Disaggregation may also help find places where experts agree. Experts who disagree strongly about proceeding with a SG field experiment might nevertheless agree on specific technical judgments, such as the mortality caused by SG aerosols that add to particulate matter pollution or the reduction in mortality from heat waves when SG reduces peak temperatures.

When experts provide an aggregate policy recommendation, they combine their judgment about the likelihood of specific technical and or political outcomes with their personal valuation of those outcomes. This is unhelpful when the audience does not share the expert's valuation. Disaggregation can help avoid conflation of facts and values (*9*).

Support for SG research seems to be stronger in poorer countries (*10*, *11*). It is plausible that this arises from divergent weights given to the outcomes of SG. Residents of poorer and hotter countries may weigh the benefits of short-term cooling more strongly, whereas residents of richer, cooler countries who feel less threat from the immediate impacts of heat may accord more weight to the long-term concerns about SG. There is no value-free resolution to trade-offs between the benefits and harms of SG. What is certain is that experts' valuation of outcomes will likely differ from their audience, and that climate experts are generally more educated, wealthier, and less racially diverse than their audiences. So experts do their audience a disservice by implicitly folding their values into policy recommendations.

How to encourage disaggregation? Experts should strive to delineate areas in which they have expertise from areas in which they do not and should give audiences the opportunity to use their own values. Policy intermediaries such as journalists and opinion-leaders can encourage the distinction between factual judgments and valuation.

A community-based taxonomy of SG concerns could help. Such a taxonomy might be seen as reasonably unbiased if it were maintained by a community using rules adapted from Wikipedia in which substantive statements require pointers to peer-reviewed literature.

Organizations such as the National Association of Science Writers can help by explicitly promoting best practices for reporting on politicly contentious topics. Journalists might better encourage experts to provide narrower answers that are better supported by data in the expert's arena of expertise.

This is not an injunction that experts "stay in their lane." Transdisciplinary research requires collaboration across disciplinary boundaries. Moreover, experts are also citizens and, as citizens, have a right to participate in public policy. But in participating, they have a duty to distinguish statements made on the basis of their expertise from statements they make as citizens.

Nor is this a claim that facts and values can be sharply separated; they cannot. But more careful reporting of expert judgments could help to reduce the role of "cultural cognition" in determining policy preferences (*12*).

Behavioral social science may help untangle interplay between expert judgments, values, and public understanding. Analysis of SG is oversupplied with generic normative claims about governance and undersupplied with detailed empirical research to understand the mental models of relevant groups. Empirical social science could adapt research projects to identify and characterize subjective aspects of expert judgments and anticipate and clarify conflicts that arise from inequitable effects of climate change and geoengineering (*13*).

A coordinated SG research program could support development of community-based taxonomies of SG's benefits and concerns. The program could then use such structures to aid program managers in supporting research that addresses concerns that are both salient and researchable. The program could also encourage development of community-based codes of conduct that include best-practice guidelines for reporting results.

There is no recipe to resolve hard problems at the science-policy interface, but that should not discourage incremental improvements that may allow experts to better serve the public. ■

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CLIMATE POLICY

Social science research to inform solar geoengineering

What are the benefits and drawbacks, and for whom?

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As the prospect of average global warming exceeding 1.5°C becomes increasingly likely, interest in supplementing mitigation and adaptation with solar geoengineering (SG) responses will almost certainly rise. For example stratospheric aerosol injection to cool the planet could offset some of the warming for a given accumulation of atmospheric greenhouse gases (*1*). However, the physical and social science literature on SG remains modest compared with mitigation and adaptation. We outline three research themes for advancing policy-relevant social science related to SG: (i) SG costs, benefits, risks, and uncertainty; (ii) the political economy of SG deployment; and (iii) SG's role in a climate strategy portfolio.

Some concerns have received increased attention in debates over SG and thus illustrate the need for greater social science evidence and understanding. For example, some stakeholders have suggested that undertaking SG research could create a form of moral hazard by deterring emission mitigation efforts, whereas other scholars have challenged this claim. Still other scholars have questioned the ethics of seeking to hide from future generations policy choices that they may wish to consider. And given the evidence of strong free-riding incentives for emission mitigation, it is not clear that there would be much of an additional emission mitigation disincentive from SG. But these questions deserve further study in more realistic models of multiple, heterogeneous actors (*1, 2*).

Further, if a major economy with the technical capacity to implement SG makes a decision about its use, this would have important equity and justice implications, especially for the people living in least developed countries and small island states. These implications take the form of procedural justice—do these peoples have a voice in the decision-making process—as well as the distributive justice of the outcomes associated with a SG intervention decision. Such justice considerations arise regardless of whether the decision is to take or opt against an SG intervention. A critical assessment of the justice implications of SG implementation would enrich the political economy evaluation of government decision-making.

SG is one of several emerging climate engineering technologies. For example, carbon dioxide (CO_2) removal would reverse the flow of greenhouse gases into the atmosphere through large-scale biological and chemical sequestration and industrial direct air capture technologies. In contrast to CO_2 removal, SG faces fewer technological and financial hurdles and would likely influence temperatures more quickly. Indeed, the largest developed and developing nations have the resources and technical means to implement SG interventions in no more than a few years.

Despite the potential for SG to reduce climate change risks, the international community has not addressed SG under the UN Framework Convention on Climate Change. This is mirrored by a dearth of national programs and governance. The limited policy landscape provides an opportunity for new social science research to inform the design of institutions, policy, and governance of SG.

COSTS, BENEFITS, RISK, AND UNCERTAINTY

Policy-makers would gain from assessments of SG's costs and benefits, recognizing uncertainties in quantification, potential indirect costs, and risk-risk trade-offs. The direct costs of implementing SG interventions could be about $5 billion per year (*3*), two to three orders of magnitude less than estimated climate change damages and the costs of ambitious emission mitigation (*4*). These estimates, however, represent direct engineering costs of deploying SG interventions, and more extensive SG assessments can better inform decision-making. This work should be informed by advances in physical science and engineering research on SG deployment, including alternative technologies and design choices, potential small-scale experiments, and the resulting impacts of climate change and SG interventions. For example, building on high spatial resolution, climate change modeling can enable greater precision in estimating benefits and costs and help identify social science data needs where official economic statistics may be limited.

Higher-resolution representation of physical and socioeconomic impacts can also illustrate the distribution of costs and benefits from SG interventions (*5*). Like climate change, SG interventions would impose heterogeneous impacts across the world and over time (*6*), which would have important social welfare, equity and justice, social, and political implications. SG research can build upon and integrate with the growing empirical evidence of climate change impacts on conflicts, migration, health, labor and agricultural productivity.

The outputs of such analyses could be inputs in models with modified social welfare functions that vary in how they weight inequality and justice of outcomes. They can also serve as inputs in models of political economy and international relations. Taking a multi-objective assessment framework to evaluating SG can also guide survey work and laboratory experiments to elicit preferences and trade-offs over SG impacts, risk, inequality, and other considerations. Drawing study participants from developing countries can help address concerns about how integrated assessments reflect the attitudes and preferences of those populations most likely to be affected by climate change.

Integrating science, engineering, and economic analyses can help address uncertainties in the benefits and costs of SG design and deployment decisions, which could vary across geography, altitude, seasonal timing, technique, magnitude of intervention, and other factors. Integrated frameworks that incorporate risk analysis and decision theory can improve the characterization of, and reduce uncertainty about, SG benefits and risks (*1*).

Integrated assessments of SG interventions should also account for the costs of monitoring, attribution, redundancy, evaluation, updating, and any necessary risk management mechanisms. Such analyses can also consider the benefits of learning through a value of information framework. Theoretical and integrated assessment models (IAMs) can illustrate the dimensions of SG deployment with the greatest potential for learning, which in turn could focus future experimentation and measurement.

An SG intervention is not simply reversing climate change. Some climate change impacts, such as ocean acidification, are only to a small extent directly influenced by SG, and SG would occur against the backdrop of recent decades of rapid warming. Moreover, SG may result in unintended, ancillary risks (*7*). A rich array of research tools—models calibrated to real-world observations as well as statistical evaluations—can provide insights on ancillary impacts of SG interventions. For example, studying potential adverse respiratory health outcomes from SG interventions could inform future technical design of SG interventions—e.g., substituting new materials for sulfur particles—and direct evaluations of alternative policy remedies—e.g., improved health care access and treatment. Evaluations of ancillary or unintended impacts could serve as inputs in survey-based research on SG risk communication and political acceptance. SG interventions could also necessitate updating of damage functions used in IAMs, because such damage functions are typically calibrated to temperature as a proxy for climate change (*8*).

POLITICAL ECONOMY OF DEPLOYMENT

Solar geoengineering deployment scholarship has typically focused on either (i) a single, global actor or (ii) a stylized depiction of strategic interactions among possible SG actors. To understand the roles of incentives, institutions, norms, and international relations in SG deployment, the next generation of analyses could build on these to develop more realistic scenarios of SG intervention and political economy dynamics (*1*).

For example, absent strong international governance, a globally coordinated SG regime is unlikely, and decision-making

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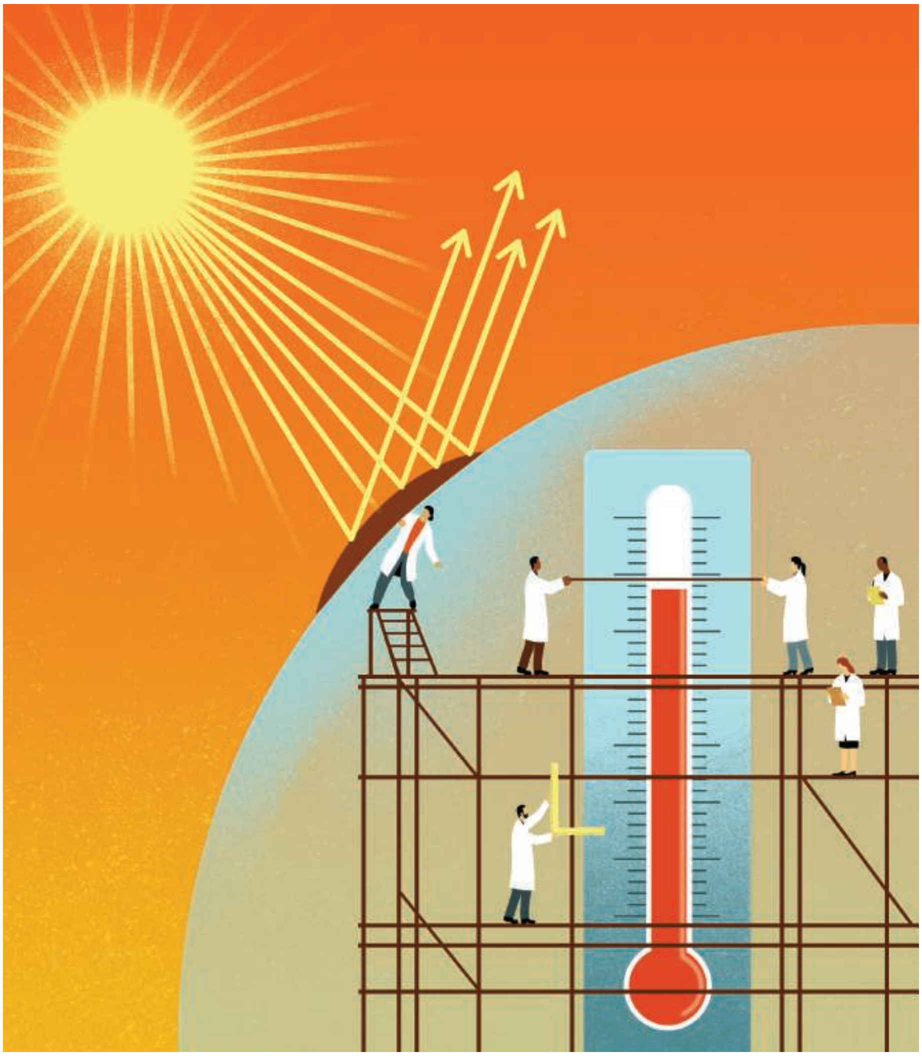

would rest primarily among national governments. Weak global governance, coupled with modest SG engineering costs, has raised concern about "free drivers" unilaterally deploying SG interventions. Social science research can explore the options and incentives for a state (or nonstate) actor to deploy a global SG project or a local intervention (e.g., marine cloud brightening, regional cirrus thinning, or enhancing surface albedo). Such local intervention possibilities raise the prospect that multiple state actors could pursue independent SG strategies without explicit coordination. The atmosphere, however, has nonlocal "teleconnections," so a local intervention's impacts may spill over to other regions, raising governance challenges. Game theory and lab experiments could be used to explore the political, economic, and sociological drivers and inhibitions on a state actor to pursue or refrain from unilateral SG—including the types of events that could trigger unilateral SG deployment.

Inadequate efforts to reduce emissions have also prompted calls for retaliatory measures, such as border tax adjustments. This reaction points to the prospect for countermeasures targeting states that deploy SG by those opposed to such actions (*9*). Might states respond through counter-geoengineering or alternative means, such as military interventions or trade sanctions (*10*)? Such responses could influence incentives for deployment, international conflict, and the efficacy, costs, and benefits of SG interventions. This suggests new social science research convening national security experts to understand the theory, models, and evidence that can be drawn from related international problems.

A smaller group of countries could work together for a collectively managed SG intervention. Such a club approach to governance raises additional questions about legitimacy, political organization, and effectiveness. A club could test technologies and governance regimes to build mutual trust and support for SG as a credible climate change response strategy. The emergence, composition, and decision-making of such a club would likely play a key role in determining whether it would enhance confidence in SG as a strategy, or spur greater concern among states outside the club. This suggests a combination of decision- and game-theory tools to explore possible outcomes and equilibria. For example, a club of countries that are simultaneously pursuing ambitious mitigation efforts may be more credible and sustainable than a coalition of mitigation laggards. There may be opportunities to explore clubs in which SG is one element of a broader climate partnership. The prospect of a club could also benefit from study of the procedural justice implications of such institutional design.

Yet another possibility is a mutual restraint agreement. Countries might build the capacity to launch SG and then agree with other SG-capable peers to a mutual agreement to restrain unilateral deployment. This would be akin to an arms control treaty and suggests that legal expertise and experience with such treaties could be leveraged to answer these questions, alongside game theory and lab experiments. For example, the prospect of such a restraint game raises questions about incentives and institutions for such participation and verification to yield a stable outcome.

The incentives and political economy of SG will reflect actors' assessments of the benefits, costs, risks, fairness, equity, and justice. In turn, the institutional design of SG decision-making will also influence the efficacy and related SG outcomes. The need for redundancy and risk management requirements that may emerge through negotiations could likewise affect the returns on SG deployment. The value and risk trade-offs of SG—evaluated through cost-benefit analysis—would also depend critically on how it may be paired with, or affect, emission mitigation and adaptation.

A PORTFOLIO APPROACH?

Policy-makers have long pursued a portfolio of policies and programs, in lieu of a single policy instrument, to combat climate change. Though initially focused on ways to mitigate emissions—through subsidies, regulatory mandates, carbon pricing, etc.—and more recently advancing ways to enhance resilience to the impacts of a changing climate, future policy portfolios could be broadened to include SG.

Consideration of SG alongside mitigation and adaptation raises important economic, political economy, and decision science questions. Recent analyses have examined scenarios that optimize the mix of strategies—emission mitigation, carbon dioxide removal (CDR), adaptation, and SG—that

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minimize the costs of achieving a specific temperature goal (*8*, *11–13*). Such an optimized framework illustrates the potentially large benefits of coupling SG with mitigation and adaptation. This work, however, does not address the strategic and behavioral responses that SG projects may entail. Decades of experience with suboptimal and inadequate emission mitigation policies suggest that a more realistic treatment of the factors influencing SG decision-making—and the possibility of suboptimal SG policy—could advance this literature (*14*). For example, how feasible are peak-shaving scenarios—which rely on carefully coordinated timing of emission mitigation, SG, and CDR to limit temperature increases and damages until mitigation efforts realize global net-zero (or lower) emissions—given real-world decision-making processes among multiple actors facing heterogeneous impacts? Moreover, SG research may influence the strategic incentives for investing in other climate change risk reduction technologies.

Exploration of SG options by decision-makers could make climate change more salient for the public and galvanize support for more ambitious emission mitigation (*4*, *15*). Rigorous theoretical analysis, coupled with well-designed surveys and laboratory experiments, could better inform our understanding of how SG deployment would influence emission mitigation. This could be integrated with behavioral decision-making scholarship to explore how political leaders would interpret and act on information about the efficacy of a mitigation+adaptation+SG approach to climate change. The public perception of and engagement in SG research and policy serves as another key element of an SG research agenda (*1*).

Given the uncertainties about climate change and SG, a decision-making under uncertainty framework could guide research on the interactions among climate change strategies. For example, decision-makers may respond to new information that shows climate change is worse than expected by implementing SG and investing in more climate-resilient infrastructure. Constructing models of decision-making that can generate such policy response functions for SG and adaptation has implications for the optimal mitigation strategy, as well as for the estimation of the social cost of carbon. Anticipating SG as an active policy response to knowledge of more severe climate change could preclude the most extreme climate change damages, but could also raise tail risks from SG ancillary impacts. Advancing social science research to characterize these potential risk-risk trade-offs would better inform decision-makers.

Social science approaches to solar geoengineering

- Interdisciplinary work among social and natural scientists to address the gaps in our SG understanding most relevant for decision-making
- Convening experts on SG and international relations, along with the use of game theory and behavioral experiments and simulations, to better understand the possible evolution of SG strategies and countermoves
- Numerical modeling to integrate the climate and social systems and to understand how multiple interactions "add up" in a consistent framework
- Assessments by sociologists and cultural anthropologists, as well as science and technology studies scholars, to understand how norms and culture evolve as new technologies enter the policy space
- Applications of behavioral science to explore the mental models of relevant decision-makers in government and throughout society with respect to SG and other climate risk reduction strategies

Given the persistence of climate change risks even with SG, additional research could explore how learning about the benefits—and shortcomings—of SG could guide future adaptation efforts. For example, ocean acidification will worsen with continued CO_2 emissions even if SG interventions effectively halt the increase in temperatures. Or SG implementation may occur too late to prevent substantial sea level rise, locking in the need to manage coastal retreat worldwide over the coming centuries.

THE WAY FORWARD

In addressing these research themes, we envision contributions from an array of social science disciplines through a mix of approaches (see the box). Effective communication and engagement among the scientific community, decision-makers, and the public on this research could also lead to SG's integration into a broader range of climate change research assessment and synthesis activities (e.g., the Intergovernmental Panel on Climate Change). The governance of social science SG research should also evolve in tandem with broader governance considerations for SG scientific and engineering research.

The evolution of SG social science research should also engage scholars from around the world. The consideration of the justice implications of climate policy can be richer and more credible through a more inclusive approach in undertaking research and the production of evidence. Considering the potential for climate change and SG to have substantial impacts on developing countries, the next generation of SG research should integrate existing scholars and contribute to the training of new scholars in developing countries.

Given the mounting evidence of the economic and social impacts of climate change, the development of new emission mitigation policies and the notable public spending on resilience and adaptation illustrate decision-makers' interest in exploring new ways to combat climate change. Advancing SG social science scholarship—and integrating such research with that undertaken in the physical sciences—can help inform what role SG might or might not play in reducing the risks of climate change. ■

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