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UNDERSTANDING CLIMATE ENGINEERING

DEBORAH GORDON | AUGUST 21, 2017

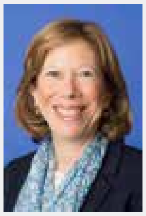
There is no doubt that a rapid rise in the earth's temperature will impose high costs on not only our environment and health but also our economic and physical security. In recognition, most nations have committed to significant mitigation efforts.[1] But will these collective efforts be enough? Some scientists are trying another approach, exploring new tools that can deliberately alter the global climate system. The problem is, while several tools seem to be gaining traction, knowledge of them is not widespread and there has been too little transparency and international dialogue around their progress, feasibility, risks, and benefits.[2] Documenting and tracking the array of tools in development will be crucial for understanding their full impact, debating their implementation, and safeguarding their appropriate use.

WEATHERING A WARMING WORLD

The earth's twentieth-century average temperature record has been broken year after year since 1976.[3] The global average temperature has increased by about 0.8 degrees Celsius (1.4 degrees Fahrenheit) since records were first kept in 1880, and experts predict that temperatures will mount in the decades to come.[4]

While a few degrees may not be enough for a person to spike a fever, the earth is different. According to NASA, a one-degree *global* change is significant because it takes a vast amount of heat to warm all the oceans, atmosphere, and land by that much.[5] The earth was once plunged into the Little Ice Age by a one- to two-degree Celsius drop in temperature; and 20,000 years ago, a five-degree Celsius drop buried much of North America under towering blocks of ice.

The effects of recent climate change are already apparent; island nations are being inundated by rising sea levels, and Arctic sea ice is disappearing and glaciers are melting.[6] In response, considerable efforts are under way worldwide—from replacing fossil fuels with renewable energy to using energy more efficiently. Many initiatives focus simultaneously on mitigation (reducing greenhouse gas, or GHG, emissions) and adaptation (restoring wetlands, erecting seawalls, and otherwise creating



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resilience to climate change).[7] Newer, lesser-known initiatives involve the development of technologies to "engineer" the climate, but how these measures fit with those of mitigation or adaptation has not been fully analyzed.

SEARCHING FOR ADDITIONAL CLIMATE TOOLS

Scientists are beginning to experiment with discrete and diverse technologies, often grouped under the all-encompassing and poorly defined rubric of "climate engineering." The radically different approaches, in various stages of development, aim to either intentionally offset warming already under way or remove carbon dioxide and other GHGs from the atmosphere, oceans, and elsewhere.

This emerging field is not mutually exclusive of current mitigation and adaptation efforts. Experts generally agree that these new technological approaches alone cannot safely provide adequate protection.[8] Thus, it is important to compare technologies and assess where they intersect with mitigation and adaptation—requiring input from not only the wider scientific community but also social scientists, policymakers, lawyers, ethicists, nongovernmental organizations, and citizens. Broader expertise is needed to anticipate, prevent, or moderate unintended consequences for natural, social, political, and economic systems.

The first concrete step is to publicly track climate engineering so that relevant stakeholders are informed about current experiments and future deployment. Such transparency will foster public discourse, which is vital in working toward national and international governance mechanisms to oversee the safe, effective, and publicly acceptable development of climate engineering.

DEFINING CLIMATE ENGINEERING TECHNOLOGIES

Climate engineering is loosely defined as a broad set of methods that aim to deliberately alter the climate system in order to limit the impacts of climate change on a planetary scale.[9] While some actors refer to the overall field as geoengineering, the U.S. National Academy of Sciences prefers the term climate intervention, so as not to convey predictability and control.[10]

Disagreements persist over how to classify technologies under the climate engineering rubric.[11] The most straightforward option is to separate them into two initial categories: (1) removing carbon dioxide (or other GHGs) from the atmosphere or (2) managing the earth's heat. However, there are also other ways to sort them: they could be categorized as mitigation or adaptation or grouped normatively according to their anticipated outcomes, expressly including or omitting those technologies believed to be benign or to have larger environmental trade-offs.[12] Ultimately, whatever classification scheme is adopted, it must be flexible enough to capture all ongoing research, development, demonstration, and deployment efforts.

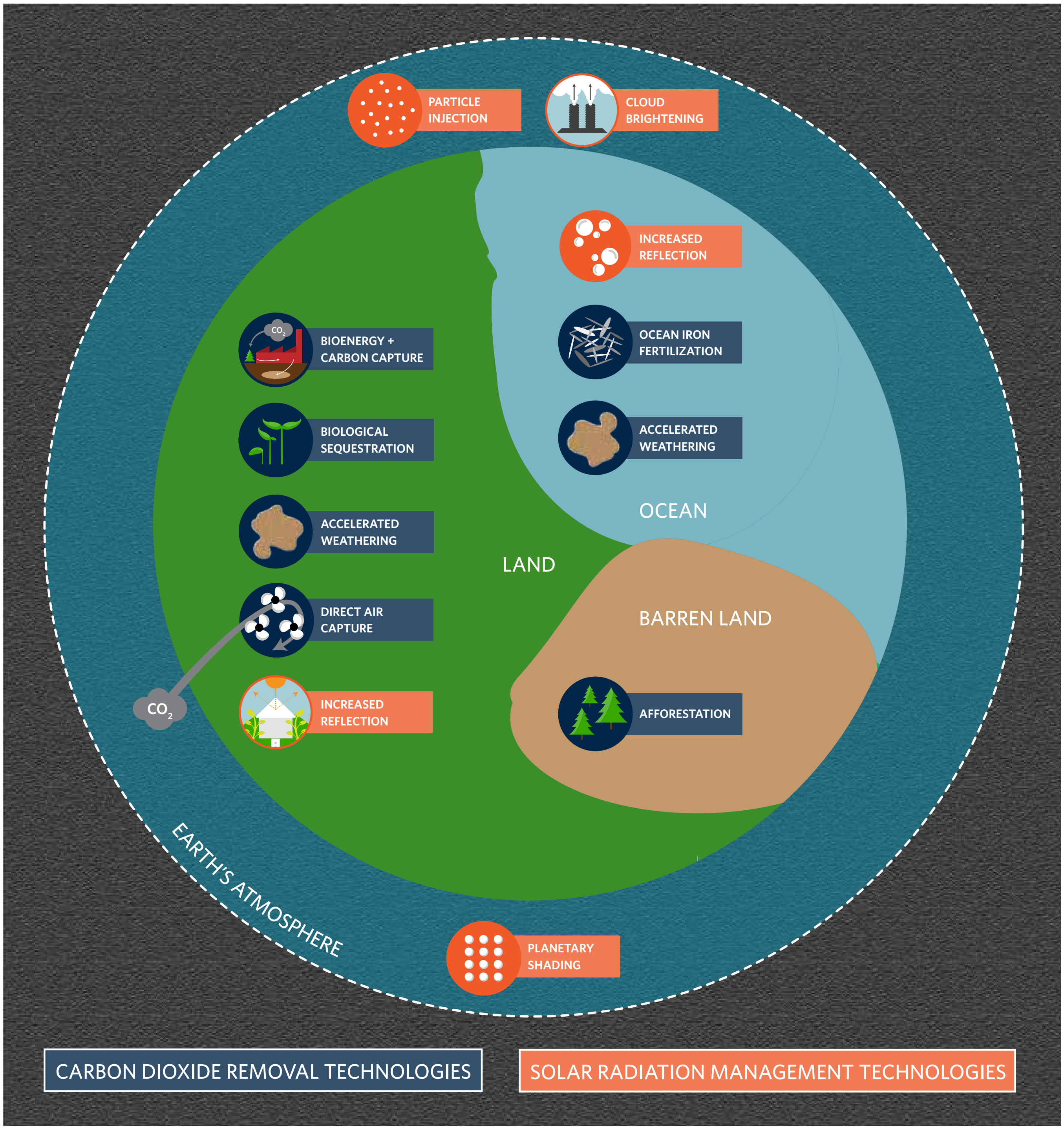
Comparing the costs, benefits, interactions, side-effects, limitations, and risks of climate engineering technologies is another challenge. They are subject to different baseline assumptions, are modeled by different institutions, are at different stages of development, and are evolving in different ways. More is known about some techniques than others, and uncertainty varies widely.[13] Looking ahead, progress will not necessarily be linear, which means that some information will remain relevant and some will not.

Efforts to fully classify and compare technologies should focus first on creating a common, basic understanding about the technologies currently under development. Only then can they be evaluated by a range of actors to assess the trade-offs and the cultural, social, economic, and political implications. In this article, for simplicity, the technologies are categorized under those that remove carbon dioxide and those that mitigate the warming effects of climate change.

REDUCING THE BUILDUP OF CLIMATE POLLUTANTS

Carbon dioxide removal (CDR) entails removing the buildup of carbon dioxide and sequestering it in the ocean, terrestrial biosphere, geological reservoirs, or commercial materials. A number of different technologies currently fall into this climate engineering category, as identified in the figure.

CLIMATE ENGINEERING TECHNOLOGIES UNDER DEVELOPMENT



CDR is not a quick climate fix. There is a significant delay between the initiation of a CDR program and any meaningful reductions in atmospheric GHG concentrations. An even longer delay may exist before there is an observed reduction in global temperature given the ocean's capacity to stabilize heat flows.

While CDR entails removing carbon dioxide from the atmosphere on a larger planetary scale, it shares similarities with smaller-scale mitigation efforts, such as carbon capture and storage (CCS) that removes and sequesters CO_2 from fossil fuel combusted in industrial processes.[14] This makes CDR seem more acceptable, even though its impacts and their distribution are not well understood. Some analysts posit that the impacts could be local, regional, or even global, while others assume CDR is relatively benign.[15]

Overall, an assessment of CDR feasibility must account for the potential nonclimatic impacts that large-scale CO_2 removal could have on water cycles, storm surges, ecosystems, and biodiversity.[16] Numerous biological and climate factors that reinforce one another need to be considered—including the impacts on soils, surface albedo, and other interdependencies—to determine the net effect of CDR approaches. Subject to the CDR technology employed, negative effects could arise depending on sequestration effectiveness, the amount of fertilizers required, associated risks to ocean life, and space limitations.[17] Impacts on water, such as increased alkalinity and pH, require further research. CDR safety controls are needed to prevent the spread of invasive species, protect water resources, and monitor other unintended consequences given the complexity of biological systems.

Bioenergy with Carbon Capture and Storage

The CDR technology currently gaining the most traction is known as bioenergy with carbon capture and storage (BECCS).[18] Its goal to deliver negative emissions, if achieved, could make a measurable difference in addressing climate change.[19] Dating back to the 1990s, BECCS is now officially included in the Intergovernmental Panel on Climate Change (IPCC) models and being considered by the United Nations as a strategy to limit the projected global temperature rise to 1.5 degrees Celsius.[20] BECCS utilizes the carbon naturally stored by plants (or biomass) during photosynthesis. By burning biomass to generate energy *before* it decomposes and releases its bounty of carbon and then capturing the carbon released during biomass combustion and storing it underground, BECCS removes carbon dioxide from the atmosphere. If BECCS was to remove relatively small amounts of carbon dioxide, it could be considered a CCS mitigation measure.[21] However, large-scale applications of BECCS that zero out or result in negative emissions globally—and ultimately alter the earth's overall balance of carbon stored in plants—would be classified as climate engineering.

Afforestation

Afforestation, or planting trees on land that was not previously forested, is another CDR technique that can blur the line between mitigation and climate engineering.[22] This method becomes engineering when implemented on a large enough scale to reconcile with global GHG concentrations. This, in turn, raises questions about setting goals for acreage, determining species to plant, and safely siting afforestation projects. If the land and forest were to become an integral part of the global system being engineered, then this CDR technique would be considered climate engineering.

Biological Carbon Sequestration

Biological carbon sequestration can take various forms and qualify as CDR.[23] Technologies are under development that seek to engineer the biological building blocks of plants and other systems in order to alter the climate. Enzymes can be used to convert carbon dioxide into biomass and chemical byproducts. Plants can be used to sequester carbon. For example, experiments are under way to create plants with an increased appetite for carbon dioxide.[24] Researchers are aiming to alter the biochemistry of photosynthesis—the process by which plants use sunlight to produce their nutrition from carbon dioxide and water.

Direct Air Capture

Another CDR technology is direct air capture (DAC), which deploys various industrial processes to capture industrial-scale quantities of carbon dioxide from the air in the atmosphere.[25] DAC differs from CCS, a mitigation technique that collects carbon dioxide only from industrial flue stacks where it is much more concentrated. Several approaches are being tested, including designing mechanical trees that absorb carbon dioxide, altering chlorophyll in plants to pull carbon dioxide out of the air, and running air through a caustic chemical process to remove carbon dioxide like submarines and spaceships do.[26] Different solutions and catalysts are used at different temperatures and humidity levels to separate out the carbon dioxide from the air. DAC must sequester carbon by storing it underground or reuse it.[27]

Accelerated Chemical Weathering

As the earth's minerals slowly dissolve, they react and remove carbon dioxide from the atmosphere. It takes centuries or longer for this to occur naturally. When this technology is used to intentionally accelerate chemical weathering and enhance this natural process, it qualifies as CDR. Finely ground silicate minerals can be applied over the land surface to absorb atmospheric carbon dioxide.[28] Offshore, carbonate minerals can be dissolved into the ocean.

Ocean Iron Fertilization

The oldest CDR technology deployed to date sequesters carbon in oceans. Small-scale field tests have been undertaken since 1993. Ocean iron fertilization (OIF) uses iron to promote algae blooms that absorb carbon dioxide from the air.[29] When the algae die, their stored carbon sinks and traps carbon dioxide. Yet another fertilization technique, ocean alkalinity addition, uses other nutrients such as nitrogen and phosphate and requires a larger mass than iron. Most members of the U.S. National Research Council believe that OIF is ineffective, but these findings have not stopped experimentation with this technique.[30]

TURNING DOWN THE EARTH'S HEAT

Solar radiation management (SRM), also referred to as solar climate engineering and albedo modification, seeks to offset GHG-induced warming by either increasing the amount of sunlight reflected back to space or preventing radiation from reaching the earth's surface in the first place.[31] A number of different technologies fall within this category, as depicted in the figure on page 3.

Compared to CDR, SRM is thought to be a quick fix because it masks warming rather than actually removing the buildup of GHG emissions. If SRM is not accompanied by effective mitigation efforts to simultaneously cut emissions, when it is curtailed, it can cause precipitous warming. The perpetual need for SRM is called "lock in," which means once SRM is deployed, it may be difficult to safely stop.

SRM feasibility differs by technology.[32] Energy inputs can be large and variable. It can be difficult to accurately track injected particles and anticipate dynamic atmospheric conditions. It may also be impossible to predict changes from place to place and season to season, avoid ozone depletion, and prevent disruptions to local weather patterns. There are numerous unanswered technical and environmental questions that require further investigation and vetting. Limiting the consequences will depend on developing a better understanding of related natural processes, chemical interactions, and physical alterations.

Second-order impacts revolve around the scale and distribution of effects. Even if SRM succeeds on a planetary scale, it may invoke local and regional conflicts due to real or perceived relative harms caused or relative benefits bestowed.[33] For example, if regional water (or rainfall) quantity shifts or water quality varies within a region, cross-border tensions could rise.

Particle Injection

The idea of cooling the planet by injecting particles into the stratosphere was motivated by the 1991 volcanic eruption of Mount Pinatubo, where the sulfur emitted formed into reflective aerosols and reduced global temperatures.[34] Sulfates and other aerosols present in the second layer of the earth's atmosphere scatter sunlight back into space, reducing the amount of heat that can enter. There is a wide range of climate engineering methods for deploying sulfates, including, but not limited to, aircraft schemes, aviation fuel additives, rockets, artillery, balloons, and tethered hoses. New experiments are being planned to inject particles into the earth's upper atmosphere.[35] In addition to sulfates, different chemical compounds, such as calcium carbonate and silver nitrate, are being investigated. Aerosol injection is relatively inexpensive, making it easier to deploy than many other climate engineering methods.

Cloud Brightening

Aerosol injection could also be accomplished without sulfur (for example, by seeding marine clouds with seawater droplets to increase the reflection of sunlight). Such marine cloud brightening or whitening might be achieved by introducing fine particles near the base of low clouds.[36] British physicist John Latham first proposed this technique in 1990 in the journal *Nature*, and today, research continues.[37] Hypothesized techniques employ ocean vessels, aircraft, or drones to spray low-lying clouds with a fine mist.

Increased Reflection

The more sunlight the earth reflects back to space, the cooler it will be. Increasing reflectivity can be accomplished through many different scientific and engineering means (for example, by altering biology or using new construction materials). Specific surface albedo-based methods include painting rooftops, roads, and other surfaces white; employing crop varieties that increase albedo; covering deserts and glaciers with reflective plastic sheeting; putting floating panels over lakes; and creating microbubbles under the ocean.[38]

Planetary Shading

Another technique aims to reduce the amount of sunlight that enters the earth's atmosphere in the first place. Space reflectors employ a range of technologies—large mirrors, rotating lenses, small aircraft fleets, a large ring of space dust, or encasing of the planet in reflective materials—to reflect a portion of sunlight back to space, effectively shading the planet.[39]

OTHER TECHNOLOGIES ON THE HORIZON

Climate engineering research is ongoing and could take scientists in various directions. Several new approaches are already emerging, including the engineering of thicker ice by refreezing seawater during the winter.[40] Also, the rapid buildup of methane (a powerful short-lived climate pollutant) is invoking other climate engineering techniques, such as mixing methane with chemicals to dissolve it or trapping methane in manmade nanotechnology structures to generate electricity.[41] Research is also being done to remove methane from water, which may be important if rising sea temperatures melt permafrost methane or dislodge methane hydrate deposits. Discussion around technologies to deal with extremely potent chlorofluorocarbons (CFCs) has been renewed. In the 1980s, work was done to simulate the use of concentrated infrared beams in the atmosphere to destroy CFCs.[42]

The field of climate engineering is in its relative infancy. New climate engineering techniques are likely to materialize the more we learn. If climate disruption accelerates, so could the demand for climate engineering solutions.

An important caveat underpins the potential effects of CDR, SRM, and other future technologies: restoring climate conditions (for example, temperature, precipitation, ocean conditions, feedbacks) to their pre-industrial state—or any unperturbed climate state—at all locations worldwide will not be possible. Moreover, intervening while the climate continues to change as a result of previously emitted GHGs could introduce new feedbacks—processes that can either amplify or diminish the effects of climate change—into the system.[43]

INCREASING KNOWLEDGE

Increased knowledge enables deeper thinking on complex topics and can lead to changes in attitudes as new technological approaches emerge and further research is conducted. While an improved understanding should not be confused with acceptance, it can reduce backlash and promote a more constructive debate. Information is interpreted according to individuals' prior experiences and point of view. Recent climate engineering surveys in Germany, for example, find that values, sociodemographic variables, gender, age, and attitude toward risk influence how information is viewed and used in decisionmaking.[44] Acceptance of climate engineering efforts may be largely influenced by the perceived risks of climate change, societal risk preferences, current policy environments, capacity for coordinated international action, and trust in institutions.

In recognition, simultaneous efforts should be made to (1) create transparency on climate engineering through extensive public disclosure; (2) encourage the voluntary disclosure of climate engineering activities (or, in its absence, mandating disclosure); and (3) invite a broader conversation through global dialogues to better integrate Western and non-Western perspectives on climate engineering and its governance. Probing and incorporating lessons learned from other areas (for example, nuclear power, waste, and proliferation) could also facilitate greater understanding of climate engineering.

Documentation

Climate engineering initiatives need to be thoroughly documented by clearly defining individual technologies, illuminating the field overall, tracking the status of current efforts, discussing next generation applications, and voluntarily disclosing future technologies under development. This entails publishing information globally on research, field experiments, and large-scale deployments, while keeping track of meetings, simulations, and laboratory experiments. A public clearinghouse that includes an online database of technical, procedural, and financial information is needed to reliably track the full slate of climate engineering activities worldwide.

Global Dialogue

Dialogue with various groups of stakeholders can help frame issues, identify risks, set agendas, and track progress. For example, researchers at American University's Forum for Climate Engineering Assessment have been exploring using public deliberative mechanisms to directly engage citizens in the climate engineering conversation. Methods include citizen juries that allow academics to respond to popular concerns, interactive working groups that wrestle with big questions, hands-on experiential approaches conducted in partnership with science museums, and multisite consultations that simultaneously engage thousands of people around the world.[45] Such open, broad engagement and stocktaking on climate engineering and its social license generates valuable input from different countries, peoples, communities, and disciplines.

Integration of Lessons Learned

Climate engineering efforts likely face challenges similar to those experienced by other endeavors, and these are worth exploring. Nuclear energy programs, for example, have had to contend with accidents, liability, proliferation, and weaponization. Theories about a nuclear winter brought on by smoke from fires following a nuclear war may evoke thoughts about climate engineering.[46] Nuclear accidents at Chernobyl and Fukushima may offer lessons on national and transnational concerns about climate engineering.[47] Sweeping technological issues can arouse biases for and against. As such, those actors that note greater real or perceived risks to the environment may view climate engineering with less skepticism than others. For example, at a climate conference at the Massachusetts Institute for Technology in 2012, the Dalai Lama urged an engineering professor who views climate engineering as a moral hazard (because it diminishes the urgency of people and society to address the underlying fundamental climate problem) to seriously consider technological solutions because climate change is a long-term problem that merits action.[48] Probing different perceptions could reveal central questions that remain unanswered and provide guidance on how to prudently proceed.

TAKING THE LONG WAY AROUND

In 1965, president Lyndon Johnson's Science Advisory Committee raised concerns about anthropogenic climate change and warned that "man is unwittingly conducting a vast geophysical experiment." The committee suggested thoroughly exploring climate engineering to deliberately bring about "countervailing climactic changes."[49] More than fifty years later, the field of climate engineering remains largely unknown, especially to policymakers and the public. A coherent, global climate engineering plan still does not exist. As technologies advance, they will need to respect physical borders, protect the global commons, and abide by cultural norms.

There are real risks to opting into—or out of—climate engineering. Either way, there is broad agreement that climate engineering research must be governed, but to date there are few, if any, established actors, incentives, or requirements to do so. According to researchers at Columbia University's Sabin Center for Climate Change Law, several key questions remain: What qualifies as climate engineering research subject to governance? At what point do governance requirements kick in? What substantive rules should apply? Who should do the governing?[50]

To this end, new efforts are now under way. The Carnegie Council for Ethics in International Affairs has launched an initiative to create effective governance of climate geoengineering technologies.[51] This entails shifting the conversation from the scientific and research community to the global policymaking arena and encouraging broad discussion about the risks, potential benefits, and ethical and governance challenges raised by climate engineering.

While it is tempting to simply be categorically for or against climate engineering, at this juncture, it is more critical—and more responsible—to gather scientific facts and ask as many questions as possible about what the deployment of these technologies might mean for individuals, societies, nations, and regions. While a comprehensive approach will increase effort and time at the front end of decisionmaking, ultimately, it could help to save time, safeguard well-being, protect resources, and reduce conflicts by thoughtfully guiding outcomes.

ACKNOWLEDGMENTS

The author thanks her Carnegie colleagues, including Jessica Mathews, David Livingston, Thomas Carothers, Madeleine Scher, Smriti Kumble, Samuel Wojcicki, and the Communications staff, for their valuable assistance in bringing this publication to fruition. Gratitude also goes to staff at the Forum for Climate Engineering Assessment (FCEA) at American University, including Simon Nicholson, Michael Thompson, David Morrow, and Carolyn Turkaly, and to FCEA Advisory Board member Neil Craik, from the University of Waterloo, for their guidance on, and commitment to furthering, climate engineering transparency. Additionally, the author recognizes Michael Gerrard and Michael Burger from the Sabin Center for Climate Law at Columbia University for their keen insights on this document and Janos Pasztor and Kai-Uwe Barani Schmidt for their input as they launched a new geoengineering governance initiative at the Carnegie Council for Ethics in International Affairs. Finally, thanks also go to Abigail Lambert, a high school student at Moses Brown, and Alexandra Barba, a graduate student in Public Affairs at the Watson Institute at Brown University, for their research assistance and discerning reads of this document.

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