Governing geoengineering research: why, when and how?

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2 authors, including:

Lisa Dilling
University of Colorado Boulder

Climatic Change
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Lisa Dilling · Rachel Hauser

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Abstract Research on geoengineering – deliberate management of the Earth's climate system – is being increasingly discussed within the science and policy communities. While justified as necessary in order to expand the range of options available to policy makers in the future, geoengineering research has already engendered public controversy. Proposed projects have been protested or cancelled, and calls for a governance framework abound. In this paper, we consider the reasons why geoengineering research might be subject to additional governance and suggest mechanisms that might be usefully applied in developing such a framework. We consider criteria for governance as raised by a review of the growing literature on geoengineering and other controversial scientific topics. We suggest three families of concern that any governance research framework must respond to: 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. We review what mechanisms might be available to respond to these three families of concern, and consider how these might apply to geoengineering research.

1 Introduction

"Geoengineering research has a problem." So stated the editors of *Nature* in May 2012 after the lead scientists called off an experimental field test-bed portion of a high-profile project in the UK over protests from the public about governance and disputes over patents and intellectual property rights (Macnaghten and Owen 2011; EPSRC 2012). The editorial concluded with a call for "detailed, practical actions that need to be taken to advance governance in the field" (Anonymous 2012).

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L. Dilling (✉) · R. Hauser
Environmental Studies Program and Center for Science and Technology Policy Research, Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, CO, USA
e-mail: ldilling@colorado.edu

R. Hauser
National Center for Atmospheric Research, Boulder, CO, USA

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The idea of geoengineering the planet's climate as response to climate change is not a new one (Marchetti 1977), but starting with Crutzen (2006), the past few years have seen a sharp increase in articles, media reports, and government interest. [1] While the topic is not particularly salient to the lay person as yet (only 8 % could correctly define the term geoengineering in a 2010 survey (Mercer et al. 2011; Corner et al. 2012)), many in the climate change science community have engaged the issue, often with trepidation, acknowledging that the idea can seem far-fetched or even "shockingly bad" on first hearing (Keith et al. 2010).

Geoengineering has garnered attention largely because of the specter of rapid, non-linear responses of the climate system brought on by a possible 4.5 ° C warming trend by the end of the 21st century if adequate progress in curbing greenhouse gases in the atmosphere is not made (Battisti et al. 2009; MacCracken 2009; Betts et al. 2011). While nearly every scientific article written states the preference for mitigation of carbon dioxide through reducing emissions as the preferred policy avenue for addressing climate change (including Crutzen's 2006 piece), many express skepticism that society will act in time to prevent significant change.

The calls to develop governance mechanisms for geoengineering research have multiplied in the past 2 years (Anonymous 2010a, b; The Royal Society 2009; GAO 2010; SRMGI 2011; Bipartisan Policy Center 2011). Concerns about the ethics of geoengineering research have also led to urgent calls for "the discussion and establishment of appropriate institutions," especially for research that might occur outside of a computer simulation environment (Morrow et al. 2009). Several scholars have already taken on the task of asking whether or not we *should* do geoengineering or geoengineering research (Jamieson 1996; Morrow et al. 2009; Bunzl 2009; Gardiner 2010; Hale and Dilling 2011) — here we ask the question, *if* we pursue geoengineering research, how might we govern it and with what institutions?

Geoengineering is defined as "the deliberate large-scale manipulation of the planetary environment to counteract anthropogenic climate change" (The Royal Society 2009). Some discussions of governance structures for geoengineering have split out carbon dioxide removal (CDR) techniques from solar radiation management (SRM) techniques (e.g., Anonymous 2010a; SRMGI 2011). However, we suggest that CDR and SRM should both be considered in designing geoengineering research governance mechanisms, as some types of SRM seem relatively benign and might even have co-benefits (e.g., roof-top whitening), with no direct transboundary effects, while some CDR efforts (e.g., iron fertilization of the ocean) may generate worries on par with those of large-scale atmospheric SRM research (Hale and Dilling 2011; SRMGI 2011). Moreover, as we will show, concerns about geoengineering research go far beyond the physical impacts of the research experiment itself.

Do we even need governance for geoengineering research?

Ralph Cicerone, President of the U.S. National Academy of Sciences, suggested that geoengineering "research be considered separately from implementation" and that "we should proceed as we would for any other scientific problem, at least for theoretical and modeling studies" (Cicerone 2006). But, is geoengineering really just like any other "scientific problem?" One sign that geoengineering research may need special attention for governance is the tone of the scientific community in approaching the topic thus far. Leading proponents of geoengineering research admit that the proposal seems to smack of "dangerous hubris" and that the public's first reaction to geoengineering may be "revulsion" (Keith et al. 2010; Victor et al. 2009). There is limited data on public perception of geoengineering but as Corner et al. (2012) state, the idea has provoked "strong and often divided positions" and engendered public protest. The cautious language, the call for public discourse (e.g., Cicerone 2006; Anonymous 2010b; The Royal Society 2009; Gardiner 2010; Bipartisan

[1] Search of major world publications using Academic Lexis Nexis database conducted February 21st, 2013.

Policy Center 2011), and attention being paid to the ethics of conducting such research (Gardiner 2010; Jamieson 1996; Morrow et al. 2009; Bunzl 2009) also suggest that geoengineering studies may be seen differently than your average research program. In fact, the governance challenges and issues for geoengineering research might be best compared to those from other controversial areas such as nanotechnology and synthetic biology (Sarewitz 2010).

Simply because a topic engenders public controversy does not by itself necessarily imply the need for additional governance, although it does raise the topic for consideration. However, as we discuss below, the controversy does reflect some of the real concerns that have been articulated about either the risks of the research itself, the extent to which non-researchers have a say in the research, and what the existence of a research activity might mean for larger questions of our interactions with the environment and the planet. Beyond the public controversy over geoengineering, based on our review of the literature we therefore suggest that there are underlying issues that support the need for governance of geoengineering research.

Moreover, nearly every article advocating for attention to research studies on geoengineering states that we must do so not for reasons of fundamental curiosity, but as an obligation to produce knowledge that could support future decision making on responding to climate change (Keith et al. 2010). Proponents, as Gardiner (2010) points out, state that research into the possibility of geoengineering would “arm the future” with knowledge and additional options for managing the climate in the event of a planetary emergency. Geoengineering research has been promoted even as a defense against potential “rogue” states that might act unilaterally (e.g., Victor et al. 2009; Virgoe 2009; SRMGI 2011; Bipartisan Policy Center 2011). This intentionality of the research program places geoengineering clearly in the sphere of science for policy, or usable science (Keith et al. 2010; Dilling and Lemos 2011). Science policies for research that would seek to inform decision-making must necessarily engage a more deliberate strategy for governance and public engagement than more basic types of research (Dilling and Lemos 2011).

Furthermore, others have described research in areas like geoengineering where there exists deep uncertainty and high public stakes as ‘post-normal science,’ where we can no longer maintain the artificiality of separation between science and its potential uses in society (Funtowicz and Ravetz 1993; Gibbons 1999; Sarewitz 2010). The very discourse of “saving the planet” in itself necessarily points to the need for a more inclusive conversation than the one currently occurring among interested scientists and a limited number of others.

In this paper, we review the categories of concern related to geoengineering expressed in the literature. We then analyze existing mechanisms of governing research that might be used as a model for addressing each of these categories. Finally we suggest a way forward to begin a governance framework for geoengineering research, building on existing networks and institutions that will be responsive to the public and researchers’ needs, learning and adaptive, and innovative in that it will offer a new paradigm for more open and transparent research in this highly controversial area.

2 Review of concerns related to geoengineering research

Many geoengineering governance discussions in the literature have thus far focused on the scale of physical risk of perturbing the environment, and while issues of scale are essential, we argue that other factors are just as important to the public in terms of participation, accountability, and transparency. As Rayner and Cantor (1987) discuss, evaluations of societal risk involve much more than absolute probabilities of events occurring, and need to take into account issues of liability, trust in institutions and distribution of power in decision making. They suggest that “…while assessment of probabilities and magnitudes of undesired outcomes are essential to making engineering decisions about competing designs or alternative materials, they are largely irrelevant to societal technology choices" (Ibid). The protests, cancellations, and threat of cancellation of three small field experiments conceptually linked with geoengineering but with negligible direct physical impacts (a deep ocean injection experiment off Hawaii, the German-Indian cruise LOHAFEX, which studied the effects of ocean fertilization on phytoplankton bloom development (Hale and Dilling 2011) and the UK SPICE field trial, mentioned at the start of this article, which, in its early stage, had only sought to deploy and test equipment with ordinary water) demonstrate that objections are not only about the risks of the actual experiment – it is what the experiment represents that matters.

The concerns about geoengineering research expressed in the literature thus far can be grouped into three major categories: 1) the physical risks and impacts of the research itself; 2) transparency in decision making and responsibility for research; and 3) the "meaning" or implications of the research.

2.1 The physical risks and impacts of the research

The physical risks arising to the environment and humans from the large-scale impacts of geoengineering are a central concern. The very nature of the scale of environmental manipulation that might be contemplated makes geoengineering research unique (SRMGI 2011). Some have argued, even, that it is difficult if not impossible to answer some research questions in geoengineering at the necessary scale without actually implementing geoengineering itself (Robock et al. 2010). Thus geoengineering experiments become difficult to distinguish from implementation, which no-one is suggesting should be done at this time (SRMGI 2011; Bipartisan Policy Center 2011). Moreover, as is the nature of most experiments, it is difficult to predict exactly how they will turn out ahead of time. The climate system is particularly complex and often chaotic, and our understanding is still far from complete (Robock et al. 2010), however, in the case of SRM, perturbation of global temperature is projected to affect precipitation and hydrologic cycles, including likely changes to tropical monsoon patterns, among other influences (MacCracken 2009; SRMGI 2011).

2.2 Transparency in decision making and responsibility for research

A second category of concerns revolves around the nature of decision making in conducting research and who is responsible for the outcome. Calls for transparency are a common refrain of geoengineering scholars (Victor et al. 2009; Blackstock and Long 2010), policy makers (GAO 2010) and the general public (Corner and Pidgeon 2010). Specific transparency concerns have been raised in the context of the participation of the private sector in geoengineering research (Anonymous 2010b). On the one hand, the private sector can be a source of innovation, and competition might bring out the best options available for technology. On the other hand, research conducted in the private sector is often proprietary, results are often not fully disclosed to the public, and research is not published in the open peer-reviewed literature.

Many point to the issue of equity and power in making decisions over research (e.g., The Royal Society 2009; Corner and Pidgeon 2010; Gardiner 2010; Bipartisan Policy Center 2011). Even in a democratic society, the more technically dense an issue is, the more likely its discussion will be limited to a select few with the necessary expertise to be able to engage (Lovbrand 2007). Thus a highly technical issue such as geoengineering already effectively discourages entry and dialogue by non-specialists. Moreover, wealthier nations are likely to be more influential in global debates involving technical issues, as they field a greater capacity in terms of the number of experts available to engage an issue compared with less affluent nations, whose less numerous experts are likely to be stretched thin among multiple issues under discussion internationally (Corner et al. 2012). The availability of information for the general public and ability to solicit opinions on potential future actions, a fundamental principle of informed consent, is thus an area of concern (Morrow et al. 2009; Hale and Dilling 2011).

Liability for the effects of geoengineering has been raised as an implementation issue, but also could apply in the case of geoengineering research (Keith 2000). Concerns about liability involve questions of how liability for consequences would be established, how compensation would be determined, and who would be responsible for damages (Anonymous 2010a; GAO 2010; SRMGI 2011). Given the difficulty of attributing outcomes in a chaotic system to any one particular action, definitively establishing liability will likely be a challenge. Furthermore, the nature of the climate system and the involvement of international boundaries suggest these concerns about transparency, conflicts of interest, liability, responsibility and openness in decision making will likely pose a much more difficult challenge.

2.3 The "meaning" or implications of the research

A third area of concern about geoengineering research relates not to the research itself but to its multiple implications. The deep uncertainty and high decision stakes associated with climate change place geoengineering in the realm of "post-normal" science, and suggest that uncertainty cannot be eliminated but must be "managed," and values, rather than being assumed, must be made explicit (Funtowicz and Ravetz 1993). Many of the concerns raised thus far suggest that values and views toward research are already inextricably linked in the area of geoengineering. For example, some worry that the availability of geoengineering research knowledge might reduce pressure on leaders to deal with the difficult problem of cutting carbon and other greenhouse gas emissions (Morrow et al. 2009). This so-called "moral hazard" argument has been dismissed by some (e.g., Bunzl 2009; Humphreys 2011; Hale 2012) but others have suggested knowledge itself would overcome or lessen the moral hazard (Keith et al. 2010), and that identifying the extent of the moral hazard may be a necessary area of study (The Royal Society 2009).

Another concern raised about conducting geoengineering research is that the act of doing research may make it more likely that geoengineering itself will be carried out regardless of potential societal concerns. While many have stated that research should be considered separately from geoengineering (e.g., Cicerone 2006), others have argued that conducting geoengineering research builds up a constituency of scientists and others who could lobby for the continuation of research programs, and may create momentum for the eventual deployment of geoengineering technology even if it is shown to not be supported by the public (Morrow et al. 2009; SRMGI 2011; Corner et al. 2012).

A third concern stems from differing views on the appropriate role or limits of technology. Fleming (2007) points out a societal – and scientific – tendency to have strong confidence that technological fixes will resolve difficult problems. Given the complexity of the climate system, and despite all best intentions to do good, Fleming suggests that in the case of geoengineering this faith in human ingenuity and technological prowess may fail us. The debate over geoengineering may reflect echoes of more ancient debates about the appropriate role of man in the universe, and whether actions such as deliberate engineering of the climate usurps a role better suited to "Mother Nature" or whether we have a right to "play God" with the planet's temperature (Hamilton 2011; SRMGI 2011).

3 Elements and options for a geoengineering governance framework

Geoengineering is not the first scientific endeavor to garner extra scrutiny from the public. Some types of research or technology development raise concerns more than other types, e.g., nuclear power, genetically modified crops, and nanotechnology (Slovic 1987). Because the concerns raised about geoengineering research thus far are not solely focused on the risks of the research itself, in this era of post-normal science, a governance framework must take into account notions of managing risk and also be reflective of values.

3.1 The physical risks and impacts of the research

Physical risk and impact of research has been most closely examined for SRM research (Robock et al. 2010; Anonymous 2010a, b, SRMGI 2011). The SRMGI report focuses on Solar Radiation Management methods and proposes four levels of environmental risk categories for research (from modeling and desktop research to full-scale in situ experiments that would affect the environment in a large and significant way) and a fifth for full-scale deployment (SRMGI 2011). A system for evaluation based on level of perturbation may well provide a useful method for screening proposed geoengineering experiments for the issue of physical harm to the environment or people directly affected by the perturbation. Indeed governance mechanisms under the London Convention and London Protocol currently in place for ocean fertilization experiments (a form of CDR) require that "expected impacts" on the environment be "slight, if any" for an experiment to go forward (Williamson et al. 2012).

Tiered evaluation systems are not uncommon and are already used to judge research in the United States and elsewhere. Several existing policies evaluate levels of environmental disturbance and weigh the proposed risks and benefits. For example, the U.S. National Environmental Policy Act (NEPA) reviews "major federal actions significantly affecting the quality of the human environment" and ensures that a public process is followed to weigh alternatives (eCFR 2012). In the United States, research activities such as seismic surveys of the ocean or construction of observatories by the National Science Foundation (NSF) are already subject to review under NEPA. NEPA does not itself regulate actions or prohibit actions; it guides the process for investigating level of impact, allows for public comment and review, and provides a recommendation for alternative actions that could be followed. Levels of evaluation considered under NEPA fall into one of the three process categories: a categorical exclusion (CE), an environmental assessment (EA), or an environmental impact statement (EIS). CEs are those actions that are routine, non-controversial and do not pose a significant threat to the environment (Council on Environmental Quality 1978). If an action is well-characterized and the effects are minimal, as is the case with research that has been reviewed and performed many times before, it may not require any further scrutiny at least with respect to potential impacts. An example of a CE might be a forest thinning project of small scope or of a type that has occurred many times before. Most of NSF's research portfolio is considered CE. Under NEPA, actions that might be considered controversial or politically charged are generally selected for the highest level of scrutiny at the EIS level.

Similar to NEPA, human subject institutional review board (IRB) panels follow a three-tiered process – exempt, expedited review, and full review. The major determining factors triggering a more in-depth review are whether vulnerable populations are involved (e.g., children, the mentally ill, or prisoners) and whether there exists a chance for significant harm as a result of the research (e.g., a relatively untested drug, or a sensitive area of research that could result in the loss of a job). Obviously human subjects review is not a direct analog for how we might account for impacts of geoengineering research on humans, as it does not address the impacts of research on non-enrolled human subjects. However, there are lessons from the structure of governance of research on human subjects that can be useful for a governance framework for geoengineering (Morrow et al. 2009). One of the primary areas of concern in the Human Subjects review is concern over the distribution of risks and benefits of the study, and whether some individuals are disproportionately bearing the risks for the gain of knowledge that might benefit others. Secondly, and relatedly, informed consent (the operationalization of the principle of respect, as stated by Morrow et al. (2009)) is paramount in human subjects review. A governance framework could include an evaluation step that took stock of the vulnerabilities of exposed populations to the research, whether the most vulnerable might be disproportionately affected, and whether affected populations could be informed sufficiently or not.

3.2 Transparency in decision making and responsibility for research

As Liu and Priest (2009) write: "…trust can be very predictive of the general public's attitudes toward science controversies." Mercer et al. (2011) found that respondents trusted university researchers the most to deliver reliable information on SRM while industry was the least trusted. Building and earning trust goes beyond simply providing information, however, and extends to the area of transparency in planning and potentially including stakeholders in decision making – in essence building social capital among interested parties (McNie 2007).

Mechanisms for establishing transparency Transparency is a value that has repeatedly come up as a necessary component of a geoengineering governance framework (Anonymous 2010b; The Royal Society 2009; Blackstock and Long 2010; Bipartisan Policy Center 2011; SRMGI 2011). How does one create transparency? Mechanisms to provide information on what is planned and for what purpose can be a first step toward providing transparency such as voluntary, public registries that include information on funding sources, personnel, research plans, project outcomes, etc. Being proactive rather than defensive about engaging the public may allow for the discussion of concerns early on, and the development of mutual respect (Corner and Pidgeon 2010).

Research warns that deliberate attention must be given to the format and details of a public participation effort lest it fail to meet objectives (Dietz and Stern 2008). Other options include formal public notification processes (such as is required by NEPA), the formation of networks, discussion groups, citizen panels, and media outreach. Several of the "*Oxford Principles*" address the issue of transparency, and call for research to be regulated as a public good, including disclosure of geoengineering research and open publication of results (Anonymous 2010b). A geoengineering research governance framework might consider going a step further, as the public does not typically read even open-access journal articles, and perhaps requires a paragraph summary in layman's terms of the (societal) benefits driving the research, as well as the research program findings.

Mechanisms for establishing shared decision making Unfortunately, the public has shown some skepticism that public processes actually provide them much power in the decision over whether geoengineering techniques would be used (Corner et al. 2012). In the United States to date, most "typical" research is funded and conducted through decision processes that are largely internal to the scientific community and not subject to input from the average citizen. These processes typically involve submission of proposals and review of proposals by those engaged in the research, who, it is argued, can best judge the scientific merit of the proposed work. Some other nations more openly struggle with how research priorities are set and who is invited to the table. For example, the decision process for developing the European Union's major Framework Research and Development programs came under fire in the past for being too beholden to industry, leading to the establishment of a working group on science and governance that included citizens (Wilsdon et al. 2005).

Technology is a constantly evolving, ubiquitous part of life, suggesting that different processes might be needed to open up the largely insular science and technology decision-making sphere to the broader influence of various publics (Wilsdon and Willis 2004). Most proposals to do so have not had much impact as current decision makers have successfully argued that these publics lack the expertise to adequately engage in the discussion (Parthasarathy 2010). However, in areas of medical research examples exist in which patient advocacy groups and those directly affected by a disease have begun to influence research direction, prioritization, and even patient care recommendations. For example, proposals submitted to the Alzheimer's Society receive comments from not only scientists evaluating scientific merit, but from patients, patients' family members, and others in the care field, which often broaden the perspective of the researcher and enrich the research that ultimately gets done (Wilsdon et al. 2005).

As part of the SPICE team's SRM research design, external experts assessed whether the research project met a number of pre-determined criteria ('stage gates'), including public engagement and governance development, with funding moving forward upon successful stage-gate clearance. After a September 2011 assessment, external reviewers felt SPICE addressed the technical and scientific questions, but needed more thorough stakeholder engagement and project-risk explanation (McNaghten and Owen 2011). Delaying the experiment to address these issues, the SPICE principal investigator and UK Engineering and Physical Sciences Research Council (EPSRC) ultimately cancelled the test-bed trial in May 2012 citing intellectual property rights issues and noting that public engagement and the social and ethical implications of the research had not been adequately addressed (EPSRC 2012).

A wide range of levels of public engagement might be contemplated in a geoengineering research program, spanning from simply allowing public comment to involving non-scientists in review panels, all the way to requiring that a proposed project respond to critiques sufficiently prior to implementation. *Substantive* public engagement (sensu Stirling 2008 as cited in SRMGI 2011) – that is engagement with the goal of improving the quality of decision making around the issue – is particularly important in areas with "intractable scientific and technological uncertainties," as is certainly the case for geoengineering research (SRMGI 2011 page 40). The level of input on decisions allowed to those outside of the research community will likely determine whether or not public engagement efforts are seen as "window dressing" or as substantive opportunities to provide input. A public process properly designed, however, can provide substantial benefits for transparency and a feeling of inclusion (Dietz and Stern 2008).

Mechanisms for adjudicating liability concerns In the U.S. context, in most cases liability for geoengineering research would be a new area to be addressed (GAO 2010). A first step might involve describing how geoengineered effects might be distinguished from background processes (such an assessment will be a necessary scientific research requirement). However, the complex science of attribution and detection as it exists today suggest that it could be very difficult to attribute all of the potential effects from a geoengineering experiment, and liability therefore may be difficult to definitively establish. Unintended or unanticipated consequences are by definition impossible to predict ahead of time, and alternate mechanisms may be necessary to address liability for consequences and potential claims such as "no-fault" insurance, and compensation funds.

Experiments occurring outside of a particular country's jurisdiction (such as over open ocean) or that occur in the atmosphere but affect neighboring nations would exist in an even more complicated liability situation than within-nation activities. It has been suggested that an international body might be established to assess techniques and provide a venue for consultative activities (Bodansky 2011), although successful examples are rare, especially in the area of negotiating liability across borders (Bodansky 1996).

3.3 The societal meaning of the research

Establishing mechanisms to support scientific community and public reflection Part of the public apprehension for geoengineering, as seemed to occur for SPICE, will likely arise from concern over the meaning or implications of the research rather than the impacts themselves. For more controversial research topics such as geoengineering, Sarewitz (2010) argues, "…a commitment to *reflecting on technological futures* needs to be integrated into the research and development enterprise [emphasis added]." As pointed out by the SRMGI (2011, p 41), public engagement requires more than asking people to define the effects of poorly understood innovations, it requires robust public discussion that relates to the "visions, ends, and purposes of science and technology." Such debate would be usefully integrated into both a research program and the overarching governance framework. Guston and Sarewitz (2002) have advocated for a technique called "real-time technology assessment." More recently, these ideas have been built upon by Karinen and Guston (2010) and reframed as anticipatory governance. Anticipatory governance incorporates notions of post-normal science in that value inclusion is explicit within the research, with one approach being engagement with diverse audiences. Anticipatory governance also fosters generation of "anticipatory knowledge" through scenario building or other methods (as suggested above by Guston and Sarewitz 2002); this might occur even before the technology reaches the streets or before an understanding of what the technology is has developed. Further, anticipatory governance prescribes integration of engagement and foresight with scientific and technical research efforts, so as to assist scientists in developing a greater awareness of the nature of an emerging capability with a view on incorporating societal values and perspectives as part of the technology research and development process (Guston 2008). For example, Fisher (2007) found that embedding a social scientist within a nano-engineering research center offered a useful feedback mechanism with numerous research benefits. Finally, as with any governance framework, real power must be given to the mechanisms lest they become only for "show" (McCain 2002).

Conducting research that is usable for decision making Science conducted in support of decision making must engage the decision context up front, and recognize that the research is taking place in a context of politics, values, vested interests and other "messy" conditions. Science can most effectively support decision making with "two-way" communication and balance of power in setting the research agenda (Rayner and Cantor 1987; Dilling and Lemos 2011). In the case of geoengineering research, this suggests that a dialogue should be established between potential decision-making entities and researchers, in addition to the public at large, in order to understand what lines of inquiry might be more salient to eventual decisions that might be made about future geoengineering.

4 Next steps: governance mechanisms, structures, and venues

We have identified three areas of concern to which a governance framework for research needs to be responsive: actual physical risks, decision-making power/responsibility for outcomes, and the societal meaning of the research. We assert that to be truly effective, a framework should provide elements to address all of these concerns. To date, such a comprehensive framework is lacking for geoengineering research. While some research currently takes place under national research programs that could be counted as geoengineering research, we suggest that existing governance structures do not effectively address all three areas. Again, because the concerns go beyond simply the physical risks, all geoengineering research should be subject to some level of governance, whether in norms of behavior of researchers or as part of a regulated system. How is geoengineering research identified? If the research is justified by investigators or programs as informing the idea of intentionally manipulating the earth's climate, whether in a computer simulation or in the environment, it would be classified as geoengineering research.

Frequently scientists working in emerging technology research areas, e.g., nanotechnology, raise concerns that a governance framework might be too restrictive and impede their work (Roco and Bainbridge 2005). In the case of geoengineering, given the public attention and the high-profile project cancellations or near cancellations, as well as the gingerly approach of public funders thus far, an effective governance framework may well be the only way forward.

How then might we proceed to develop a framework within such a fragmented system of national research programs, transboundary venues for experimentation, and international public scrutiny of geoengineering? Because of the fact that some research is already underway in labs and modeling centers around the world, scientists as well as funding agencies have the power and opportunity to act proactively to establish such a framework, drawing upon tools, mechanisms and concepts already in use. Research community members interested in geoengineering research can send a powerful signal by organizing to create such a framework, replicated, to start with, within each country with currently active geoengineering researchers, and linked together through an international research organization such as the International Council for Science (ICSU) or the World Meteorological Organisation (WMO). Recent cooperation on physical/social science projects (e.g., ICSU's Earth System Science Partnership and new "Future Earth" programs) coupled with calls from both these programs for research to be more relevant to society at the international level suggest that the time may be ripe for such a collaborative experiment (http://www.icsu.org/future-earth). The conversation still needs to spread more widely across non-research organizations, however – perhaps such a dialogue could become part of regular conversations occurring within transnational networks of actors at the local scale (e.g., ICLEI, an international association of local governments and their associations; Bulkeley et al. 2012) and linked to an ICSU framework, or through a formal international institution such as the UN.

As Parson and Keith (2013) suggest, it is likely that government will need to assert some authority over geoengineering research in order to effectively manage risks. One way forward is to require, either through funding requirements or community standards and norms, that all project proposals include a section detailing how they will address the three components of the proposed governance framework. This will maximize flexibility for researchers, while ensuring they have a plan for each component. In terms of precedent, this is no different from requiring a section on post-doc mentoring, a data archival plan, or an articulation of broader impacts, to name a few standard NSF requirements currently in place for any grant proposal. There may be some need to develop common community resources, such as a registry site, or to pool resources among projects, such as a physical impacts screening team, or a public visioning process, that more than one research team can participate in. Such common-pool resources can be proposed and judged as with other types of community resources such as data centers or observing systems. Just as additional expertise beyond the physical sciences contributes to proposals to make for meaningful broader impacts, for example, experience in public participation, engagement or other anticipatory governance mechanisms could be drawn upon to make these plans meaningful.

Over time, researchers and stakeholders could meet to assess progress in governance, identify emerging norms, and correct problems. Governance norms could spread through the sharing of "best practices," and the gradual institutionalization of successful ones. Parthasarathy et al. (2010) discuss the importance of "bottom-up" governance in the case of SRM in the Arctic region and Keith et al. (2010) also suggest that a governance framework could be built from the bottom-up based on organic experience of smaller groups. It is likely that a structure for governance should include both the development of strong norms among researchers, and an identified network of practicing researchers and public participants whose work is placed into an international research framework such as ICSU. Given that geoengineering is a new area, any governance structure should be adaptive and subject to periodic evaluation, so that adjustments in institutionalization and participation can be made as issues evolve (SRMGI 2011; Bipartisan Policy Center 2011).

To conclude, based on a review of the literature and arguments thus far surrounding geoengineering research, we propose practical steps to provide governance in three themes of concern: physical risks, transparency in decision making and responsibility for research, and meanings and implications of the research. As outlined above, several possibilities exist to implement these elements, and many options should be tried to ensure flexibility and innovation in governance techniques. Just the idea of contemplating geoengineering research itself is sobering to most people, as it suggests both that we have run up to the edges of a planetary emergency and that we have the capacity to deliberately engineer the future state of our environment. An investment in a governance framework and instituting norms to be followed in the conduct of future research in geoengineering is not only appropriate but necessary in the face of the seriousness of the undertaking.

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