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Pursuing Geoengineering for Atmospheric Restoration

Geoengineering is fraught with problems, but research on three approaches could lead to the greatest climate benefits with the smallest chance of unintentional environmental harm.

A few decades ago, the notion of actively controlling Earth's climate resided primarily in the writings of science fiction authors such as Frank Herbert, Isaac Asimov, and Arthur C. Clarke. Today, planetary engineering is being discussed openly by scientists and policymakers in Congress, the UK House of Commons, and many other settings. Clarke's advice apparently struck a chord: "Politicians should read science fiction, not westerns and detective stories."

Geoengineering can be thought of as intentionally manipulating Earth's climate to offset the warming from greenhouse gas emissions. Its activities can be divided into two loose groups. One set of options cools Earth by removing carbon dioxide (CO_2) and other greenhouse gases from air, essentially reversing the process of fossil fuel emissions. The other cools the planet by blocking or reflecting sunlight, offsetting the consequences of increased greenhouse gases for temperature but leaving the buildup of greenhouse gas concentrations unchecked.

Several developments have fueled the rise of geoengineering from fiction to possible reality in a remarkably short period of time. The first is our inability to reduce greenhouse gas emissions in any substantive way. A wealth of scientific evidence shows that Earth's climate is already changing because of such gases, posing a threat to people and other animals and to plants. A second factor is the concern that some planetary engineering may already be needed to reduce the harmful effects of climate change, even if emissions fall in the future. A third is the hope that geoengineering could be cheaper than cutting emissions, even if it treats only a symptom of climate change, not the root cause.

The promise and peril of geoengineering raise a host of unanswered questions. Will such approaches actually work? If they do work, who will control Earth's thermostat? What other environmental consequences might arise? Where would effects be the greatest, keeping in mind that the en-

vironmental consequences should be compared not just against our world today but against a future world with rapid climate change?

There are many risks and uncertainties in the geoengineering approaches being considered. In addition, there will be appropriate public resistance to at least some of them. But given that our climate is already changing and that pressure to use geoengineering may increase, what would be the most practical and sensible ways of proceeding? Our approach involves extending the concept of ecological restoration to the atmosphere, with the goal of returning the atmosphere to a less degraded or damaged state and ultimately to its preindustrial condition. Based on this idea, which we call atmospheric restoration, we recommend three types of geoengineering for fast-track research support. We believe that these approaches could provide the greatest climate benefits with the smallest chance of unintentional harm to the environment.

The basic approaches

The first category of geoengineering removes or "scrubs" CO_2 from the atmosphere. Carbon removal can be biological, including planting trees or fertilizing the oceans to stimulate phytoplankton growth. It can also be industrial. Industrial options include using chemicals to capture CO_2 from the air, with renewable energy regenerating the chemicals, or mining silicates or other geologic materials that react naturally with CO_2, reburying the deposits after they have absorbed carbon. Whether biological or industrial, the goal of the activities is to reduce greenhouse gas concentrations in the air.

The second type of geoengineering reflects or blocks sunlight to cool Earth without reducing CO_2 concentrations. Some commonly proposed "sunshades" include placing dust into the stratosphere with rockets and airplanes, placing space mirrors between Earth and the Sun, or increasing the extent and brightness of ocean clouds. Sunshade approaches are conceivable because reducing sunlight by a couple of percentage points is all that is needed to offset the warming from a doubling of atmospheric CO_2. There is a natural analog for this approach: volcanic eruptions, such as Mt. Pinatubo in 1991, which blasted sulfur dust into the stratosphere and cooled Earth by 1° Fahrenheit for more than a year. A concise description of both types of approaches can be found in the Royal Society report *Geoengineering the Climate*, published in 2009.

Sunshade and carbon removal approaches differ in how fast they can be applied and what they will cost. Sunshade technologies could be applied quickly and fairly cheaply to

Jennifer Trask builds often on the physical and metaphorical meaning of bone. Her large wall installation *Intrinsecus* is made from a found 19th century Italian wood and gold leaf frame, bones, teeth, antlers, silver, and gold leaf. While harking back to the Dutch tradition of Vanitas, it also addresses the traditional practice of isolating examples/ideals of beauty stylization of nature, "in effect a death of the real, the imperfect, the individual."

Above and opposite (detail):
Jennifer Trask, *Intresecus*, 19th century Italian gilt frame, bone, antler, silver, and gold leaf, Dimensions variable, 2010.

reduce Earth's temperature, at a price of perhaps several billion dollars per year and within months of a policy mandate for stratospheric dust seeding. This combination of speed and cost is the main reason why sunshade approaches are being discussed. No other technology allows us to alter the effects of global warming so quickly if Earth's climate begins to spin out of control.

In contrast, carbon removal technologies would take decades to scale up, at significantly higher cost. For instance, at a price or tax of $100 per metric ton of CO_2—roughly five times the European CO_2 price in May 2010 but cheaper than industry can scrub CO_2 from air today—removing a billion tons of CO_2 using industrial approaches would cost $100 billion. Removing the entire fossil fuel emissions from the United States would take about $600 billion annually, and $3 trillion would pay for removing the 30 billion tons of CO_2 emitted globally each year. These numbers dwarf the cost of sunshade approaches, even if cheaper biological options such as tree planting can help bring the price down.

Is geoengineering dangerous?

Tinkering with our life-support system may at first glance seem like a crazy idea. (To many, it still seems crazy at second and third glances.) What makes it less so is that we are already changing Earth in ways that will last for thousands of years. Why might intentional climate change be worse than unintentional change? Put differently, is geoengineering more dangerous than climate change?

The same things that make some geoengineering solutions quicker and cheaper also make them potentially more dangerous if something goes wrong. Separating the risks and effects of different technologies is crucial for informed debate about geoengineering.

Because of their global nature, sunshade technologies could cause global harm at the same time as they help to cool Earth. For instance, evaporation is roughly twice as sensitive to sunlight as temperature is, so mirrors or stratospheric dust that block the sun are almost certain to reduce rainfall globally. In fact, the same Pinatubo eruption that cooled Earth by 1° also caused a global drought and substantially reduced river flows, as described by Kevin Trenberth and Aiguo Dai of the National Center for Atmospheric Research (NCAR) in a 2007 study.

Less certainly, stratospheric dust seeding could cause ozone depletion elsewhere or prolong the ozone hole over Antarctica, if the wrong chemicals are used or if surprises occur with the "right" chemicals. Simone Tilmes of NCAR and colleagues in 2008 concluded that an injection of sulfate aerosols large enough to compensate for the warming from a CO_2 doubling could both delay the recovery of the Antarctic ozone hole by 30 to 70 years and increase Arctic ozone depletion throughout this century because of interactions with stratospheric chlorine.

The history of ozone depletion and chlorofluorocarbons (CFCs) should give us pause here. Paul Crutzen, Nobel laureate for his work on atmospheric chemistry and ozone, once noted that the plausible use of bromofluorocarbons instead of CFCs would have led to catastrophic global ozone depletion, a circumstance we avoided by luck. Loading the stratosphere with chemicals for centuries is risky and could prove downright dangerous. The spring 2010 oil spill in the Gulf of Mexico reminds us that, given enough time, some very unlikely events will eventually happen.

Sunshades also have some fundamental weaknesses compared to carbon removal approaches. Except for temperature, they reduce neither greenhouse gases nor other environmental effects caused by the gases. For instance, acidification from a buildup of CO_2 threatens the marine food chain and ocean biodiversity, including the ability of phytoplankton, coral reef species, and other marine organisms to grow and maintain their skeletons. Sunshade approaches might cool Earth but would do nothing to fix this insidious problem.

In contrast, the risks and environmental effects of most carbon-scrubbing technologies are likely to be smaller than for sunshade techniques. Industrial carbon removal is not fundamentally different in risk or scope from current industrial operations we live with today. The primary barrier remains cost.

Two large-scale processes for carbon removal that do raise environmental concerns are enhanced weathering of minerals and ocean fertilization. Mining, using, and reburying billions of tons of silicate minerals to remove CO_2 from the atmosphere would be both expensive and immense in scale, probably larger than current coal-mining efforts. The reason is that it takes at least a ton or two of such minerals to absorb one ton of CO_2. Ocean fertilization remains a potentially useful but scientifically unproven approach for carbon removal. It isn't clear that ocean fertilization works to store carbon, and in places it might release other greenhouse gases such as methane and nitrous oxide and would probably produce hypoxia, low-oxygen zones similar to those produced in polluted water. The notion of fertilizing large regions of the oceans to create phytoplankton blooms has also been strongly opposed by the public. Private companies have had to cancel research plans because of such opposition.

Is geoengineering socially acceptable?

Despite the technical challenges and uncertainties of geoengineering, sociopolitical barriers rather than scientific or economic ones will ultimately determine geoengineering's fate. In fact, barriers to public acceptance will probably keep all global sunshade approaches and some carbon removal ones from ever being applied. These barriers include concerns over risk, ethics, governance, laws, geopolitics, and the perception of geoengineering as a tool for global control.

The divisiveness that accompanies nuclear energy, biotechnology, and other hot-button issues bears on the potential fate of geoengineering. The science behind nuclear fission and genetic engineering surely matters in these debates, but few people would argue that scientific uncertainty is the only cause of the controversies surrounding them. Without public support, or at least limited opposition, approval for implementing many kinds of geoengineering will be hard to obtain.

Public support turns on a series of shifting perceptions. These include the magnitude of the danger or opportunity faced, the risks posed by the ameliorative technology, public confidence in the people behind the technology, the cost of the technological fix, and issues of social equity. To our knowledge, there has been no thorough public assessment of these issues for geoengineering, particularly for individual geoengineering activities. Such an assessment is sorely needed.

Two concerns about geoengineering arise consistently among the many that are voiced. One is the fear that researching or even discussing geoengineering will make it more likely to happen, undercutting efforts to reduce greenhouse gas emissions. Another concern is that geoengineering at a scale large enough to influence climate could have large-scale unintended consequences. This fear of surprises has proven a contentious issue for genetically modified organisms locally. Globally, such concerns will probably be far greater. They surely must be considered and discussed before implementing geoengineering.

Beyond public acceptance, political leadership will be needed to implement geoengineering. The political calculus will be influenced by the same interest groups that influence every political process. For instance, the private sector will emerge as a major player by investing in particular technologies and promoting their use. Numerous companies are investing in industrial carbon-scrubbing technologies, and others have actively promoted ocean fertilization experiments. Diverse advocacy efforts from environmental and scientific organizations are also likely.

What should politicians do? They first need to think carefully about governance. Large-scale geoengineering could change almost every aspect of our planet, from Earth's albedo to its temperature to its rainfall. It's not hard to see how these changes may, in turn, influence water availability, patterns of human settlement, agricultural productivity, and other critical factors. In light of these interactions, creating mechanisms to manage rules for notice, environmental impact assessments, compensation for transboundary impacts, and other aspects of implementation are all needed. Importantly, however, not all geoengineering technologies will require huge capital investments. Ocean fertilization or sulfate aerosol seeding may be feasible not only for single governments but even for single companies or wealthy individuals. If so, this raises the very real possibility of unilateral implementation.

Some forms of geoengineering, in other words, may be closer to a backyard project than to creating an international space station. The combination of unilateral implementation and disparate effects among nations suggests that consensus will be hard to reach. As David Victor of Stanford University and colleagues noted in a 2009 article, "One nation's emergency can be another's opportunity, and it is unlikely that all countries will have similar assessments of how to balance the ills of unchecked climate change with the risk that geoengineering could do more harm than good." The 2009 study by Britain's Royal Society made a similar point, noting that "Geoengineers keen to alter their own country's climate might not assess or even care about the dangers their actions could create for climates, ecosystems, and economies elsewhere. A unilateral geoengineering project could impose costs on other countries, such as changes in precipitation patterns and river flows or adverse impacts on agriculture, marine fishing, and tourism."

A key question, therefore, is the extent to which governance mechanisms can be created beforehand to address these potential conflicts. Should the precautionary principle be employed? If so, how would it operate? As one example, a moratorium on the practice of coastal iron fertilization has been called for within the context of the Convention on Biological Diversity, but a moratorium could simply drive R&D to nations that do not comply with the treaty or that make a reservation to this restriction.

Indeed, there are no regulatory mechanisms in place, domestically or internationally, that explicitly address geoengineering. As a result, legal and governance frameworks will probably borrow initially from existing structures. Existing treaty language calls for states engaging in transboundary activities to, among other things, conduct environmental impact assessments, avoid doing harm across boundaries, cooperate in mitigating risks and harms created by their activities, and apply the precautionary principle. These guidelines were not adopted with geoengineering activities in mind, however, and their potential influence remains weak.

Tracy Heneberger uses natural materials such as mushrooms, fish, and stones in his sculptures and favors the circular "tondo" form that is hung on a wall. His recurrent theme is water and its association with continual change.

Calls for large-scale geoengineering to combat climate change have increased significantly in the past year or two and are likely to grow louder. So what is needed right now? For starters, the government and leading authorities in the private sector and academia need to initiate broad-based discussions with stakeholders about the nature of geoengineering. What is it, what can it do to address the threats of climate change, and what potential concerns does it raise? Increasing R&D on its own will do nothing to ensure the successful implementation of geoengineering and may, in fact, prove counterproductive if it is not matched by comparable investment in strengthening the social and political understanding of geoengineering.

Principles for guiding action

How should we think about the geoengineering option? One promising model resides in the principle of restoration. In a well-cited primer from 2004, the Society for Ecological Restoration defined ecological restoration as "the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed."

We propose to extend the concept of restoration to the atmosphere, suggesting the term "atmospheric restoration" as a guiding principle for prioritizing geoengineering efforts. The goal is to return the atmosphere to a less degraded or damaged state and ultimately to its preindustrial condition.

Given an umbrella of atmospheric restoration, we prioritize geoengineering efforts based on three principles. The first is to treat the cause of the disease itself, through CO_2 removal, instead of a symptom of the disease, through the use of sunshades. Because carbon-scrubbing technologies will take far longer to deploy than sunshades, policy incentives for research on them are needed now. Without such incentives, we will face unnaturally high greenhouse gas concentrations in our air (as compared to the past 100 million years of Earth history) or a world where sunshade approaches must be maintained for centuries once we start using them. For instance, large-scale stratospheric dust seeding, if stopped abruptly, would cause Earth's temperature to shoot up rapidly. (Consider the analogy of a dim cloud passing, exposing the Earth to full sunlight.) This rapid increase would likely be far more damaging environmentally than a gradual increase to the same temperature would have been. Is global governance likely to keep sunshades in place for 500 or 1,000 years?

A second guiding principle is to reduce the chance of harm. The greater the scale of a manipulation, the more probable it is that the manipulation will cause unforeseen changes or even dangerous surprises. Sunshades, in particular, will have to be regional to global in nature to be globally effective, suggesting that unintended harms may be regional or global as well. We believe that the policy priority should remain on reducing greenhouse gas emissions, coupled with restoring the atmosphere through carbon removal, which would obviate the need for riskier sunshade approaches.

A third and final principle is to prioritize activities with the greatest chance of public acceptance. We remain skeptical that the public will ever broadly accept sunshades, particularly stratospheric dust seeding, and some carbon removal strategies such as ocean fertilization. Recognizing this barrier provides another filter for prioritizing research. The likelihood of public acceptance suggests a few good geoengineering choices from among the broader set of less direct and potentially dangerous geoengineering activities.

Based on these principles and the Hippocratic spirit of first do no harm in medicine, we propose three forms of geoengineering that could provide the greatest climate benefits with the smallest chance of unintentional harm to the environment. All three are forms of atmospheric restoration, will probably have fewer unintended consequences than other forms of geoengineering, and are more likely to be accepted by the public than many other forms of geoengineering.

The first geoengineering activity, forest protection and restoration, is an opportunity available now. The other two, industrial carbon removal and bioenergy linked to carbon capture and storage, need extensive research to make them effective and to reduce their costs. Unlike forest protection, these will take decades to scale up to a level that lowers at-

TRACY HENEBERGER, *Moon*,
Anchovies, epoxy, shellac, resin,
24 x 24 x 1.5 inches, 2006.
Courtesy of the artist. Photo: Tony Holmes.

mospheric CO_2 concentrations substantially, because they require a distributed network of facilities.

The most immediate opportunity is forest preservation and restoration. Plants and other photosynthetic organisms provide one of the oldest and most efficient ways to remove CO_2 from air. Efforts to regrow forests or keep forests from being cut both provide greenhouse gas benefits. If a policy incentive keeps a rainforest in Amazonia or Alaska from being harvested, carbon that would have moved to the atmosphere is "removed" from the atmosphere.

An important policy incentive in this area is Reduced Emissions from Deforestation and Forest Degradation (REDD), featured prominently at the 2009 Copenhagen climate change negotiations. Tropical deforestation contributes roughly 5 billion tons of CO_2 to the atmosphere each year, approximately one-sixth of fossil fuel emissions. Providing financial incentives to stem this tide of carbon loss and restore degraded forests is an immediate opportunity, although accounting and monitoring protocols still need work. Activities such as REDD help the environment by storing carbon, slowing erosion, improving water quality and flow, and preserving biodiversity. Their benefits reach far beyond climate.

Let's contrast the benefits of REDD with an equally bad idea for land-based geoengineering. In a 2009 article in *Climatic Change*, Leonard Ornstein of the Mount Sinai School of Medicine and co-workers proposed turning the Sahara and Australian deserts into lush forests by irrigating them with desalinated seawater. (Frank Herbert's characters in the Dune series might approve.) They estimated that we could offset all of today's CO_2 emissions from fossil fuels, roughly 30 billion metric tons a year, by greening the Sahara, an area comparable in size to the continental United States. Although it is an interesting thought exercise, such a proposal would cost trillions of dollars (the authors' estimate), would require massive amounts of energy to make, transport, and distribute fresh water and perhaps fertilizers for each tree, and would create an unsustainable forest

Above and opposite (detail):
JIM RITTIMAN, *Tree of Life*, Mixed bones, botanical parts, insect parts, glass eyes, steel, Plexiglas, and paint, 2010.

Jim Rittiman relies on animal bones, plant seeds, and other organic matter to create skeletal sculptures of insects. For this exhibition he created *Tree of Life*, depicting an upside-down evolutionary tree, its branches terminating with mutant hybrid creatures made from bones, wings, and carapaces of disparate and incompatible species.

vulnerable to dieoff from pests, storms, irrigation loss, and many other "surprises." The picture of the Sahara as a wasteland to be improved is also in our view ecologically, culturally, and anthropocentrically myopic and doomed to fail.

A second geoengineering opportunity that should be encouraged with research incentives is industrial carbon removal, specifically facilities that use renewable chemicals rather than continuously mined ones such as silicates. Imagine a series of power plants run in reverse. The facilities use renewable energy to drive a chemical reaction that removes CO_2 from the atmosphere and regenerates the chemical used in the reaction. It's as simple as that.

What isn't simple about the process is its cost. Current amine-based technologies or next-generation chilled-ammonia chemistry for capturing CO_2 from power plant smokestacks are too expensive to be used widely today. Moreover, CO_2 in air is far more dilute than in the exhaust of a coal- or gas-fired power plant, making the job even more difficult and costly. We need immediate research incentives to reduce the costs of industrial CO_2 capture.

Another aspect of cost with industrial carbon removal is where the carbon-free source of power comes from. For starters, are you really removing CO_2 from the atmosphere with this approach if you could instead plug the carbon-free energy consumed in it into the grid to offset emissions from a coal- or gas-fired plant somewhere else? One advantage here is that a carbon-removal facility could be set up anywhere on Earth where energy is plentiful. You don't have to be near a power grid in choosing locations. Renewable energy for the process could also be used at times and in places where it isn't needed for normal uses, such as off-peak hours.

Finally, for industrial carbon removal, you have to do something with the billions of tons of CO_2 removed from air. On the one hand, you could generate carbon-based fuels as one possibility. This use of the carbon does not really remove CO_2 from air unless the CO_2 is subsequently captured, perhaps analogous instead to generating corn ethanol and other biologically based renewable fuels. To be truly carbon-negative, however, you have to store the carbon permanently away from the atmosphere, most likely thousands of feet underground or under the oceans. This, too, is expensive and needs research to guarantee its safety and effectiveness.

Overall, the combination of generating the power needed, capturing the CO_2 chemically, and storing it underground is likely to cost at least \$100 to \$200 per metric ton of CO_2 removed with next-generation technologies. We need research to cut these costs, ideally by at least two-thirds. Ultimately, we will have to use at least some technologies that can remove hundreds of billions of tons of CO_2 if we are ever to restore the atmosphere to its preindustrial state. That is the scale of the problem we face.

The third technology that we believe needs immediate but perhaps more cautious research support combines bioenergy with carbon capture and storage. This technology fuses aspects of the previous two, including its focus on trees and other plants as a cheap way to capture CO_2 biologically instead of chemically, and its reliance on carbon capture and storage to move CO_2 from the atmosphere back underground. Unlike the previous option, it has the benefit of supplying its own energy generated from the biomass instead of requiring large energy inputs.

Bioenergy with carbon capture and storage also has some important differences, however. Although bioenergy provides energy from biomass rather than consuming it, harvesting the needed biomass will affect millions of acres of land if applied broadly. In that sense, bioenergy may in some places be at odds with the forest restoration and avoided deforestation efforts highlighted earlier. We acknowledge this contradiction, invoking a 19th-century adage for household management: "A place for everything, and everything in its place." There are places on Earth where habitat preservation and restoration are particularly important right now, including the tropics, whereas other places have lands that could be managed productively for fast-rotation biomass.

The places for bioenergy generation will take careful consideration to maximize benefits and minimize environmental harm. Municipal garden wastes, crop and forest residues, and trees that have been damaged by insects or are at risk of burning naturally are good places to start. The scale of the problem, though, will require millions of acres of land to be managed and harvested differently if we are to make a difference. The enormous potential footprint of bioenergy is what makes our third recommended option the riskiest in terms of environmental effects. The need for carbon capture and storage technologies is also the component of these activities that will probably face the greatest public opposition, as has already occurred in places in Holland and Germany.

What bioenergy with carbon capture and storage provides is an extensive, cheaper complement to industrial carbon removal. Neither approach is perfect. Both will eventually be needed to draw down the concentration of CO_2 in the atmosphere, because energy efficiency and renewables alone can't get us to a carbon-negative economy.

In conclusion, to discuss even the possibility of engineering Earth's climate is to acknowledge that we have failed to slow greenhouse gas emissions and climate change. Emitting less CO_2 through increased energy efficiency and renewables should remain a top policy priority. These options will be cheaper than most forms of geoengineering and will provide many additional benefits, including improved air and water quality, national security, balance of trade, and human health.

Our climate is already changing, and we need to explore at least some kinds of carbon-removal technologies, because energy efficiency and renewables cannot take CO_2 out of the air once it's there. Some scientists increasingly argue that we need to do research on sunshade technologies as a backup plan if climate change starts to accelerate dangerously. This argument has merit. However, the sooner we invest in and make progress on reducing greenhouse gas emissions today and promote ways to restore the atmosphere through carbon-scrubbing technologies in the future, the less likely we are ever to need global sunshades. The principle of atmospheric restoration should guide us in curing climate change outright, not in treating a few of its symptoms.

Recommended reading

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