by measures such as self-regulation, transparency, and information-sharing (Smith, 2018). Proponents of such measures—in settings which separate research from deployment—typically overlook the potential for certain interventions to increase the capabilities of elites at the expense of others, regardless of whether geoengineering reduces collective risks in models. Smith highlights that the moral intentions of those developing solar geoengineering capacities would be irrelevant to whether those capacities changed power relations. Moreover, in an unequal world it is implausible that the underlying research programs would not reflect rich-world presumptions and values (McLaren, 2017). As Parson notes, "The scientific and technical challenges of doing [geoengineering] well—developing high-benefit, low-risk interventions—are sufficiently large that rich, scientifically advanced nations are likely to have substantial advantages in developing them" (2014, p. 101). In this context ethics research suggests that solar geoengineering research should be targeted to help develop geoengineering measures and configurations that might reduce global injustice (Morrow, 2019) but analysis by political scientists raises the concern that current research is advancing an expert–elite technocratic form of climate intervention that would further concentrate contemporary forms of political and economic power, currently vested in security and fossil fuel interests backed by states such as Russia or Saudi Arabia (Stephens & Surprise, 2020).

Research—especially unilateral—might fuel the potential for geopolitical conflict (Lin, 2016) or trigger other risks associated with deployment (Parson, 2014). "States might view another country's unilateral pursuit of geoengineering research as contrary to their interests … Field tests could heighten tensions or lead to preemptive strikes" (Lin, 2016, p. 2546). Yet unilateral research may be encouraged "by anticipation of economic benefits [from] … private intellectual property … [and] by the polarization of early debates on [geoengineering] governance" (Parson, 2014, p. 102).

3 | RESEARCH GOVERNANCE PROPOSALS

Having outlined ways in which research co-constructs technologies, communities, governance, and international relations, we now turn to existing proposals for research governance. The literature is diverse, with some proposals specific to research and others arising from discussions of deployment governance. In this section we first outline the proposals, highlighting common themes among the frameworks, principles, institutions, and procedures suggested. Subsequently we explore some common presumptions revealed in the proposals: that research is separable from deployment; that more knowledge will reduce uncertainty and better inform policy; and that self-regulation is desirable as a means of enabling research.

3.1 | Frameworks

Pasztor (2017) argues that the global governance framework for climate needs to include geoengineering, and extend from research to deployment. Nicholson et al. (2018) advocate a polycentric framework intended to simultaneously minimize direct risks from deployment, enable and legitimize research and policy-making, and ensure that solar geoengineering is only considered within a portfolio of climate responses (to limit mitigation deterrence). Dilling and Hauser (2013) suggest that a research governance framework must respond to three sets of issues: "the direct physical risks of the research; the transparency and responsibility in decision-making for the research; and the larger societal meanings of the research" (p. 553). Such breadth would be facilitated by inter- and trans-disciplinary research, which could encourage reflexivity, helping reveal inappropriate presumptions and framings (Kreuter et al., 2020), deter solutionism (Asayama et al., 2019), and generate more socially relevant knowledge (Sugiyama, Asayama, Kosugi, et al., 2017).

Responsible research and innovation (RRI) promotes and is responsive to social engagement (at all stages of research from agenda setting to evaluation), backed by transparency, precautionary anticipation, and reflection (Stilgoe, Owen, & Macnaghten, 2013). It is widely advocated in Europe, and has been applied to some early geoengineering research projects. In the case of the Stratospheric Particle Injection for Climate Engineering (SPICE) project, the responsible innovation framework imposed by funders required a stage-gate in which public engagement and anticipatory analysis were central (MacNaghten & Owen, 2011). Low and Buck (2020) suggest that assessment procedures for geoengineering research should be thoroughly embedded in RRI practices, rather than using them merely as a supplement to more technical approaches. As one tool to help deliver responsible research Keith (2017) recommends formal division of research groups into "red" and "blue" teams tasked respectively with developing best-case scenarios and exploring risks.

RRI has many similarities with "anticipatory governance," which also advocates foresight, engagement, and integration of multiple disciplinary perspectives (Foley et al., 2018; Long et al., 2012). Originating in US practice, anticipatory governance takes a less precautionary stance than RRI, although both envisage some form of public involvement in determining the purpose of research and innovation and emphasize the inadequacy of conventional one-way approaches to science communication. "Mission driven research" similarly seeks to legitimize geoengineering research by reference to a guiding public interest (MacMartin & Kravitz, 2019)—which could steer research to support justice in deployment (Morrow, 2019)—but places less emphasis on public engagement per se as the means of understanding the public interest. It also often ignores the implications of the co-existence of multiple societies and hence plural interacting publics.

3.2 | Principles and codes

There have been many proposals for principles for research, sometimes in the form of a code of conduct. Principles are derived from two main schools: a more instrumental approach—legitimating research as "safe, ethical and subject to appropriate public oversight and independent evaluation" (Hanafi & Hamburg, 2018), and a broader normative approach appraising research by its material consequences, distributional effects, and procedural concerns such as accountability, participation, and transparency (Callies, 2018; Gardiner & Fragnière, 2018; Morrow et al., 2009).

Some researchers have drawn on pre-existing models, such as medical ethics (Morrow et al., 2009) to suggest a case for representative consent from the global community, and research design that minimizes scale and impacts, especially on human rights and on the most severely affected. Like later London Convention/London Protocol measures regarding marine geoengineering (Ginzky & Frost, 2014), and other scholars (Dilling & Hauser, 2013; Hogue, 2010) Morrow et al. emphasize that experiments should be science driven (i.e., not commercially inspired, nor even intended to provide climate change relief). A similar aspiration for scientific "purity" has been shown in publics' concern over geoengineering research (Bellamy et al., 2017; McLaren et al., 2016).

Also resembling the London Convention provisions, a proposed code of conduct for geoengineering research based in principles of international law (Hubert, 2017; Hubert et al., 2016; Hubert & Reichwein, 2015) suggests a moratorium with exceptions for responsible scientific research defined using principles of harm-minimization, proportionality, prior independent assessment and public engagement, and transparency. Unusually, this code attempts to implement a principle of precaution, interpreting it as requiring measures to anticipate, prevent, or minimize harmful consequences of reasonably foreseeable threats of serious or irreversible damage. However, the code would be voluntary and applicable only to outdoors/field research (despite the authors' recognition that societal implications and responses constitute a principal reason for governance—alongside health, safety, and environmental impacts).

Another pre-existing model, that of scientific self-regulation, has been proposed and applied to geoengineering; taking their cue from the 1975 Asilomar conference on recombinant DNA research, researchers organized an Asilomar conference for geoengineering in 2010 (ASOC, 2010). Participants developed five principles for research governance (implicitly separated from deployment): aims of collective benefit (public interest); defined responsibilities and mechanisms for governance of *large-scale* research activities; open and cooperative research (transparency); independent technical assessments to inform the public and policymakers; and public participation and consultation in research planning and oversight, assessments, and development of decision-making processes. However, Schäfer and Low (2014) highlight an important shortcoming of the Asilomar process: while rDNA scientists successfully framed societal concerns purely in terms of technical risk, geoengineering continues to raise social, political, and ethical concerns, where scientists lack the level of public trust needed for self-regulation.

Several Asilomar recommendations echo those in the Oxford Principles proposed in 2009 (Kruger, 2018; Rayner et al., 2013), which target geoengineering governance more generally but highlight public participation in decision-making (generally) and public disclosure of research and open publication of results, as part of regulating geoengineering as a public good. The Oxford principles contradict the implicit separation of research and deployment in the Asilomar text, but themselves are criticized by Gardiner and Fragnière (2018) as too narrow and instrumental; governance goes "beyond the mere monitoring and control of geoengineering technologies, and is instead [a matter] of moral and political justification" (Gardiner & Fragnière, 2018, p. 160). In their "Tollgate Principles" Gardiner and Fragnière argue that any approved geoengineering research should serve a global, intergenerational, and ecological public, and be ethically defensible with reference to norms including precaution, justice, and human rights. They call for legitimate representative institutions to make decisions (rather than existing researchers and research bodies) and for independent review that extends to the objectives and methods of research, not just its impacts. They argue further that separation of research and deployment is practically and theoretically misguided.

3.3 | Formal procedures

Proposals for procedures are diverse, but generally reflect the most commonly cited principles reviewed above.

Greater public or stakeholder engagement is almost universally advocated, and even the exceptions presume that publics will be represented in governance processes by public bodies or governments (e.g., Parson & Keith, 2013). Some see engagement as an ethical duty to those potentially affected (Carr et al., 2013; Rayner et al., 2013), or a means to widen involvement, especially internationally and to indigenous cultures, and thus increase the consideration of questions of distributional justice (Carr et al., 2013; Morrow, 2019). Frumhoff and Stephens (2018) argue for a "systematic process for meaningful international engagement" including "informed consent." Nicholson et al. (2018) suggest a global forum (involving publics) as part of polycentric governance of solar geoengineering. Most encourage upstream, early public engagement in research, some explicitly calling for engagement in research design and scenarios (McLaren, 2018; Sugiyama et al., 2018). Several note the serious challenges of recognizing fully all relevant groups and suggest extending engagement practices to enable recognitional justice (Hourdequin, 2018; McLaren, 2020; Preston & Carr, 2018). Public engagement is a central aspect of both RRI and anticipatory governance, reflecting expectations that it can deliver not just greater legitimacy, but also substantively improve decisions and meet normative expectations (Fiorino, 1990).

Many proposals suggest forms of tiered assessment separated by thresholds relating to the potential risks or harms arising directly from the research (Dilling & Hauser, 2013). Most distinguish modeling (harmless) from laboratory studies or outdoor experiments, either explicitly (Winickoff & Brown, 2013; Zelli et al., 2017), or implicitly, by advocating a moratorium on deployment, with internationally defined exceptions for outdoor experiments (Bodle et al., 2014), or for field experiments of particular scales or impact with a voluntary moratorium beyond those limits (Morgan et al., 2013; Morgan & Ricke, 2010). Some limit the scope of the governance discussion to outdoor experiments (Parker, 2014), or propose a boundary such that further regulation of outdoor research, experiments, or field trials is required (e.g., Schäfer & Low, 2014). For example, the SPICE stage-gate procedure required the research team to address multiple additional questions and undertake public engagement to obtain authorization—with reference to an independent panel assessment—for an outdoor experiment (MacNaghten & Owen, 2011). The Royal Society (2009) proposed a voluntary international code of conduct for experiments exceeding some de minimis level. Such boundaries and thresholds are not however consistent even as proxies for potential direct harm. To better enforce proportionality, Parson and Keith (2013) suggest "forcing-based" thresholds related to the scale of climate impact; while Bellamy et al. (2017), drawing from deliberative research, instead suggest a focus on "controllability," which includes both technical considerations of containment, uncertainty, and reversibility, and whether the research is seen to be free of malign or commercial intensions. Many such proposals resemble environmental impact assessment procedures. These might encourage more transparency and monitoring, but would in their present form not apply to research programs, and possibly not to all field experiments. Furthermore, they cannot be triggered by social or ethical concerns and are unsuited to such assessments (Craik, 2015).

Most proposals still see such procedures as *enabling* research, albeit with more safeguards for riskier activities. Some scholars suggest that there should be a ban or moratorium on research beyond a particular threshold (Bodle et al., 2014; Cicerone, 2006; Hubert, 2017; Parson & Keith, 2013), but others explicitly reject moratoria (e.g., Carlarne, 2011; Parker, 2014). Several commentators argue that moratoria would be ineffective and limit transparency as they would incentivize researchers to "disguise the true purpose" (Lin, 2016) of their research. Reynolds (2019b) argues additionally that moratoria would cause a form of "adverse selection" in which only the "responsible" would comply. Morgan et al. (2013) fear that even national regulation on notification and reporting would drive research abroad. Some suggest alternatively that research norms might include provisions for compensation in case of harms arising (Lempert & Prosnitz, 2011).

To ensure transparency, several proposals include a formal international clearinghouse or registry of research (Craik & Moore, 2014). Openness is endorsed by many commentators (e.g., Lempert & Prosnitz, 2011; Victor, 2008). Reynolds et al. (2018) recommend a bottom-up, primarily non-state, voluntary "research commons" for data (and patents) related to solar geoengineering, so as to facilitate information sharing and limit data fragmentation and trade secrecy. Any such proposal would rely on a clear definition of "geoengineering research." Most commentators seem content with a voluntary approach here, but Winickoff and Brown (2013) suggest a national committee to advice on demarcating geoengineering research (and also for establishing the boundary for research that needs little to no extra oversight). Frumhoff and Stephens (2018) suggest that transparency should extend to funding sources, and that researchers should voluntarily eschew funding from vested interests (as well as voluntarily accepting independent oversight).

Another measure discussed as a means to protect public interests in research is patent constraints. Conventional innovation models assume private sector involvement in making research commercially viable, and patents as the mechanism to reward innovators. But Parthasarathy et al. (2010) document a rapid increase in patent applications with problematic characteristics (broad patent language; concentration of patent ownership; similar patents issued by multiple patent offices) and see the extant regime working against the public interest. In contrast to Reynolds et al. (2018), they argue for a sui generis system for geoengineering based on experience with nuclear research.

3.4 | Institutions

Despite the need for institutions to implement procedures, proposals for governance institutions are less prominent in the literature, and in many cases it appears that the procedures proposed are to be delivered through self-regulation.

Several scholars suggest institutions to screen out inappropriate experimentation. Some proposals involve anchoring research governance in existing national or international institutions. Morrow et al. (2009) suggest institutions within the United Nations Environmental Programme or the World Health Organisation could enforce parameters agreed upon by the international community, and ensure coordination of experiments. Nicholson et al. (2018) propose a near-term polycentric and multi-level governance framework to address research as well as deployment, utilizing existing national and international institutions. Galaz (2012) also calls for a polycentric institutional setting designed to reject "proposals that carry considerable ecological risk", but permit "fail-safe experimentation," and continuous learning to "uncover the potential" of geoengineering. All such proposals imply a form of acceptable research enabled and legitimated by such institutions.

Others also see roles for new institutions in establishing principles. Winickoff and Brown (2013) propose a US national advisory commission to establish research guidelines, with the US President's Council on Bioethics as a model for establishing guidelines for intellectual property, financial interests, and transparency. Jinnah et al. (2018) argue that public engagement is necessary but not sufficient for legitimate governance of outdoor research. They propose the creation of (US) state-level advisory commissions to oversee solar geoengineering research in key states. Such proposals have the merit of specificity, but leave big question marks regarding international effect: Parson and Keith (2013) argue that inadequate coordination of state-level governance would incentivize "shopping for lax jurisdictions." The justice of establishing principles at such national or regional levels is also left unaddressed, as are concerns regarding research funding and wider challenges linked to the political economy of research.

Zelli et al. (2017) describe "hybrid multilateralism" in climate governance, with novel initiatives and institutions—such as the Oxford Principles and the SRMGI—involving both public and private actors. SRMGI was founded by the Royal Society, TWAS (the science academies for the developing world) and the US NGO Environmental Defence Fund to promote scientific and policy engagement in geoengineering research across the global South. However, it structures the dialogue in terms of the existing science, established methods and a Northern model. Similarly, Reynolds and Parson's (2020) suggestion that collaboration between researchers, universities, funders, academic publishers, professional societies, and nongovernmental organizations would be adequate (and even preferable) for governance of research, if not deployment, offers little to challenge established cultural norms or differential access to resources.

Dilling and Hauser (2013) by contrast, despite suggesting that research governance could be founded in existing state funding review processes, and built "bottom-up" by the research community through developing norms and standards, argue that such a model would need to be supplemented with distributional concerns, and with more public participation. Sugiyama, Asayama, Ishii, et al. (2017) suggest using a voluntary network of experts as a bridge to a more formal institution, critically, funded by a multilateral research organization such as START or Future Earth, rather than by a single country. Although this would still risk empowering existing scientific experts to structure governance, these scholars also highlight an important need to develop dialogue practices in the context of local cultural traditions and experience. Wolff (2019) argues further that institutions alone are inadequate, without a vibrant civil society holding them, and the governance processes, accountable to the public.

4 | RESEARCH GOVERNANCE IN PRACTICE

Most solar geoengineering research—modeling, laboratory studies, public engagement—so far has been conducted under normal scientific research governance procedures, such as university ethics committees. The few examples of *experimental* research highlight the limitations of such procedures. Doughty (2018) reviewed early examples, noting that those which largely ignored social implications (a helicopter-based aerosol distribution experiment in Russia in 2009, and the Eastern Pacific Emitted Aerosol Cloud Experiment, studying cloud physics in simulated ship track emissions in 2011) received little scrutiny, and that mainly after the event, and from other scientists. On the other hand, the SPICE experiment, with its responsible innovation setting, and stage-gate governance imposed by funders, generated public and NGO debate and commentary, and the outdoor element was cancelled. This was partly in response to revelations of undisclosed patents, but also reflected the incomplete consideration of social and ethical issues highlighted by the stage-gate panel, even though local public deliberation had been carried out (Dilling & Hauser, 2013). In reflecting on SPICE, key participants noted that the public engagement revealed a concern with "the purposes of research that is hard to account for in current governance. … [and] an acute awareness … that research could be a step onto a slippery slope" (Stilgoe, Watson, & Kuo, 2013, p. 3). They conclude that distinguishing areas of research as not deserving of public scrutiny, by using thresholds, however defined, would lack public credibility. Moreover, they acknowledge that "Geoengineering is unavoidably entangled in a political discussion that scientists should seek to understand and engage with" (Stilgoe, Watson, & Kuo, 2013, p. 2).

Subsequently, Harvard's proposed Stratospheric Controlled Perturbation Experiment project (to measure side-effects of small amounts of aerosols released from a balloon in the stratosphere) (Dykema et al., 2014) has designed a novel oversight and scrutiny mechanism, with the experiment currently voluntarily on hold, awaiting approval from an independent advisory committee (appointed on the initiative of the research team some five years after the experiment was first proposed).[4] In contrast, in 2020 a consortium of Australian researchers tested marine cloud brightening techniques as a localized measure for cooling the Great Barrier Reef, under specific rules governing research within the Great Barrier Reef Marine Park. This followed publication of the research plans, a report on the regulatory environment, and advance public engagement exercises including with reef stakeholders and indigenous owners (Brent et al., 2020). Such rules still fall short of robust governance for field testing, and a more consistent responsible governance framework, including detailed risk assessment and early public consultation is recommended by McDonald et al. (2019).

5 | CRITICAL REVIEW OF THEMES IN THE PROPOSALS

Here we highlight some common shortcomings of the proposals reviewed above, in the light of the ways in which research structures imaginaries of geoengineering in an inescapably international context. Four key issues arise: the emergent nature of governance privileges Northern norms and leaves many stakeholders unrecognized; instrumental approaches to public engagement leave the purpose and desirability of research unquestioned; uncertainty is seen as a reason to enable research, rather than as a reason for precautionary governance; and the attempted separation of research from deployment leaves the entire system vulnerable to the lock-in of risky imaginaries.

5.1 | Emergent governance and Northern norms

Victor (2008) predicts that governance will emerge "bottom up" through norms, especially in research. To inform such governance he advocates more research and field-testing—loosely coordinated in the largely voluntary and self-regulated model of the Human Genome Project—as a means of "socializing a community of responsible geoengineers" (2008, p. 325). Similarly, Lempert and Prosnitz (2011) suggest the United States should actively promote strong research norms (as long as SRM is assumed to be practical, and multilateral climate agreements feasible), whereas Morgan et al. (2013) advocate US leadership to develop and persuade others to adopt a light-touch code for notification and reporting on permitted low-risk experiments. More generally, across the period since 2006, frustration with slow progress on environmental issues has been accompanied by a broadening of ideas of governance, with involvement of more diverse actors and practices (e.g., Gupta & Möller, 2019; Reynolds & Parson, 2020; Zelli et al., 2017). Scientists have engaged primarily in controlled spaces into which civil society groups have also been invited (such as SRMGI or C2G), and somewhat with supportive or agnostic elements in civil society, but only rarely with initiatives seeking to constrain geoengineering research (e.g., Biofuelwatch, ETC Group, &Heinrich Böll Foundation, 2017; Muffett & Feit, 2019).

Yet most extant proposals still overlook the limitations of national or self-regulatory research governance, typically failing to recognize the extent to which the international has inevitable and deep implications for solar geoengineering research governance and the global commons more widely. Important regional interests in the global South are poorly reflected in the existing research community, despite some efforts to engage academics and policy makers in such regions (African Academy of Sciences and Solar Radiation Management Governance Initiative, 2013), such as through the SRMGI's aforementioned DECIMALS fund. But the norms promoted, and the epistemic community extended, through such mechanisms remain predominantly Northern, and the range of stakeholders is relatively narrow, leaving many relevant interests and disciplines unrecognized. This global misalignment reflects far deeper issues than merely access to research outcomes (Smith, 2018). The self-regulatory model of de facto governance that has emerged over the last decade is primarily a model that reinforces existing norms and values in the Northern, elite scientific community.

5.2 | Instrumental public engagement and the purpose of research

Those keen to enable research typically present public engagement as a legitimizing tool that can help overcome social and political obstacles. There is little in the generic advocacy of "public engagement" to shift the existing model rooted in science communication: publics are not recruited to shape research objectives or the scenarios modeled, but primarily to "reveal" the conditions for public acceptability of the technologies (as if such public acceptability was another objective "thing"' to be discovered rather than co-constructed in such engagements in multiple different societies). Such forms of engagement rarely broaden the stakeholder base or recognize those interests and publics whose voices are currently unheard. Indeed, the publics they help construct may well largely echo the researchers' views.

This model of engagement as science communication is strongly wedded to an ideology of disinterested science. This encourages some scholars to posit that simply doing and communicating more research will increase trust in geoengineering among publics and policy makers (Lloyd & Oppenheimer, 2014; Parson, 2014). For example, Bodansky (2013) fearing "premature rejection" of solar geoengineering, urges support for research (separate from deployment) including regulation for the explicit instrumental purpose of creating "trust through transparency, public participation and independent assessments." It is true that public trust will likely be greater where such practices are followed, but they alone do not render such research "trustworthy."

Public engagement in research should be a two-way process, one which can question the very purpose and desirability of the research and which can reconstruct the research community and its goals and practices as much as it might construct a public around the topic. The SPICE governance process, considered earlier, represents a rare effort to undertake public engagement in a way that could feed back into the project plans, through the stage-gate process (Pidgeon et al., 2013). More generally, existing research governance and research ethics procedures designed to protect the interests of human subjects do not provide such an opportunity, and can even be unhelpful, as they constrain social scientific inquiry—and deep engagement of publics—more than they limit technical experiments. Research helping us understand the political implications of solar geoengineering research would seem at least as urgent as further technical development or modeling (Matzner & Barben, 2020).

5.3 | Uncertainty and precaution

A common misconception that research is about reducing uncertainties (Bodansky, 2013; Currie, 2018; Parson & Keith, 2013) arises in the assumption (again based in conventional Northern scientific norms) that solar geoengineering is some objective technology waiting to be discovered, rather than emerging through socio-technical construction. For such commentators, research is self-obviously desirable as a means to better inform policy-making. Policy-oriented research demands governance (Dilling & Hauser, 2013; Low & Buck, 2020; Morrow, 2019), but the existing proposals do not tend to acknowledge the reflexivity of the problem: that by defining and researching solar geoengineering as a response to climate change, both the problem and the response are in turn constructed in particular ways, embodying particular values.

From the science-communication perspective, whether research suggests that solar geoengineering would be beneficial or reveals disadvantages, it is assumed that research will reduce uncertainty, rather than increasing or redistributing it. The possibilities that precaution might be better served by political or social rather than technical interventions, and worse still, that technological promises generated through or around research might slow climate action (McLaren & Markusson, 2020) are rarely considered. Thus, with some exceptions (e.g., Hubert, 2017) proposals tend to focus on ways to enable research, promote self-regulation and minimize constraints. An influential thread advocates emergent, de facto governance, rather than a sui generis regime constructed with broad public and political participation.

Some proposals further presume the desirability of including solar geoengineering in *climate* governance negotiations. Parson (2014) suggests the risk of unilateralism is grounds to pursue "open and collaborative research" to reduce uncertainties, especially about regional and seasonal implications of solar geoengineering, so as to enable its early inclusion in international climate negotiations. A cooperative approach to geoengineering "could start immediately, with informal consultations on research programmes, agreement on common standards for transparency, and joint development of assessment framework" (Parson, 2014, p. 103). Lloyd and Oppenheimer (2014) also focus on avoiding unilateralism and look for a deployment governance regime including a scientific coordinating committee. In such proposals, the lack of precaution extends to the presumption that comprehensive multilateral agreement would be feasible. Moreover, even if feasible, such a model would focus research on deployment in a "mission-led" mode and could be expected to sustain Northern dominance of research.

5.4 | Separating research from deployment

There is a persistent—arguably dominant—thread in the literature which seeks to establish or maintain a distinction between unproblematic "research" and some more intrusive practice (deployment, or steps towards it), with a threshold typically defined in terms of material risk. Even as Crutzen sought to stimulate more research on solar geoengineering, Cicerone (2006) championed separate treatment of research and "engineering interventions," positing that no special treatment is merited for research. "We should proceed as we would on any other scientific problem, at least for theoretical and modeling studies" (2006, p. 223), he argued, suggesting that for deployment, a moratorium should be considered with exceptions for small-scale, scientific research. Parson (2014) argues that "much of the field research to develop and inform [geoengineering] capabilities can be carried out with small-scale interventions that are essentially riskless" (2014, p. 92). The National Research Council (2015) advocated leaving key ethical questions to future deployment governance, even while promoting deliberation on a framework for governance of field experiments. By contrast, RRI frameworks tend to actively link research and deployment in the "governance of innovation" (Flegal et al., 2019), but in practice the focus for governance has remained on the risks involved in larger scale interventions or field experiments.

Throughout the research governance literature, the boundary between "research as normal" and "risky" research is unclear. Many authors offer diverse perspectives on where and how to draw such a boundary: modeling versus experimentation (Zelli et al., 2017), indoor versus outdoor (Parker, 2014), small scale versus large scale (MacMartin & Kravitz, 2019; Parson & Keith, 2013), "controllable" versus "less controllable" (Bellamy et al., 2017). It is not always explicit what extra hoops are required above the threshold, but it is typically clear that below the threshold standard funder, national and scientific self-regulatory processes are presumed adequate.

Our understanding of the conditioning effects of research suggests this is an inappropriate presumption. Technical, risk-based thresholds for research projects are inadequate and may even be counter-productive where the impacts are cumulative, symbolic, political or cultural. We would argue that the crux of the problem is not the parameters or criteria for such thresholds, nor the category boundary, but the implicit judgment that what needs governing is impacts of the activity rather than impacts of the knowledge generated. The idea that knowledge generation is neutral and objective is deeply rooted in scientific mythology, and it is unsurprising to see it here. But it is also long rebutted, at least with respect to research into high-risk technologies in a setting of post-normal science (Funtowicz & Ravetz, 1993). Indeed some governance proposals recognize this: Dilling and Hauser (2013) justify a call for broad governance interventions on the basis that "it is what the experiment represents that matters." Moreover scientific objectivity is deeply problematic where the objects of research are socio-technical imaginaries whose material configurations are (in part) constructed by research. As Stilgoe (2016) argues, there is no "bright-line," and no domain in which research is pristine: "The reframing of the experiment as at least partly social challenges the attempt to hermetically seal it from public scrutiny" (2016, p. 860).

Proposals rooted in assumptions of a bright-line between research and deployment—whether drawn at the laboratory door, or at some arbitrary threshold of scale—tend to overlook the conditioning or lock-in effects outlined above. Nonetheless, such proposals merit further study, at least insofar as it is important to understand how they might undermine efforts to install appropriate and effective governance. This is not to claim that all the proponents of such limited governance schemes support them because they would therefore enable particular formations of geoengineering socio-technical systems. Some advocates might genuinely believe they would constitute adequate governance in liberal democratic society because they judge the risks of lock-in low or dismiss the ways in which research conditions future trajectories.

6 | CONCLUSIONS

Most proposals for research governance reflect a shared understanding that solar geoengineering raises challenges beyond standard research ethics and governance. But we have shown that few proposals consider the ways in which research might construct technologies, publics, policy, and politics. Even fewer offer measures that could address prejudicial consequences and the slippery slope they may portend. This is a critical shortcoming: in the absence of conditioning effects of research, we might reasonably expect problems arising from weak research governance to be rectified by future mechanisms for deployment governance. In the presence of such conditioning or lock-in, such mechanisms would be too late.

Current research governance proposals focus primarily on regulating the immediate, material impacts of research activities, not the processes and implications of knowledge generation. They feature a questionable emphasis on defining a dividing line between activities requiring and not requiring additional governance. Distinguishing modeling from physical interventions, lab-work from outdoor studies, or setting thresholds according to the scale or controllability of impacts (or even a formal process to define "genuine research") all tend to distract from underlying questions and presumptions about research and knowledge generation. Current governance proposals tend to presume that researchers are value-free, rational and disinterested; instrumentalize (or at least silo) considerations of public engagement; ignore existing structural inequalities in research capacities and reproduce dominant, Northern norms in research practices, values and purposes. Put simply they abstract knowledge generation from its cultural, economic, political, and international contexts.

In current proposals, governance is typically expected to *legitimate* research. It is rarely anticipated to constrain research, or to transform its practice or purpose. The dominant framing tends towards a narrow and instrumental rather than a capacious view of the public interest in research (defined by researchers themselves rather than by international or global publics). Emergent forms of governance extending to self-regulation are commonly accepted, at least for forms of research categorized as low-risk.

Such governance approaches may be all that appears plausible in the current febrile political climate. But the result risks accepting "sleep-walking" into solar geoengineering (McKinnon, 2019) through the co-evolution of research, technological imaginaries, and political responses, while attempts at international governance struggle (McLaren & Corry, 2021). Solar geoengineering could be enlisted in further enabling (the promise of) a slow transition which protects Northern interests and the economic assets of current elites.

We conclude therefore that the patchy palimpsest of bottom-up proposals is inadequate. Instead we see a strong case for explicit, reflexive, international research governance encompassing the emergent social, ethical, and political, as well as technical, implications of solar geoengineering research. Unilateral action (especially in a Northern nation) to attempt to establish a research governance regime would be undesirable, likely to replicate unhelpful epistemological and cultural norms and reify existing power relations. There is a clear need for an international sui generis regime for geoengineering research governance, constructed with broad international and public participation. While implausible, a voluntary moratorium until such a regime is in place would halt "sleepwalking" while incentivizing regime-building. The model of the London Convention/London Protocol on marine geoengineering provides useful pointers towards firmly guiding research to the public interest and minimizing risk. Ideally a geoengineering research regime needs to also ensure that all research recognizes and engages with its political and ethical context and is governed in a fully international framework, implemented by national and international research funders.

We are not holding our breath for such a breakthrough, especially given the hesitancy of most civil society organizations to engage in detail with solar geoengineering.[5] But in the absence or even implausibility of such a regime, even research into solar geoengineering can be expected to reinforce and magnify the complexities which already beset global climate politics and make the pursuit of solar geoengineering risky, controversial and ethically questionable. While concrete proposals for a detailed research governance regime cannot be developed without international participation, here we suggest some principles and directions for such a regime.

Even though the extant research governance proposals focus on technical and natural science experiments, our review has suggested that other research—from modeling to ethics and critical social science—can contribute to conditioning or prejudicial effects, and should be encompassed by a governance regime. Nonetheless it is important to remember that—as indicated in Section 2, certain forms of research—notably modeling, and the natural sciences—are privileged in political institutions and processes such as the IPCC, while others, such as ethics and critical social science, while contributing to the salience of particular techniques or configurations of geoengineering, seem to have less political impact in terms of their content.

We would not recommend seeking to replicate a regime from some other controversial technology. This is despite the similarity in principles outlined above, and those—inclusiveness, transparency, public engagement, and precaution—promoted in international research collaborations on issues such as nuclear power and the human genome (Ghosh, 2018). There is no analogue in which research is governed without being simultaneously enabled: examples such as the human genome project involved international bodies providing funding or critical hardware as leverage to impose rules on research (e.g., on intellectual property or liability). And for such examples it seems equally hard to separate research from subsequent deployment. Nonetheless, further studies of research governance in other controversial technologies could help us design more practical tools and regimes for geoengineering research.

Our analysis supports arguments that any meaningful research governance regime should include—and be based upon—public engagement, transparency, and accountability. But most existing proposals fall short in all three respects: presenting engagement in instrumental ways, failing to recognize many interests (especially in the global South); applying limited, and often voluntary approaches to transparency; and—with rare exceptions—shying away from consideration of funding, liability, or accountability mechanisms.

Even without an overarching framework, researchers (and funding agencies) could adopt more responsible standards and approaches, particularly through early public engagement in research design and purpose. Funders could prioritize improving understandings of the complexities of political and cultural constructions of solar geoengineering and other climate policy responses. There is also a case for building on the most developed process for international engagement on research, the SRMGI. So far this arguably offers inclusion without real recognition, and suffers the weaknesses of an inbuilt separation of research and deployment. Yet it could become a platform for support to be given to research and governance activities which engage broader Southern interests and values and thus open meaningful international discussion and contestation over the purposes and desirability of solar geoengineering research.

At the same time support should be directed into much more trans-disciplinary, reflexive research on governance mechanisms and their roles in technological and political co-evolution. Research processes in geoengineering should be consistently used as sites for experimentation and contestation over governance, in processes of "collective experimentation" (Stilgoe, 2016) or "learning by doing" (Parker, 2014). Lessons could be learned from more developed efforts at meaningful engagement and co-production in other climate research areas (Klenk et al., 2015; Lemos et al., 2018). Moreover, a reflexive assessment of "governance research" could usefully broaden our gaze to encompass equally vital political questions of democracy, accountability, security, or justice—critical points of departure that raise different questions about solar geoengineering research. Conceiving of the challenge in terms of governance—as a set of rules or norms for particular forms of research—should not distract from reflections upon research as an unavoidably political activity, nor the critical need to reconfigure its purposes as well as its practices.

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CONFLICT OF INTEREST

The authors have declared no conflicts of interest for this article.

AUTHOR CONTRIBUTIONS

Duncan Mclaren: Conceptualization; writing-original draft; writing-review & editing. **Olaf Corry:** Conceptualization; funding acquisition; project administration; writing-review & editing.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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ENDNOTES

[1] Here "prejudice" refers to the unintended constitutive effects of research unduly shaping or prematurely limiting future policy.

[2] A note on our own positionalities *regarding research into solar geoengineering* may be helpful to the reader. As scholars, we have conducted social, political science, and international relations research into geoengineering and other technologies closely related to climate discourse. We both endorse the view that research into solar geoengineering may indeed be merited by the growing severity of the climate crisis. Yet we are increasingly concerned that the wider body of research is—largely against the intent of its participants—becoming complicit in a process prone to abetting climate procrastination. We have found that research plays a constitutive role in a wider process in

which exploration of technology and governance options has effects that at a critical moment could enable continued delay in cutting emissions. We therefore would support measures to appropriately govern all research into solar geoengineering—including our own—not to delay or prevent important work, but to ensure that it serves wider goals of sustainability and justice.

[3] https://www.srmgi.org/decimals-fund/

[4] https://projects.iq.harvard.edu/keutschgroup/scopex-governance

[5] We note that the Climate Action Network has recently issued a statement on solar geoengineering, confirming its basic opposition to deployment or outdoor experimentation (although noting softer positions from certain members) http://www.climatenetwork.org/sites/default/files/can_position_solar_radiation_management_srm_september_2019.pdf

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