United States Government Accountability Office

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Report to the Chairman, Committee on Science and Technology, House of Representatives

September 2010

CLIMATE CHANGE

A Coordinated Strategy Could Focus Federal Geoengineering Research and Inform Governance Efforts

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Highlights

Highlights of GAO-10-903, a report to the Chairman, Committee on Science and Technology, House of Representatives

September 2010

CLIMATE CHANGE

A Coordinated Strategy Could Focus Federal Geoengineering Research and Inform Governance Efforts

Why GAO Did This Study

Policymakers have raised questions about geoengineering—large-scale deliberate interventions in the earth's climate system to diminish climate change or its impacts—and its role in a broader strategy of mitigating and adapting to climate change. Most geoengineering proposals fall into two categories: carbon dioxide removal (CDR), which would remove carbon dioxide (CO_2) from the atmosphere, and solar radiation management (SRM), which would offset temperature increases by reflecting sunlight back into space.

GAO was asked to examine (1) the state of geoengineering science, (2) federal involvement in geoengineering, and (3) the views of experts and federal officials about the extent to which federal laws and international agreements apply to geoengineering, and any governance challenges. GAO examined relevant scientific and policy studies, relevant domestic laws and international agreements, analyzed agency data describing relevant research for fiscal years 2009 and 2010, and interviewed federal officials and selected recognized experts in the field.

What GAO Recommends

GAO recommends that within the Executive Office of the President, the appropriate entities, such as the Office of Science and Technology Policy (OSTP), establish a clear strategy for geoengineering research in the context of the federal response to climate change to ensure a coordinated federal approach. OSTP neither agreed nor disagreed with our recommendation, but provided technical comments.

View GAO-10-903 or key components.

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What GAO Found

Few geoengineering experiments or modeling studies have been conducted, and major uncertainties remain on the efficacy and potential consequences of geoengineering approaches. GAO's review of relevant studies and discussions with selected experts indicated that relatively more laboratory and field research relevant to certain CDR approaches exists, although most of this research was not designed to apply to geoengineering. In contrast, few modeling studies or field experiments have focused on SRM approaches, according to experts and recent studies. Experts identified only one SRM field experiment with published results—a 2009 Russian experiment that injected aerosols into the middle troposphere to measure their reflectivity. Experts, as well as relevant studies, identified several major uncertainties in need of further investigation for CDR and SRM.

Federal agencies identified 52 research activities, totaling about $100.9 million, relevant to geoengineering during fiscal years 2009 and 2010. GAO's analysis found that 43 activities, totaling about $99 million, focused either on mitigation strategies or basic science. Most of the research focused on mitigation efforts, such as geological sequestration of CO_2, which were identified as relevant to CDR approaches but not designed to address them directly. GAO found that nine activities, totaling about $1.9 million, directly investigated SRM or less conventional CDR approaches. Officials from interagency bodies coordinating federal responses to climate change indicated that their offices have not developed a coordinated strategy, and believe that, due to limited federal investment, it is premature to coordinate geoengineering activities. However, federal officials also noted that a large share of existing federal climate science research could be relevant to geoengineering. Agencies requested roughly $2 billion for such activities in fiscal year 2010. Without a coordinated federal strategy for geoengineering, it is difficult for agencies to determine the extent of relevant research, and policymakers may lack key information to inform subsequent decisions on geoengineering and existing climate science efforts.

According to legal experts and federal officials, the extent to which federal laws and international agreements apply to geoengineering is unclear. The Environmental Protection Agency (EPA) has taken steps to regulate one CDR approach and has determined that it has sufficient authority to regulate two other approaches. EPA officials said EPA has not assessed the applicability of other laws because geoengineering research is in its initial stages. Similarly, legal experts and Department of State officials said that, except for three instances, parties to international agreements have not addressed their agreements' applicability to geoengineering, largely due to limited geoengineering activity and awareness of the issue. Legal experts' and officials' views differed on the best approach for international governance, but generally agreed that the federal government should take a coordinated, interagency approach on domestic regulation. Experts and officials also identified governance challenges, such as the need to address liability.

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Abbreviations

BECS	biomass energy with carbon dioxide capture and sequestration
CCS	carbon capture and storage
CDR	carbon dioxide removal
CEQ	Council on Environmental Quality
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act of 1980
CO_2	carbon dioxide
Commerce	Department of Commerce
DOD	Department of Defense
DOE	Department of Energy
EOP	Executive Office of the President
EPA	Environmental Protection Agency
IEA	International Energy Agency
Interior	Department of the Interior
London Convention	Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter
London Protocol	1996 Protocol to the London Convention
NASA	National Aeronautics and Space Administration
NEPA	National Environmental Policy Act of 1969
NIAC	NASA Institute for Advanced Concepts
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
NSF	National Science Foundation
OSTP	Office of Science and Technology Policy
RCRA	Resource Conservation and Recovery Act of 1976
SRM	solar radiation management
State	Department of State
UNFCCC	United Nations Framework Convention on Climate Change
USDA	U.S. Department of Agriculture
USGCRP	U.S. Global Change Research Program

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United States Government Accountability Office
Washington, DC 20548

September 23, 2010

The Honorable Bart Gordon
Chairman
Committee on Science and Technology
House of Representatives

Dear Mr. Chairman:

Changes in the earth's climate attributable to increased concentrations of greenhouse gases may have significant environmental and economic effects within the United States and internationally. These effects are expected to vary across regions, countries, and economic sectors. In its recent study *Advancing the Science of Climate Change*, the National Research Council (NRC)[1] stated that temperature increases related to rising greenhouse gas levels are closely associated with a broad spectrum of climate impacts, such as changes in rainfall and widespread ocean acidification.[2] These impacts pose significant risks for—and in many cases are already affecting—a wide range of human and environmental systems, including freshwater resources, the coastal environment, agriculture, fisheries, human health, ecosystems, and national security, according to the study. Furthermore, NRC previously reported that human alterations of the climate system may increase the possibility of large and abrupt regional or global climatic events. NRC also found that because abrupt climate changes of the past have not yet been fully explained, future abrupt changes cannot be predicted, and climate surprises are to be expected.[3]

Key scientific assessments have underscored the urgency of reducing emissions of carbon dioxide (CO_2), the most prevalent greenhouse gas produced by human activity, as a risk-management strategy to help reduce

[1]NRC is the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering.

[2]Ocean acidification is defined by the Royal Society as a decrease in the pH of sea water due to the uptake of carbon dioxide produced as a result of human activity.

[3]According to NRC, historical climate records indicate that the climate system can experience abrupt changes in as little as a decade. As discussed in the background, these changes may be linked to "tipping points" in the earth's climate system.

or limit the negative effects of climate change—also known as mitigation.[4] However, many countries with significant greenhouse gas emissions, including the United States, China, and India, have not committed to binding limits on CO_2 emissions, and atmospheric CO_2 levels continue to rise. Another strategy for responding to climate change is adaptation. We have reported that policies to prepare for and adapt to the potential adverse effects of climate change could help reduce the vulnerability of countries and regions and, in conjunction with emissions reductions, may be viewed as part of a risk-management strategy for responding to climate change.[5] In particular, we reported that federal entities such as the President's Council on Environmental Quality (CEQ), the Office of Science and Technology Policy (OSTP), and the U.S. Global Change Research Program (USGCRP) had begun to develop governmentwide strategies to address adaptation and reduce the nation's vulnerability to adverse impacts from climate change. We recommended that the appropriate entities within the Executive Office of the President (EOP), such as CEQ and OSTP, develop a national strategic plan to guide the nation's efforts to adapt to a changing climate. Furthermore, we recommended that the plan, among other things, define federal priorities related to adaptation and build on and integrate ongoing federal efforts related to adaptation.[6]

Recently, policymakers and scientific organizations have begun to raise questions about a third possible risk-management strategy for climate change—geoengineering. The Royal Society,[7] the United Kingdom's

[4]There are six primary greenhouse gases that are generally monitored and reported by countries: CO_2, methane, and nitrous oxide, as well as three synthetic gases: hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride. Because greenhouse gases differ in their potential to contribute to global warming, each gas is assigned a unique weight based on its heat-absorbing ability relative to CO_2 over a fixed period. This provides a way to convert emissions of various greenhouse gases into a common measure, called the CO_2 equivalent.

[5]GAO, *Climate Change Adaptation: Strategic Federal Planning Could Help Government Officials Make More Informed Decisions*, GAO-10-113 (Washington, D.C.: Oct. 7, 2009).

[6]CEQ and OSTP, together with the National Oceanic and Atmospheric Administration (NOAA), are co-chairing an Interagency Climate Change Adaptation Task Force to develop recommendations for adapting to climate change impacts both domestically and internationally. The task force released an interim progress report on March 16, 2010, which can be accessed at: http://www.whitehouse.gov/sites/default/files/microsites/ceq/20100315-interagency-adaptation-progress-report.pdf.

[7]The Royal Society, *Geoengineering and the climate: Science, governance and uncertainty* (London: September 2009).

national academy of sciences, provided the definition of geoengineering that we use in this report: deliberate large-scale interventions in the earth's climate system to diminish climate change or its impacts.[8] At the same time, some scientists and nongovernmental organizations have raised concerns that exploration of geoengineering as a policy option could further decrease incentives to reduce greenhouse gas emissions.

A September 2009 study from the Royal Society divided most geoengineering proposals into two main categories: carbon dioxide removal (CDR) and solar radiation management (SRM). CDR addresses what scientists currently view as the root cause of climate change by removing CO_2 from the atmosphere.[9] For example, one approach to CDR would be to enhance the biological processes for removal and storage of CO_2 by microorganisms in the ocean. In contrast, SRM offsets temperature increases by reflecting a small percentage of the sun's light back into space. For example, one SRM approach would be to add reflective particles to the upper atmosphere to reflect incoming sunlight back into space. More recently, NRC addressed geoengineering in a series of studies requested by Congress, collectively titled *America's Climate Choices*.[10] In addressing the subject of geoengineering, NRC utilized the Royal Society's definition and categorization of geoengineering approaches, but noted that there is no consensus regarding the extent to which the term geoengineering should be applied to various widely accepted practices that remove CO_2 from the atmosphere, such as reforestation.[11]

[8]Geoengineering is also referred to as climate engineering, or climate remediation and climate intervention.

[9]In addition to these two types of approaches, other large-scale interventions in the earth's climate system, such as removing other greenhouse gases from the atmosphere, have been considered as part of a potential response to reduce the impacts of climate change.

[10]The suite of studies for *America's Climate Choices* examines issues associated with global climate change, including the science and technology challenges involved, and provides advice on actions and strategies the United States can take to respond. The four studies issued to date are: *Limiting the Magnitude of Future Climate Change*, *Advancing the Science of Climate Change*, *Adapting to the Impacts of Climate Change*, and *Informing an Effective Response to Climate Change*. These studies can be accessed at: http://americasclimatechoices.org/

[11]Questions about how to define geoengineering and what approaches should be included were also part of the discussion at the March 2010 Asilomar Conference on Climate Intervention Technologies, which classified geoengineering approaches into climate intervention technologies (equivalent to SRM) and climate remediation technologies (equivalent to CDR).

According to the Royal Society, CDR would work more slowly than SRM to reduce global temperatures but, with some exceptions, would involve fewer potential environmental risks. This is because CDR is intended to return the climate closer to its preindustrial state by reducing atmospheric concentrations of CO_2. In contrast, the study reported that SRM would begin to reduce temperatures more quickly than CDR, but would create an artificial and approximate balance between increased atmospheric greenhouse gas concentrations and reduced sunlight. This artificial state would introduce additional environmental risks and require long-term maintenance. Additionally, SRM approaches generally have greater potential to cause uneven environmental impacts beyond national or regional boundaries. This creates social, ethical, legal, and political implications that should be addressed before many of the SRM technologies are implemented on a large scale, according to the Royal Society.

The House Committee on Science and Technology held hearings on geoengineering science and governance issues, and as part of those hearings, the committee asked expert witnesses to testify about the extent of existing geoengineering research and areas where additional study is needed to better understand geoengineering approaches and their potential impacts. In March 2010, we provided preliminary observations on our work to the committee as part of these hearings.[12] Additionally, due to the interest of the committee and the strategic relevance of this topic, we have initiated a technology assessment on geoengineering. Internationally, the European Union has initiated a research program to study the scientific issues, as well as the policy implications of SRM geoengineering approaches. Furthermore, some nongovernmental organizations have begun to examine the scientific and policy issues surrounding geoengineering.[13]

Within this context, you asked us to review geoengineering. Our objectives were to examine (1) the general state of the science regarding geoengineering approaches and their potential effects; (2) the extent to

[12]GAO, *Climate Change: Preliminary Observations on Geoengineering Science, Federal Efforts, and Governance Issues*, GAO-10-546T (Washington, D.C.: Mar. 18, 2009).

[13]For example, the American Physical Society and the National Commission for Energy Policy have undertaken studies to examine geoengineering. Additionally, the American Meteorological Society and American Geophysical Union have issued policy statements regarding geoengineering.

which the federal government is sponsoring or participating in geoengineering research or deployment; and (3) the views of legal experts and federal officials about the extent to which federal laws and international agreements apply to geoengineering activities, and associated challenges, if any, to geoengineering governance.

To address these objectives, we reviewed relevant studies from peer-reviewed journals, law reviews, scientific organizations, and nongovernmental organizations related to geoengineering. We also selected 10 knowledgeable scientific or policy experts and 8 legal experts to interview based on criteria, including participation in one of several expert panels related to geoengineering, the number of articles authored in peer-reviewed journals or law reviews, and recommendations from other recognized experts in their respective fields. To determine the extent to which the federal government is sponsoring or participating in geoengineering research or deployment, we provided a document defining geoengineering and describing proposed geoengineering approaches based on the Royal Society study to officials from the 13 USGCRP-participating agencies, and asked them to identify relevant federal activities during fiscal years 2009 and 2010 that fit these descriptions.[14] Because the federal government does not have a formal policy on geoengineering, we relied on agency officials' professional judgment to identify relevant activities. We collected these data through July 2010. We analyzed the officials' responses and removed 12 activities that did not appear related to geoengineering based on the definition we provided.[15] We then categorized the remaining activities into three broad types: (1) activities related to conventional carbon mitigation efforts that are directly applicable to a proposed geoengineering approach, although not

[14]USGCRP-participating agencies are the Departments of Agriculture, Commerce, Defense, Energy, Interior, Health and Human Services, State, and Transportation; and the U.S. Agency for International Development, the Environmental Protection Agency, the National Aeronautics and Space Administration, the National Science Foundation, and the Smithsonian Institution.

[15]These 12 activities were (1) investigating green roof behavior in dense urban environments, (2) developing membrane technology for hydrogen purification, (3) converting municipal solid wastes to liquid fuel, (4) developing technology for generating hydrocarbon fuels using solar energy and CO_2, (5) water desalinization project using solar energy, (6) internationally collaborating with China to foster emissions mitigation research, (7) developing technology to facilitate the conversion of methane gas to liquid fuel, and five activities to develop technologies related to biofuels. Based on their description, we determined that these 12 activities did not appear relevant to identified CDR or SRM approaches.

designated as such; (2) activities related to improving basic scientific understanding of earth systems, processes, or technologies that could be applied generally to geoengineering; and (3) activities designed specifically to address a proposed geoengineering approach that does not overlap with a conventional carbon mitigation strategy. In addition, we met with officials and staff from interagency bodies coordinating federal responses to climate change, including OSTP, CEQ, and USGCRP, as well as the Department of Energy (DOE), which coordinates the Climate Change Technology Program—a multiagency research and development program for climate change technology. We also reviewed federal laws and international agreements, interviewed 7 legal experts,[16] and interviewed officials from the Environmental Protection Agency (EPA) and the Department of State (State) to identify potentially relevant federal laws and international agreements and discuss how these laws and international agreements might apply to future geoengineering efforts, and associated challenges, if any, to geoengineering governance.

We conducted our work from December 2009 through September 2010 in accordance with generally accepted government auditing standards. Those standards require that we plan and perform the audit to obtain sufficient, appropriate evidence to provide a reasonable basis for our findings and conclusions based on our audit objectives. We believe that the evidence obtained provides a reasonable basis for our findings and conclusions based on our audit objectives.

Background

Geoengineering proposals to deliberately alter the climate in response to the greenhouse effect have appeared in scientific advisory reports since at least the 1960s. Until recently, these proposals generally remained outside the mainstream discussions of climate policy, which focused either on strategies to reduce emissions or adapt to climate change impacts. However, there is growing concern among many scientists that the lack of progress on emissions reductions will lead to gradual increases in atmospheric concentrations of CO_2 beyond a threshold that could prevent substantial impacts to human health and environmental systems. Furthermore, there is also concern about the existence of “tipping points,” where the earth’s climate system reaches a threshold that unexpectedly results in abrupt and severe changes. One example would be the rapid

[16] One of the eight legal experts we selected did not respond to our request for an interview. See appendix II for more information on the legal experts we selected for this review.

collapse of the West Antarctic Ice Sheet—which would lead to a large and sudden contribution to sea level rise.[17] These concerns have led to increased interest in geoengineering as a potential tool to help reduce the impacts of climate change, although the NRC study noted that few, if any, individuals are promoting geoengineering as a near-term alternative to emissions reductions.

While both CDR and SRM are intended to reduce global temperatures, there are substantial differences in how CDR and SRM operate on the climate system, the timescales required for results, and their associated risks and trade-offs. Consequently, CDR and SRM are often discussed separately. The Royal Society identified several CDR approaches that would directly remove CO_2 from the atmosphere, as shown in figure 1. Many of these methods are designed to enhance natural physical, biological, or chemical processes that capture and store CO_2 in the ocean or on land. Examples of ocean-based CDR approaches include:

- **Enhanced removal by physical processes**. Enhanced upwelling/downwelling—altering ocean circulation patterns to bring deep, nutrient rich water to the ocean's surface (upwelling), to promote phytoplankton growth—which removes CO_2 from the atmosphere, as described below—and accelerating the transfer of CO_2-rich water from the surface of the ocean to the deep-sea (downwelling).

- **Enhanced removal by biological processes.** Ocean fertilization—introducing nutrients such as iron, phosphorus, or nitrogen to the ocean surface to promote phytoplankton growth. The phytoplankton remove CO_2 from the atmosphere during photosynthesis, and some of the CO_2 is transported to the deep ocean as detritus.

- **Enhanced removal by chemical processes.** Ocean-based enhanced weathering— accelerating chemical reactions between certain minerals and CO_2, which convert the CO_2 to a nongaseous state. Methods include adding chemically reactive alkaline minerals, such as limestone or silicates, to the ocean to increase the ocean's natural ability to absorb and store CO_2. (Not shown in figure 1.)

[17]According to the NRC study *Advancing the Science of Climate Change*, the West Antarctic Ice Sheet stores an equivalent of 11 feet of sea level. While there is substantial uncertainty in sea level rise projections, the consequences of extreme and rapid sea level rise could be economically and socially devastating for highly built-up and densely populated coastal areas around the world, according to the study.

Examples of land-based CDR approaches include:

- **Physical removal by industrial processes**. Direct air capture—technology-based processing of ambient air to remove CO_2 from the atmosphere. The resulting stream of pure CO_2 can either be used or injected into geological formations for storage (geological sequestration).

- **Enhanced removal by biological processes**.[18]

  - Biomass energy with CO_2 capture and geological sequestration—harvesting vegetation and using it as a fuel source with capture and storage of the resulting emissions in geological formations (geological sequestration).

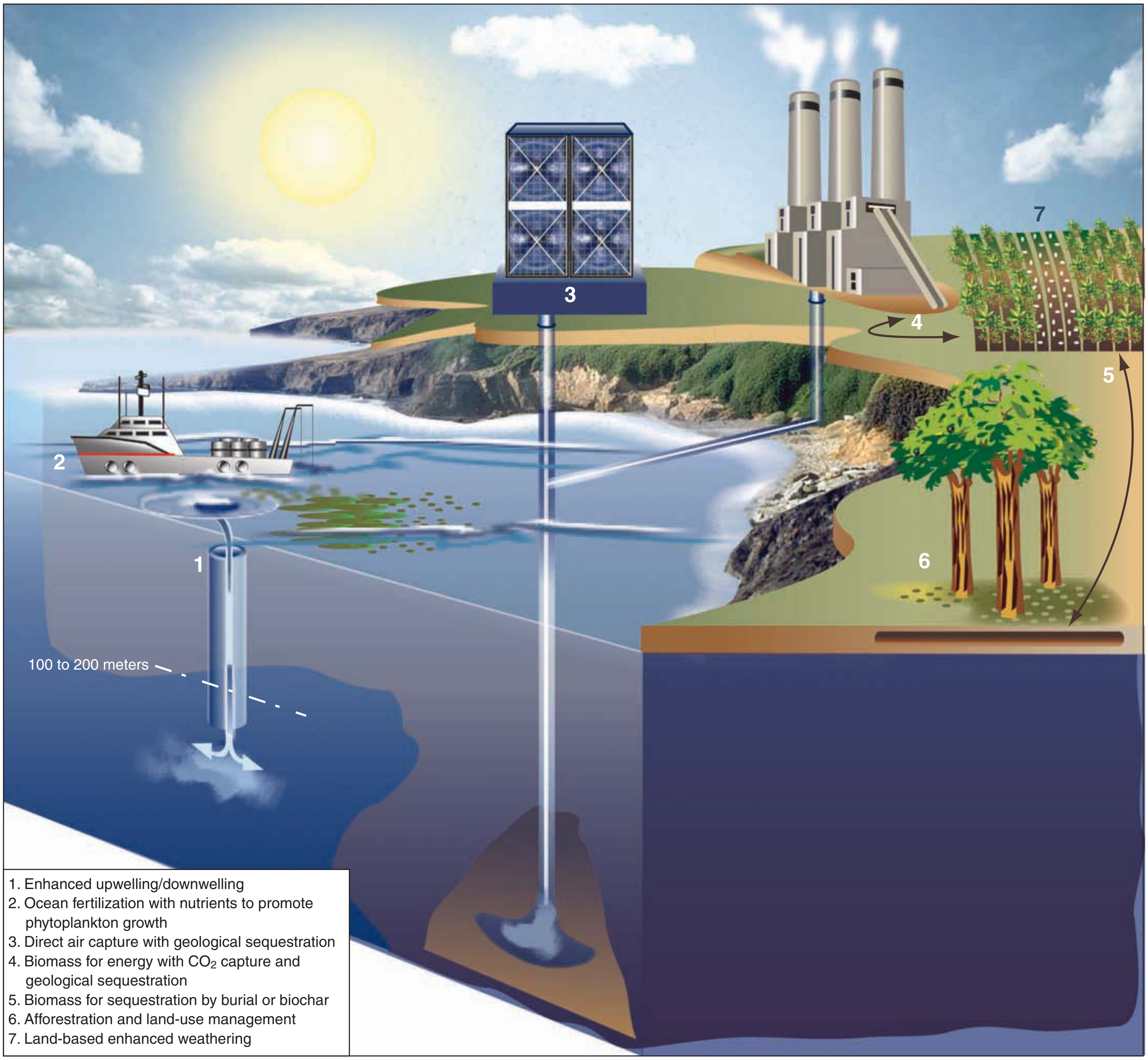
  - Biomass for sequestration—harvesting of vegetation and sequestering it as organic material by burying trees or crop wastes, or as charcoal (biochar).

  - Afforestation and land-use management—the planting of trees on lands that historically have not been forested, or otherwise managing vegetation cover to maximize CO_2 sequestration in soil or biomass.

- **Enhanced removal by chemical processes**. Land-based enhanced weathering—accelerating chemical reactions between certain minerals and CO_2, which convert the CO_2 to a nongaseous state. Methods include mining reactive minerals such as silicates, and then exposing them to the air by spreading them on agricultural fields, or injecting a stream of CO_2 into a geological formation of reactive minerals.

[18]As previously noted, the NRC study indicated that there is no consensus regarding the extent to which the term geoengineering should be applied to various widely accepted practices that remove CO_2 from the atmosphere. In commenting on this report, OSTP and U.S. Department of Agriculture officials recommended against including such land-based biological processes in an operational definition of geoengineering. For more information on their comments, see the Agency Comments and Our Evaluation section of this report.

Figure 1: Examples of CDR Approaches



1. Enhanced upwelling/downwelling
2. Ocean fertilization with nutrients to promote phytoplankton growth
3. Direct air capture with geological sequestration
4. Biomass for energy with CO_2 capture and geological sequestration
5. Biomass for sequestration by burial or biochar
6. Afforestration and land-use management
7. Land-based enhanced weathering

Sources: Lawrence Livermore National Laboratory and GAO analysis of various sources.

The Royal Society identified several SRM approaches that would reflect a small percentage of incoming sunlight back to space, as shown in figure 2. SRM approaches are generally discussed in terms of which sphere they would act upon—space, the atmosphere, or the earth's surface. Examples of SRM approaches include:

- **Space-based methods**. Reflecting or deflecting incoming solar radiation using space-based shielding materials, such as mirrors.

- **Atmosphere-based methods.**

  - Stratospheric aerosol injection—injecting reflective aerosol particles into the stratosphere to scatter sunlight back into space. Although it is possible that a wide range of particles could serve this purpose, most attention has been on sulfur particles—partly because temporary global cooling has been produced in the past by volcanic eruptions.

  - Cloud-brightening—adding sea salt or other cloud condensation surfaces to low-level marine clouds to increase their ability to reflect sunlight before it reaches the earth's surface.

- **Surface-based methods**. Increasing the reflectivity of the earth's land or ocean surfaces[19] through activities such as painting roofs white, planting more reflective crops or other vegetation, or covering desert or ocean surfaces with reflective materials.

[19]According to the Royal Society study, there appeared to be no peer-reviewed studies describing methods to increase the reflectivity of the ocean surface at the time of the study's publication. However, two ideas that have been proposed are placing reflective disks on the ocean's surface and creating microbubbles on the ocean surface, both of which would reduce the amount of sunlight absorbed by the ocean's surface and converted into heat.

Figure 2: Examples of SRM Approaches

Sources: Lawrence Livermore Laboratory and GAO analysis of various sources.

According to the NRC and Royal Society studies, geoengineering is one of several potential tools to limit the impact and consequences of climate change. However, these studies state that geoengineering is a potential complement to, rather than a substitute for, sharp reductions in greenhouse gas emissions. For example, while geoengineering includes a range of approaches with varying degrees of potential effectiveness and consequences—no geoengineering approach can provide an easy or risk-free alternative solution to the problem of climate change, according to the Royal Society study. For example, compared to current CDR proposals, using SRM to divert incoming sunlight would relatively quickly produce a cooling effect to counteract the warming influence of increased atmospheric concentrations of greenhouse gases. However, SRM does not address the rising atmospheric concentration of greenhouse gases produced by human activity, and therefore would not reduce other serious climate change impacts such as ocean acidification.

Furthermore, according to these studies, both CDR and SRM involve additional environmental risks or other trade-offs. For example, ocean-based CDR approaches, such as ocean fertilization, could have unanticipated negative impacts on ocean ecosystems. Additionally, the large-scale deployment of certain land-based CDR approaches, such as afforestation, land-use management for sequestration, and biomass for energy or burial, create trade-offs for land use. In general, the Royal Society study found that compared to CDR, most SRM approaches are associated with a higher risk of negative environmental effects, such as negative impacts on regional temperature or precipitation. For example, one study found that combining a reduction of incoming solar radiation with high levels of atmospheric CO_2 could have substantial impacts on regional precipitation—potentially leading to reductions that could create droughts in some areas.[20] Additionally, the Royal Society study said that increasing the reflectivity of desert or ocean surfaces could have major impacts on desert or ocean ecosystems. Moreover, this study indicated that the artificial balance between increased greenhouse gas concentrations and reduced solar radiation created by large-scale

[20]Gabriele C. Hegerl and Susan Solomon, "Risks of Climate Engineering," *Science* 325 (2009): 955-956.

deployment of an SRM approach would need to be maintained over decades and possibly centuries or longer.[21]

Geoengineering Is an Emerging Field with Major Uncertainties, Including Potential Effects

Experts said that geoengineering is an emerging field, with relatively few experiments or other studies conducted and with major uncertainties remaining. We found that more is known about certain CDR approaches, since related laboratory and field experiments have been conducted, whereas there is limited understanding of other CDR approaches and SRM. Moreover, major uncertainties remain regarding the scientific, legal, political, economic, and ethical implications of researching or deploying geoengineering.

More Relevant Modeling Studies and Experiments Have Focused on CDR than on SRM

We found that relatively more laboratory and field research relevant to certain CDR approaches exists, although most of this research was not designed to apply to geoengineering. For example, according to the International Energy Agency (IEA),[22] there are several projects injecting CO_2 into geological formations and monitoring it. The oldest of these is a private-sector project in Sleipner, Norway, that began in 1996, according to the IEA. However, these projects are primarily associated with public and private initiatives to study, develop, and promote carbon capture and storage technologies as a greenhouse gas emissions reduction strategy, rather than the large-scale deployment of geological sequestration that would be required to significantly alter the climate through geoengineering. For direct air capture, one expert we selected said in a recent article that a system could be created using existing technologies, and that a handful of academic groups and small start-up companies have initiated direct air capture research projects. However, the NRC study, *Advancing the Science of Climate Change*, stated that major challenges remained in making direct air capture systems viable in terms of cost,

[21]OSTP officials indicated that if greenhouse gas concentrations continued to rise, compensating SRM measures would also require a corresponding increase to maintain the balance between global heating and cooling. According to the Royal Society study, it is doubtful that such a balance would be sustainable for long periods of time if emissions were allowed to continue or increase, and any large-scale SRM deployment introduces additional risk.

[22]The IEA is an intergovernmental organization that acts as energy policy advisor to 28 member countries. Additional information on the IEA can be found at their website: http://www.iea.org. International Energy Agency, *Legal Aspects of Storing* CO_2*: Update and Recommendations* (Paris: 2007).

energy requirements, and scalability.[23] Similarly, the Royal Society study found that both land- and ocean-based enhanced weathering CDR approaches could potentially store a large amount of carbon, but face barriers to deployment such as scale, cost, and possible environmental consequences. This report also found that while some other land-based CDR approaches—such as afforestation, land-use management techniques, and biomass for energy or burial—can remove CO_2 from the atmosphere, their relative potential to significantly reduce atmospheric concentrations of CO_2 on a global scale is low.[24]

Other CDR approaches have been the focus of relatively few laboratory and field experiments, and fundamental questions remain about their potential efficacy. For example, according to the Royal Society and NRC studies, while ocean fertilization has received some sustained research activity, its potential to remove CO_2 from the atmosphere and keep it sequestered remains unclear. Specifically, we found that several ocean fertilization experiments using iron have been conducted as part of existing marine research studies or small-scale commercial operations. However, one scientific researcher familiar with these experiments noted that they were designed to improve scientific understanding of the role of iron in ocean ecosystems and the carbon cycle, not to investigate geoengineering.[25] For example, according to researchers who designed a 2009 joint German and Indian iron fertilization experiment, their experiment was designed to test a range of scientific hypotheses pertaining to the structure and functioning of Southern Ocean ecosystems and their potential impact on global cycles of biologically-generated elements, such as carbon and nitrogen.[26] Furthermore, these researchers noted that future long-term experiments to study phytoplankton blooms and their effect on the deep ocean and underlying sediments would have to be much larger than experiments to date.

[23]National Research Council, *Advancing the Science of Climate Change* (Washington, D.C.: 2010).

[24]The Royal Society, *Geoengineering and the climate: Science, governance and uncertainty* (London: September 2009).

[25]In a 2008 report, *Fertilizing the Ocean with Iron*, the Woods Hole Oceanographic Institution said that previous research looking at ice-core records suggested that naturally occurring iron fertilization had repeatedly drawn carbon out of the atmosphere during past glacial periods.

[26]The experiment was sponsored by the German Alfred Wegener Institute for Polar and Marine Research and the Indian National Institute of Oceanography.

According to our review of relevant studies and expert interviews, understanding of SRM is more limited than that of CDR because there have been few laboratory experiments, field experiments, or computer modeling efforts. Two of the most frequently discussed SRM approaches are stratospheric aerosol injection and cloud-brightening, according to many of the scientific experts we spoke with. For stratospheric aerosol injection, some of the experts said that research to date consisted primarily of a few modeling analyses. They also said that more work would need to be done to assess whether this approach could reduce incoming solar radiation without serious consequences. For example, one study identified the potential for regional impacts on precipitation—potentially leading to drought in some areas.[27] Based on our literature review and interviews with experts, to date only one study has been published for a field experiment related to SRM technologies—a 2009 Russian experiment that injected aerosols into the middle troposphere to measure their reflectivity.[28] Similarly, in the case of cloud-brightening, several experts said that there currently is not enough research to assess its effectiveness or impacts. According to the 2010 NRC study, other methods for SRM, including using space-based reflectors and increasing the solar reflectivity of buildings or plants, have limited potential, either due to the cost of deployment or the limited potential to affect the climate.

Experts and Relevant Studies Identified Major Uncertainties that Merit Further Investigation

Experts we interviewed and relevant studies identified several major uncertainties in the field of geoengineering that are in need of further investigation. These uncertainties ranged from important scientific questions for CDR and SRM, to political, ethical, and regulatory issues. Areas that merit further investigation include:

- **Technical feasibility and effectiveness of SRM and certain CDR approaches**. Experts we interviewed and the Royal Society and NRC studies agreed that SRM approaches generally were not researched sufficiently to be considered well-understood or technically feasible. Additionally, questions remain regarding the effectiveness of certain

[27] Gabriele C. Hegerl and Susan Solomon, “Risks of Climate Engineering,” *Science* 325 (2009): 955-956.

[28] Yu. A. Izrael, V. M. Zakharov, N. N. Petrov, A. G. Ryaboshapko, V. N. Ivanov, A. V. Savchenko, Yu. V. Andreev, V. G. Eran’kov, Yu. A. Puzov, B. G. Danilyan, V. P. Kulyapin, and V. A. Gulevskii, “Field Studies of a Geo-engineering Method of Maintaining a Modern Climate with Aerosol Particles,” *Russian Meteorology and Hydrology* 34, no. 10 (2009): 635-638.

CDR approaches, such as ocean fertilization and some land-based methods, to significantly reduce atmospheric concentrations of CO_2 on a global scale, or sequester CO_2 over the long term, according to relevant studies.

- **Unintended consequences**. According to the NRC and Royal Society studies as well as some of the experts we interviewed, modeling studies indicate that stratospheric aerosol injection could change regional precipitation and that other unintended effects are possible.[29] The Royal Society study also noted that large-scale deployment of CDR approaches, such as methods requiring substantial mineral extraction—including land- or ocean-based enhanced weathering—may have unintended and significant impacts within and beyond national borders. For example, the study noted that impacts from enhanced weathering approaches could include localized environmental damage caused by increased mineral extraction activity, as well as changes to soil and ocean surface water pH that could affect vegetation and marine life. Several of the experts that we spoke with agreed that potential unintended consequences of geoengineering approaches require further study.[30]

- **Better understanding of the climate and a way to determine when a "climate emergency" is reached**. The NRC study recommended additional basic climate science research, including (1) improved detection and attribution of climate change to distinguish the effects of intentional intervention in the climate system from other causes of climate change, and (2) information on climate system thresholds, reversibility, and abrupt changes to inform societal debate and decision-making over what would constitute a "climate emergency" and whether deployment of a geoengineering approach would be merited.

[29]According to a NOAA official, the idea of making up-front investments to evaluate risks (prior to any large investments in engineering or implementation) was successfully used to protect the ozone layer from unintended consequences of new chemicals that were proposed to replace ozone-depleting substances such as chlorofluorocarbons. This could serve as a potential model for risk evaluation for geoengineering approaches.

[30]In commenting on this report, a NOAA official noted that the amount of research directed specifically towards understanding uncertainties surrounding geoengineering is minimal, and that such research is important to improve our understanding of the benefits and consequences of various geoengineering activities. This official recommended that such research be interdisciplinary and take an ecosystem perspective.

- **How best to regulate geoengineering internationally**. Several of the experts we interviewed as well as the NRC study emphasized the potential for international tension, distrust, or even conflict over geoengineering deployment. The NRC study also stated that global-scale geoengineering deployment creates the potential for uneven positive and negative regional outcomes, and this raises questions of decision-making and national security. Further research can help clarify what type of governance might be useful and when, both for deployment and for field experiments that may involve risks of negative consequences.

- **Political, economic, and ethical concerns**. Some experts we interviewed and relevant studies said that geoengineering introduces important political, economic, and ethical questions. For example, several experts said that pursuing geoengineering research could unintentionally reduce interest in reducing CO_2 emissions and that social science research would be needed to assess this potential effect. The NRC studies stated that major questions remain regarding the economic viability of certain CDR approaches, such as direct air capture and enhanced weathering.[31] Additionally, one expert raised concerns over the potential economic costs associated with unintended impacts from deploying SRM.[32] Furthermore, NRC reported that public involvement is critical to making decisions about whether to pursue testing and deployment of geoengineering and that research is needed to determine how best to involve the public in such a decision-making process.

[31]National Research Council, *Advancing the Science of Climate Change* (Washington, D.C.: 2010), and National Research Council, *Limiting the Magnitude of Future Climate Change* (Washington, D.C.: 2010).

[32]DOE officials noted that any economic costs of geoengineering would also need to be weighed against the costs of damages from unmitigated climate change.

Federal Agencies Are Sponsoring Research Relevant to Geoengineering, but There Is No Coordinated Federal Strategy, Making It Difficult to Determine the Extent of Relevant Research

USGCRP agencies reported funding at least 52 research activities relevant to geoengineering in fiscal years 2009 and 2010. We found that, of these 52 activities, 43 were either related to conventional mitigation strategies or were fundamental scientific research, whereas 9 directly investigated a particular geoengineering approach. We identified approximately $100.9 million in geoengineering-related funding across USGCRP agencies in fiscal years 2009 and 2010, with about $1.9 million of this amount related to research directly investigating a particular geoengineering approach. The other roughly $99 million was related to research concerning conventional mitigation strategies that could be applied directly to a particular geoengineering approach or basic science that could be applied generally to geoengineering. However, there is no coordinated federal strategy or operational definition for geoengineering, so agencies and policymakers may not know the full extent of relevant federal research.

Most Federal Research Activities Focused on Mitigation or Basic Science, but a Few Specifically Addressed Geoengineering

The 13 agencies participating in USGCRP identified 52 research activities relevant to geoengineering—accounting for approximately $100.9 million in federal funding for fiscal years 2009 and 2010.[33] Twenty-eight of these activities—funded at approximately $54.4 million—were related to conventional mitigation strategies that are directly applicable to a particular CDR approach, such as enhancing land-based biological removal of CO_2 or geological sequestration of CO_2, according to our analysis. Fifteen of the reported activities—funded at approximately $44.6 million—were fundamental scientific efforts that could be generally applied to geoengineering, such as modeling the interactions between the atmosphere and the climate and basic research into processes to separate gas streams into their individual components, such as CO_2 or methane. The remaining nine activities—funded at approximately $1.9 million—directly investigated a particular geoengineering approach, such as stratospheric aerosol injection that does not overlap with a conventional mitigation strategy. Table 1 summarizes the reported funding for the 52 identified activities by each geoengineering approach and our categorization of the results. For more detailed information on reported activities, see
appendix IV.

[33]These activities were current as of July 2010. Accordingly, additional activities relevant to geoengineering may receive funding during fiscal year 2010.

Table 1: Summary of Reported Research Activities Relevant to Geoengineering at USGCRP Agencies, Combined Fiscal Years 2009 and 2010

(In thousands of dollars)

Geoengineering approach	Fundamental research with general applicability		Mitigation-related research with direct applicability		Direct geoengineering research		Total[a]	
	Activities	Reported funding	Activities	Reported funding	Activities	Reported funding	Activities	Reported funding
CDR								
Biological carbon removal and sequestration	2	$26,308	10	$27,323	1	$474	13	**$54,105**
Physical carbon removal and sequestration	10	2,076	16	26,695	2	293	28	**29,064**
Chemical carbon removal and sequestration			2	334			2	**334**
SRM								
Multiple approaches					4	904	4	**904**
Stratospheric aerosol injection					1	45	1	**45**
Other greenhouse gas removal	2	400					2	**400**
General geoengineering	1	15,840			1	170	2	**16,010**
Approximate total[b]	**15**	**$44,624**	**28**	**$54,352**	**9**	**$1,886**	**52**	**$100,862**

Source: GAO analysis of the agencies' responses to our data collection instrument, which provided a definition and description of geoengineering to officials. The data collection instrument also included some examples of potentially relevant activities based on our work for our March testimony on geoengineering.

Note: We collected data on agency activities through July 2010. Accordingly, additional activities relevant to geoengineering may receive funding during fiscal year 2010.

[a]Reported funding totals for each approach may not add across tables 1, 2, and 3 due to rounding.

[b]We present an approximate total because agencies used different measures to report funding data. For example, while most agencies provided obligations data, EPA reported enacted budget authority. Additionally, the Department of the Interior (Interior) reported planned obligations for a grant that had not yet been awarded.

Of the 43 activities related to fundamental research or mitigation efforts relevant to geoengineering but not designed to address it directly, the Department of Commerce (Commerce) reported the most funding—approximately $41.6 million. This was largely due to the National Oceanic and Atmospheric Administration's (NOAA) climate modeling and monitoring of biological emissions and absorption of greenhouse gases, which NOAA officials said could be relevant for assessing the impacts and efficacy of various geoengineering approaches. The U.S. Department of Agriculture (USDA), DOE, the Department of the Interior (Interior), and EPA reported similar levels of funding—from about $11.3 million to $13.9 million. These efforts were largely directed at measuring and monitoring carbon sequestration potential in soils and biomass and assessing the impacts and storage potential for geological sequestration of CO_2. Although these activities are associated with efforts to reduce or offset emissions, agency officials identified them as relevant to certain CDR approaches—such as large-scale afforestation, and direct air capture—based on the working definition we provided. Table 2 summarizes the approximately $99 million in reported funding for the 43 relevant activities related to conventional mitigation efforts and fundamental scientific research, by agency.

Table 2: Summary of Reported Mitigation-Related Research and Fundamental Scientific Research Relevant to Geoengineering, by USGCRP Agency, Combined Fiscal Years 2009 and 2010

(In thousands of dollars)

	Reported funding						Total[b]	
Geoengineering approach	**Commerce**	**USDA**	**Interior**	**DOE**	**EPA**	**Other[a]**	**Activities**	**Reported funding**
CDR								
Biological carbon removal and sequestration	$25,800	$13,900	$7,652	$5,078	$300	$900	12	$53,630
Physical carbon removal and sequestration			5,250	6,759	11,000	5,763	26	28,772
Chemical carbon removal and sequestration						334	2	334
Other greenhouse gas removal						400	2	400
General geoengineering	15,840						1	15,840
Approximate total[c]	**$41,640**	**$13,900**	**$12,902**	**$11,837**	**$11,300**	**$7,397**	**43**	**$98,976**

Source: GAO analysis of the agencies' responses to our data collection instrument, which provided a definition and description of geoengineering to officials. The data collection instrument also included some examples of potentially relevant activities based on our work for our March testimony on geoengineering.

Note: We collected data on agency activities through July 2010. Accordingly, additional activities relevant to geoengineering may receive funding during fiscal year 2010.

[a]Other represents the eight other agencies participating in the USGCRP.

[b]Reported funding totals for each approach may not add across tables 1, 2, and 3 due to rounding.

[c]We present an approximate total because agencies used different measures to report funding data. For example, while most agencies provided obligations data, EPA reported enacted budget authority. Additionally, Interior reported planned obligations for a grant that had not yet been awarded.

The National Science Foundation (NSF), DOE, and Commerce were the only agencies that reported funding for activities directly supporting geoengineering research during fiscal years 2009 and 2010. Of these agencies, NSF reported the most funding—approximately $1.1 million—directed to three research activities: a study on the potential impacts of ocean iron fertilization, a study to examine the moral challenges associated with SRM, and a modeling effort investigating stratospheric aerosol injection and space-based SRM approaches. DOE reported funding research—approximately $700,000—for two studies about direct air capture technologies, a modeling activity for stratospheric aerosol injection and cloud-brightening, as well as a study investigating the unintended consequences of climate change responses, including CDR and SRM approaches. Commerce reported funding two relevant research efforts—for about $70,000—examining the unintended impacts of SRM approaches, with one study focused on climate-related impacts and the other study exploring potential effects on solar electricity generation. Table 3 summarizes the approximately $1.9 million in reported funding for the nine relevant activities directly supporting geoengineering research, by agency.

Table 3: Summary of Reported Direct Geoengineering Research, by USGCRP Agency, Combined Fiscal Years 2009 and 2010

(In thousands of dollars)

	Reported funding			Total[a]	
Geoengineering approach	**Commerce**	**DOE**	**NSF**	**Activities**	**Reported funding**
CDR					
Biological carbon removal and sequestration			$474	1	$474
Physical carbon removal and sequestration		$293		2	293
SRM					
Multiple approaches	$25	266	613	4	904
Stratospheric aerosol injection	45			1	45
General geoengineering		170		1	170
Approximate total[b]	**$70**	**$729**	**$1,087**	**9**	**$1,886**

Source: GAO analysis of the agencies' responses to our data collection instrument, which provided a definition and description of geoengineering to officials. The data collection instrument also included some examples of potentially relevant activities based on our work for our March testimony on geoengineering.

Note: We collected data on agency activities through July 2010. Accordingly, additional activities relevant to geoengineering may receive funding during fiscal year 2010.

[a]Reported funding totals for each approach may not add across tables 1, 2, and 3 due to rounding.

[b]We present an approximate total because agencies used different measures to report funding data. For example, while most agencies provided obligations data, EPA reported enacted budget authority. Additionally, Interior reported planned obligations for a grant that had not yet been awarded.

During our review, we also found examples of other relevant activities sponsored by USGCRP agencies that were outside the scope of our data request, mostly because they occurred prior to 2009. These activities included:

- DOE sponsored studies on ocean-based carbon sequestration approaches, such as ocean fertilization and direct injection of CO_2 into deep ocean sediments, from 2000 to 2006. From 2007 to 2008, DOE also sponsored research investigating the potential application of porous glass materials for SRM approaches.

- From 2006 to 2007, the National Aeronautics and Space Administration (NASA) funded a research study investigating the practicality of using a solar shield in space to deflect sunlight and reduce global temperatures as part of its former independent Institute for Advanced Concepts program.[34] Additionally, scientists at NASA's Ames Research Center held a conference on SRM approaches in 2006, in conjunction with the Carnegie Institution of Washington. NASA also funded atmospheric modeling studies, which were used by independent researchers, in part, to assess the potential impact of stratospheric aerosols on the ozone layer.

- In 2008, NSF sponsored studies examining the long-term carbon storage potential of soils and the impact of increased nitrogen on biological carbon sequestration.

- A Department of Defense (DOD) advisory group sponsored a 1-day workshop at Stanford University on geoengineering in 2009; however, DOD officials said that no funded research projects resulted from this workshop.

- In 2007, EPA funded research relevant to the economic implications of SRM approaches through its National Center for Environmental Economics.

[34]According to its final report, the NASA Institute for Advanced Concepts (NIAC) was formed to provide an independent source of revolutionary aeronautical and space concepts that could dramatically impact how NASA develops and conducts its missions. As part of the NIAC selection process, the study related to SRM was selected through an open-solicitation and peer-reviewed competition, which was managed by the Universities Space Research Association, a private, nonprofit organization.

Furthermore, federal officials also noted that a large fraction of the existing federal research and observations on basic climate change and earth science could be relevant to improving understanding about proposed geoengineering approaches and their potential impacts. For instance, federal officials said that basic research conducted by USGCRP agencies into oceanic chemistry could help address uncertainty about the potential effectiveness and impacts of CDR approaches, such as ocean fertilization. Similarly, ongoing research conducted by USGCRP agencies related to understanding atmospheric circulation and aerosol/cloud interactions could help improve understanding about the potential effectiveness and impacts of proposed SRM approaches.

Existing Federal Efforts Are Not Part of a Coordinated Geoengineering Research Strategy, Making It Difficult to Determine the Full Extent of Relevant Research

We found that it was difficult to determine the full extent of federal geoengineering research activities because there is no coordinated federal strategy for geoengineering, including guidance on how to define federal geoengineering activities or efforts to identify and track federal funding related to geoengineering. Officials from federal offices coordinating federal responses to climate change—CEQ, OSTP, and USGCRP—stated that they do not currently have a coordinated geoengineering strategy or position. For example, a USGCRP official stated that there is no group coordinating federal geoengineering research and that such a group is not currently necessary because of the small amount of federal funding involved. However, while USGCRP agencies reported about $1.9 million in funding for activities directly investigating geoengineering, federal officials also told us that a large fraction of the existing federal research and observations on basic climate change and earth science could be relevant to understanding geoengineering. According to the USGCRP's most recent report to Congress, USGCRP agencies requested roughly $2 billion in budget authority for climate change and earth science activities in fiscal year 2010. Consequently, the actual funding for research that could be applied either generally or directly to understanding geoengineering approaches is likely greater than the roughly $100.9 million reported in response to our data request.

However, without the guidance of an operational definition for what constitutes geoengineering or a strategy to capitalize on existing research efforts, federal agencies may not recognize or be able to report the full extent of potentially relevant research activities. For example, some agency officials indicated that, without a clear governmentwide definition, in their determination of which federal research activities were relevant to geoengineering, our data request was subject to different interpretations—particularly for CDR approaches, since there is extensive overlap with existing mitigation efforts. In particular, EPA and USDA officials said that there is a large body of research regarding biological sequestration but that these officials would not consider it to be geoengineering. However, officials from other agencies, such as Interior and DOE, included certain research on biological sequestration as relevant to geoengineering based on the definition we provided. Similarly, we found that from NSF officials' perspectives, the distinction between existing efforts to develop carbon capture and storage technologies, such as membranes to separate CO_2 from other gases, and geoengineering direct air capture technologies is also not well-defined. This definitional issue is not unique to these agencies. In its recent study *Advancing the Science of Climate Change*, NRC acknowledged the lack of consensus regarding what constitutes geoengineering in relation to widely accepted practices that remove CO_2 from the atmosphere.[35]

The NRC study included other findings about the nation's climate change science efforts that may be relevant to a potential federal geoengineering strategy. The study emphasized the importance of providing decision makers with scientific information on a range of available options, including geoengineering, to limit future climate change and its impacts. According to this study, this information would help policymakers use adaptive risk management to update response strategies as new information on climate change risks and response strategies becomes available.[36] NRC recommended an integrative, interdisciplinary research effort to improve understanding of available response options, as well as of climate change and its impacts. The study indicated that this effort should be led by a single coordinating body, and NRC identified USGCRP's capacity to play a role in such an effort.[37] Similarly, several of the experts

[35]National Research Council, *Advancing the Science of Climate Change* (Washington, D.C.: 2010).

[36]We have also reported on the advantages of applying such an adaptive approach to risk-management when making decisions under substantial uncertainty. See GAO, *Highway Safety: Foresight Issues Challenge DOT's Efforts to Assess and Respond to New Technology-Based Trends*, GAO-09-56 (Washington, D.C.: Oct. 3, 2008).

[37]While recognizing USGCRP's capacity to lead a coordinated climate change science research effort, NRC also identified areas where further improvements are needed for USGCRP to implement NRC's recommendations. For example, NRC stated that USGCRP will need to establish improved mechanisms for identifying and addressing weaknesses and gaps in research and decision support activities. NRC also recommended that USGCRP will need expanded budget oversight and authority to coordinate and prioritize research across agencies.

we interviewed recommended that federal geoengineering research should be an interdisciplinary effort across multiple agencies and led by a coordinating body, such as OSTP or USGCRP.

Our recent work offers insights on key considerations for establishing governmentwide strategies, which could be relevant to a future geoengineering strategy. Specifically, our review of federal efforts related to crosscutting issues, such as climate change adaptation[38] and global food security,[39] highlighted key practices for enhancing collaboration across agencies. These practices include establishing a commonly accepted operational definition for relevant activities; leveraging existing resources to support common outcomes and address identified needs; and developing mechanisms to monitor, evaluate, and report on results. Furthermore, our review of DOE's FutureGen project—a program to help build the world's first coal-fired, zero-emissions power plant—identified important factors to consider when developing a strategy for technology-based research.[40] Specifically, we found that it is important to comprehensively assess the costs, benefits, and risks of each technological option and to identify potential overlap between proposed and existing programs. For example, the NRC study acknowledged the importance of improving understanding of SRM and its consequences, without replacing or reducing existing research on climate change science or other approaches to limiting climate change or adapting to its impacts. As the study noted, much of the research needed to advance scientific understanding of SRM, such as studying the climate effects of aerosols and cloud physics, is also necessary to advance understanding of the climate system, and could therefore contribute more broadly to climate change science. Similarly, an OSTP official said that ongoing fundamental research to investigate the relationship of cloud/aerosol interactions could also be applied to improve understanding of certain SRM approaches.

In the absence of a coordinated federal strategy for geoengineering, decisions about whether a particular research activity is relevant to

[38]GAO-10-113.

[39]GAO, *Global Food Security: U.S. Agencies Progressing on Governmentwide Strategy, but Approach Faces Several Vulnerabilities*, GAO-10-352 (Washington, D.C.: Mar. 11, 2010).

[40]GAO, *Clean Coal: DOE's Decision to Restructure FutureGen Should Be Based on a Comprehensive Analysis of Costs, Benefits, and Risks*, GAO-09-248 (Washington, D.C.: Feb. 13, 2009).

geoengineering may not necessarily be consistent across the federal government. In addition, agencies generally do not collect and share information on such research activities in the context of geoengineering. While EPA officials told us that certain agencies, such as EPA, State, and NOAA, share information about ocean fertilization and direct injection of CO_2 into deep sub-seabed geological formations as part of a working group for international regulation of the ocean,[41] a USGCRP official said there is no working group to share information or coordinate geoengineering research more broadly, because such an action would require a decision from the administration to pursue geoengineering research on a larger scale. However, without a coordinated effort to identify relevant research and share information across agencies, policymakers and agency officials may lack key information needed to inform their decisions on geoengineering research. For example, if policymakers and officials do not know the full extent of the relevant federally funded research that is under way, they may not have sufficient information to leverage existing research on climate change science to also improve understanding of geoengineering.

The Extent to Which Existing Federal Laws and International Agreements Apply to Geoengineering Is Unclear, and Experts and Officials Identified Governance Challenges

Legal experts we interviewed and EPA and Department of State (State) officials said that the extent to which existing laws and international agreements apply to geoengineering is unclear, largely because detailed information on geoengineering approaches and effects is not available.[42] EPA has taken steps to regulate one CDR approach and has determined that an existing law provides sufficient authority to regulate two other approaches. EPA officials provided their preliminary thoughts on how other laws might apply to geoengineering activities. However, according to EPA officials, they have not fully assessed (1) whether the agency has the authority to regulate or (2) how to regulate most geoengineering approaches, because the research is still in its initial stages. Similarly, legal experts and State officials stated that many international agreements could apply to geoengineering; however, most agreements' applicability is unclear because they were not intended to address geoengineering and parties to the agreements have not determined whether or how the agreements should apply to relevant geoengineering activities. This uncertainty and inaction is due, in part, to the limited general

[41]An EPA official also noted that DOE, Interior, and EPA have been informally coordinating for several years on issues related to geological sequestration.

[42]The term "legal experts" refers to nongovernmental legal experts, as listed in appendix II

understanding of geoengineering and a lack of geoengineering activity. Legal experts and federal officials identified challenges for establishing governance of geoengineering, such as the potential for unintended and uneven impacts, although their views differed on the most effective governance approach.

EPA Officials Stated the Applicability of Existing Laws is Unclear and They Have Not Fully Assessed Their Applicability Because of Limited Geoengineering Activity

EPA officials stated that the extent to which existing federal environmental laws apply to geoengineering is unclear, largely because detailed information on most geoengineering approaches and effects is not available. However, EPA officials said that there is relatively more information available about geological sequestration of CO_2—a conventional mitigation strategy—which could be relevant to certain CDR approaches that capture CO_2 from the air and sequester it underground or in the sub-seabed. EPA has taken steps to regulate geological sequestration under the Safe Drinking Water Act, and EPA officials said that the Marine Protection, Research, and Sanctuaries Act of 1972 provides the agency with authority to regulate (1) certain sub-seabed geological sequestration activities, and (2) ocean fertilization activities. Specifically:

- EPA has authority under the Safe Drinking Water Act to regulate underground injections of various substances and is using this authority to develop a rule to govern the underground injection of CO_2 for geological sequestration. Although the rule's preamble discusses geological sequestration as the process of injecting CO_2 captured from an emission source, such as a power plant or industrial facility, the rule's definition of geological sequestration is broad enough to include long-term sequestration of CO_2 captured directly from the air. The proposed rule was published in July 2008, and EPA officials told us the final rule is scheduled to be promulgated in late 2010. In addition, EPA also issued a proposed rule in 2010 that would require monitoring and reporting of CO_2 injection and geological sequestration, which is scheduled to be finalized in the fall of 2010.

- Under the Marine Protection, Research and Sanctuaries Act of 1972, as amended, certain persons are generally prohibited from dumping material, including material for ocean fertilization, into the ocean without a permit from EPA.[43] EPA officials said that certain sub-seabed geological sequestration of CO_2 and ocean fertilization activities would require a permit pursuant to this act. In addition, they said some atmospheric-based geoengineering approaches may also require a permit if the aerosol particles eventually could be deposited into the ocean.

For most other laws and geoengineering approaches, EPA officials said that the agency has not considered the applicability of existing laws because the technologies have not reached a sufficient level of development. In particular, EPA officials stated that they would need detailed information on the activity itself, including the materials used and the delivery mechanism, as well as information on potential effects from the activity, to perform a regulatory risk assessment of environmental and human health impacts under existing laws. However, such information is not available for most geoengineering approaches. Furthermore, EPA officials noted that they have difficulty determining whether a particular activity is considered geoengineering because there is no standard definition for geoengineering. For example, EPA officials said that there is a substantial body of knowledge related to terrestrial biological sequestration and to programs that offset greenhouse gas emissions, but EPA would not necessarily label these activities as geoengineering.

Although EPA officials had not formally assessed how existing laws would apply to geoengineering, they shared their preliminary thoughts on the applicability of the following laws, including how additional laws could apply to geological sequestration[44] and ocean fertilization:

- **Resource Conservation and Recovery Act of 1976 (RCRA)**. RCRA regulates the management of hazardous waste from generation of the waste to its disposal. An EPA official stated that EPA has been examining questions of RCRA's applicability to geological sequestration of CO_2 and is currently considering a proposed rule to

[43]The law is limited to disposition of materials by vessels or aircraft registered in the United States, vessels or aircraft departing from the United States, federal agencies, or disposition of materials conducted in U.S. territorial waters, which extend 12 miles from the shoreline or coastal baseline.

[44]For an in-depth discussion of how existing laws apply to the capture, transport, and geological sequestration of CO_2, see the *Report of the Interagency Task Force on Carbon Capture and Storage*, available at: http://fossil.energy.gov/programs/sequestration/ccs_task_force.html.

clarify how RCRA hazardous waste requirements apply in that context. This official also noted that RCRA's applicability to other geoengineering approaches where materials are applied to the land or oceans would depend on whether there was intent to discard the materials and whether the materials are a hazardous waste.

- **Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA)**. CERCLA authorizes EPA to clean up hazardous substance releases at contaminated sites and then seek reimbursement from the parties responsible for contaminating them or compel the responsible parties to clean up these sites.[45] Responsible parties include current and former site owners and operators, as well as those who transport or arrange for the disposal of the hazardous substances. Although a stream of pure CO_2 is not a hazardous substance under CERCLA, an EPA official noted that injected CO_2 streams could contain hazardous substances, thus subjecting the parties injecting the CO_2 to liability for any release that did not qualify as federally-permitted release. In addition, if CO_2 enters groundwater, it might also cause hazardous substances, such as some metals, to be dissolved by the groundwater from enclosing strata. If that constitutes a release of hazardous substances from a "facility," such as the strata, then the owner of that facility could be liable for any cleanup costs caused by that release. This official was not aware of CERCLA's applicability to any other geoengineering activity.

- **Clean Air Act**. This law authorizes EPA to regulate emissions of certain air pollutants from mobile and stationary sources into the ambient air, including those that destroy the stratospheric ozone layer. EPA officials said that the act could apply to geoengineering activities that emitted air pollutants into the atmosphere—either as the purpose of the activity or as a side effect—depending on where the pollutant was released and the delivery mechanism. Officials also noted that although the act regulates emissions into the ambient air, substances injected into the upper atmosphere that eventually cycle down to ground level could also be subject to regulation, depending on the definition of ambient air. EPA officials stated that they would require

[45]CERCLA defines hazardous substances as substances which may present substantial danger to the public health, welfare, or environment when released, including all hazardous wastes subject to RCRA.

further information on the specific technology and activity to determine exactly how the law might apply.

In addition, EPA and DOE officials noted that geoengineering activities undertaken, funded, or authorized by federal agencies would be subject to the National Environmental Policy Act of 1969 (NEPA), the Endangered Species Act, and the conformity provision of the Clean Air Act. NEPA requires federal agencies to evaluate the likely environmental effects of certain major federal actions using an environmental assessment or, if the projects likely would significantly affect the environment, a more detailed environmental impact statement. Under the Endangered Species Act, geoengineering activities taken or authorized by federal agencies would require consultation among federal agencies, including the Fish and Wildlife Service and NOAA, to ensure that the activity is not likely to jeopardize the continued existence of any endangered or threatened species or adversely modify habitat critical for the species. Under the Clean Air Act's conformity provision, no federal agency may approve or provide financial assistance for any activity that does not conform with a state implementation plan, which is a plan required by the act to ensure that national ambient air quality standards are met.

Experts and Federal Officials Identified International Agreements That Could Apply to Geoengineering, but Their Applicability Is Largely Uncertain

Acknowledging the lack of an existing international agreement that comprehensively addresses geoengineering, State officials and legal experts we interviewed said that many agreements could perhaps apply to a geoengineering activity and its impacts, depending on the activity's nature, location, and actors. For example, some international agreements with broad scopes, such as the United Nations Framework Convention on Climate Change,[46] could apply generally to geoengineering activities, whereas other agreements specifically addressing the atmosphere, oceans, and space could apply only if the activity occurred in or impacted that particular area. However, international agreements legally bind only those

[46]In 1992, the United States and most other nations of the world negotiated the convention, whose objective is to stabilize greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous man-made interference with the climate system within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened, and to enable economic development to proceed in a sustainable manner.

countries that have become parties to the particular agreement.[47] Therefore, the number of parties to a particular agreement determines, in part, where the agreement applies, and countries that are not parties are not legally bound to abide by the agreement. Table 4 summarizes certain agreements identified by legal experts and relevant studies as potentially applicable to geoengineering and the number of parties to a particular agreement.[48]

Table 4: Examples of International Agreements Potentially Applicable to Geoengineering, as Identified by Legal Experts and Relevant Studies

International agreement	Number of parties	U.S. participation[a]
Applicable to a variety of approaches		
Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques	73	Party
Convention on Environmental Impact Assessment in a Transboundary Context	44	Signatory but not party
Protocol on Strategic Environmental Assessment to the Convention on Environmental Impact Assessment in a Transboundary Context[b]	18	Neither a signatory nor party
United Nations Framework Convention on Climate Change (UNFCCC)	195	Party
Kyoto Protocol to the UNFCCC	192	Signatory but not party
Convention on Biological Diversity[c]	193	Signatory but not party
Ocean-based approaches		
Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (London Convention)[c]	85	Party
1996 Protocol to the London Convention (London Protocol)[c]	38	Signatory but not party
United Nations Convention on the Law of the Sea	160	Neither a signatory nor party
Atmosphere-based approaches		
Vienna Convention for the Protection of the Ozone Layer	196	Party

[47]Parties to an international agreement are those countries that have consented to be bound by the treaty and for which the treaty is in force. Generally, countries express their consent to be bound by a treaty by ratifying, accepting, approving or acceding to it. Countries that have signed the treaty but not consented to be bound to it are obliged to refrain from acts which would defeat the object and purpose of a treaty until the country's intention not to become a party to the treaty is made clear.

[48]The Royal Society noted that in addition to formal agreements between nations, there are a number of customary law and general principles that might also apply to geoengineering activities. For example, the Royal Society noted that the duty not to cause significant transboundary harm is recognized in several treaties and that states are expected to exercise due diligence in regulating activities under their jurisdiction and control.

International agreement	Number of parties	U.S. participation[a]
1987 Montreal Protocol on Substances that Deplete the Ozone Layer	196	Party
Convention on Long-Range Transboundary Air Pollution	51	Party
Space-based approaches		
Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space	100	Party
Convention on International Liability for Damage Caused by Space Objects	88	Party
Approaches in Antarctic		
The Antarctic Treaty of 1959	28[d]	Party
1991 Protocol on Environmental Protection to the Antarctic Treaty	28[d]	Party
Convention for the Conservation of Antarctic Marine Living Resources	27[d]	Party

Source: GAO analysis of expert interviews, relevant studies, and United Nations' data on party status.

Note: Because few formal analyses of existing international agreements' applicability to geoengineering have been published and geoengineering science continues to evolve, this list may not include all agreements potentially applicable to geoengineering approaches.

[a]Countries that have signed an international agreement but have not consented to be bound by the treaty are referred to as signatories.

[b]This agreement is not yet in force.

[c]The parties to this agreement have issued a decision related to geoengineering.

[d]This is the number of parties entitled to participate in consultative meetings during such time as the party demonstrates its interest in Antarctica by conducting substantial research activity there.

Almost all the legal experts and State officials we spoke with noted that, of all the potential geoengineering approaches, sub-seabed geological sequestration of CO_2 and ocean fertilization had received the most international attention to date, and that parties to international agreements had issued decisions regarding the application of the agreements to ocean fertilization and amended an agreement to include sub-seabed geological sequestration in certain circumstances. In particular:

- **Ocean fertilization**. The parties to the London Convention and the London Protocol[49] have decided that the scope of these agreements includes ocean fertilization activities for legitimate scientific research and that ocean fertilization activity other than legitimate scientific research should be considered contrary to the aims of the agreements and should not be allowed. The treaties' scientific bodies are developing an assessment framework for countries to use in evaluating whether research proposals are legitimate scientific research. Additionally, the parties to the Convention on Biological Diversity[50] issued a decision in 2009 urging countries to ensure that ocean fertilization activities, except for certain small-scale scientific research within coastal waters, do not take place until there is an adequate scientific basis on which to justify them and a global, transparent, and effective control and regulatory mechanism in place. The parties to the London Convention and London Protocol are considering an additional resolution or amendment concerning ocean fertilization, and the parties to the Convention on Biological Diversity continue to discuss the issue.

- **Geological sequestration**. In 2006, the parties to the London Protocol agreed to amend the protocol to include, in certain circumstances, CO_2 streams for sequestration in sub-seabed geological formations in the protocol's list of wastes and other matter that could be dumped. Under the amendment, CO_2 streams from capture processes for sequestration can be considered for dumping if they satisfy three criteria: (1) disposal is into a sub-seabed geological formation, (2) the CO_2 stream consists overwhelmingly of CO_2 and only incidental associated substances, and

[49]The Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (London Convention) entered into force on August 30, 1975. The London Convention requires parties to promote the effective control of all sources of pollution of the marine environment and take all practicable steps to prevent the pollution of the sea by the dumping of wastes and other matter. In 1996, the parties to the London Convention developed a protocol— the 1996 Protocol to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (London Protocol)—that generally prohibits the dumping of wastes or other matter into the ocean except for those listed in the protocol for which a party to the agreement has issued a dumping permit that meets the protocol's permitting requirements. As parties to the London Convention become parties to the London Protocol, the latter supersedes the former, but the convention remains in force for those parties to the convention, like the United States, that have not become parties to the protocol.

[50]The Convention on Biological Diversity entered into force on December 29, 1993. The convention's objectives are the conservation of biological diversity and the sustainable use of its components, among other things.

(3) no wastes or other matter are added for the purpose of disposing of those wastes or other matter. The parties also developed specific guidelines for countries to use when assessing whether applications for disposal of streams into sub-seabed geological formations is consistent with the protocol. In late 2009, the parties to the London Protocol adopted an amendment to allow the export of CO_2 streams for disposal in certain circumstances.[51] The parties are developing specific guidance for these exports and issues related to the management of transboundary movement of CO_2 after injection. The parties have also discussed, but agreed not to develop, procedures regarding liability for CO_2 sequestration in sub-seabed geological formations.

However, legal experts and State officials stated that although parties to three agreements have taken action to clarify the agreements' applicability to particular geoengineering approaches, most agreements' applicability is unclear because they were not intended to address geoengineering and the parties had not yet addressed the issue. In addition, legal experts and federal officials generally said that more detailed information on geoengineering approaches and their effects would be needed for officials to develop a regulatory and governance framework. For example, aside from ocean fertilization and other marine-focused geoengineering approaches, State officials said that many of the ideas remain too theoretical and distant from implementation to consider addressing them through international law.

Experts and Federal Officials Identified Governance Challenges, but Their Views Varied on the Most Effective Governance Approach

Legal experts and EPA and State officials identified various challenges to establishing domestic and international governance of geoengineering. For example, the legal experts and EPA and State officials we interviewed generally agreed that there needs to be further research on most geoengineering approaches and their potential effects to inform—and in federal officials' views to warrant—discussions regarding regulation. Similarly, some of these experts and federal officials said that a general lack of significant efforts to pursue geoengineering is a contributing factor to why geoengineering governance has not been pursued further to date. For example, a State official noted that geoengineering has not received much attention within international negotiations related to climate change,

[51]The amendment will enter into force for those parties that have accepted it 60 days after two-thirds of the parties to the protocol have accepted, ratified, or approved the amendment.

and there isn't enough geoengineering-related activity to drive interest in expanding international governance at this time.

Legal experts and State officials had differing views about an international governance framework for geoengineering.[52] Specifically, several legal experts recommended including all geoengineering activities with transboundary impacts in a single comprehensive agreement. Some of these experts said an existing comprehensive international agreement could be adapted to address geoengineering. Some of them specifically identified the United Nations Framework Convention on Climate Change as an appropriate agreement because it addresses climate change and geoengineering is intended to diminish climate change or its impacts. Other legal experts said a new international agreement was needed because of the difficulty reaching consensus within the United Nations Framework Convention on Climate Change. Experts in favor of a single comprehensive agreement said that it would be preferable to the patchwork of existing agreements, which were not designed to address geoengineering, because these agreements do not create comprehensive governance frameworks that could be used to address geoengineering. Additionally, some experts said that certain existing agreements rely on the parties to regulate activities under their jurisdiction without the international community's participation in decision-making, which may not be the best structure for regulating geoengineering research or deployment.

State officials we interviewed said that it would be better to rely on existing treaties to the extent they are adequate and appropriate and consider developing new international instruments if needed, since there is limited knowledge and practice of geoengineering. State officials said this approach would enable greater rigor and flexibility than trying to address all geoengineering activities within a single comprehensive agreement. They cited the London Convention and London Protocol as examples. While these agreements might not have addressed ocean fertilization several years ago, the parties took action when ocean fertilization reached a state of development where an agreed approach to regulation was considered necessary, and the agreements now unquestionably address it. In contrast, State officials said that parties to

[52]In commenting on this report, a NOAA official noted that it would be important to have a coordinated strategy for addressing international oversight and regulation of geoengineering. For more information on agency comments, see the Agency Comments and Our Evaluation section of this report.

other agreements have not addressed other geoengineering approaches because they have not reached a similar stage of development. State officials said it was hard to imagine a single agreement appropriately covering geoengineering activities with all potential transboundary effects. State officials also said that while some countries have called for a broader inquiry into marine geoengineering more generally under the London Convention and the London Protocol, the parties deemed those calls premature at best.

Legal experts and EPA officials we interviewed generally agreed that the federal government should take a coordinated, interagency approach to domestic geoengineering regulation. For example, the legal experts who spoke about domestic regulation generally agreed that the federal government should play a role in governing geoengineering research—either by developing research norms and guidelines or applying existing regulations and guidelines. One expert noted that it was important that regulators stay abreast of research on the most mature technologies so that the regulatory framework would be in place prior to field experiments. Some experts and EPA officials also agreed that because there is a wide variety of geoengineering activities, research and regulation would fall under multiple agencies' purview and expertise. For example, one expert said that there should be a coordinated interagency effort led by OSTP or USGCRP. Another said that the federal government should focus on a comprehensive policy for climate change, including geoengineering, and that that policy would determine what new regulations would be necessary to guide and govern research. EPA and State officials both said that agencies such as NOAA, NASA, and DOE should be involved in regulatory discussions due to their jurisdictional or scientific expertise. As an example, EPA officials noted that the Interagency Task Force on Carbon Capture and Storage, co-chaired by DOE and EPA, was created to propose a plan to overcome the barriers to widespread deployment of these technologies, which include geologic sequestration. The plan addresses, among other issues, how to coordinate existing administrative authorities and programs, legal barriers to deployment, and identifies areas where additional statutory authority may be necessary.

Legal experts we interviewed generally agreed that governance for geoengineering research should be addressed separately from governance for deployment of geoengineering approaches. For example, experts said that discussions of governance of deployment were premature, and one expert cautioned that discussing deployment could raise the level of controversy surrounding the subject, leading to a general gridlock that could disrupt discussions about research and lower interest in a coordinated and transparent approach. Both State and EPA officials cited the need for further research into geoengineering prior to engaging in discussions of domestic regulation or a governance framework at the international level. State officials said that, in practice, the United States and other countries have already effectively separated geoengineering research and deployment governance for ocean fertilization under the London Convention and London Protocol, because the parties decided that any ocean fertilization activities other than those for legitimate scientific research should not be allowed at this time.

However, the legal experts we spoke with also agreed that some type of regulation of geoengineering field research was necessary in the near future, particularly for those approaches where large-scale experiments could have transboundary impacts. According to these experts, any framework governing research should include several elements, such as transparency, coordination, flexibility, a review process for experiments, the use of environmental risk thresholds, and an emphasis on modeling prior to field studies. A few legal experts said that these elements could start as voluntary norms and guidelines within the research community and then evolve into formal regulations prior to field trials. As one expert said, transparent decision-making and guidelines are necessary to ensure that research does not pose unacceptable risk to the environment. State officials said that, generally, the United States supports careful consideration of research implications rather than a full ban on research. In addition, they said that some geoengineering research could be fostered most effectively through international cooperation and coordination rather than governance, or that domestic regulation is more appropriate than international regulation.

Legal experts and EPA and State officials cited other challenges related to geoengineering governance, particularly for those approaches with uneven or unintended environmental effects. For example, some legal experts said that controversy surrounding certain geoengineering approaches, as well as a lack of understanding and acceptance, could make domestic and international governance difficult. In addition, State officials said that if large-scale experiments or activities have unknown consequences or effects borne by nations other than the nation conducting the experiment or activity, this could risk undermining existing agreements on climate change strategies. Furthermore, legal experts and EPA officials agreed that liability for unintended consequences was an important issue that would need to be addressed. Specifically, one expert suggested that there should be a mechanism to compensate individuals or nations for damages resulting from geoengineering activities. Moreover, some legal experts were concerned about the ability of parties to enforce certain international agreements related to geoengineering.

Conclusions

Major scientific bodies such as the NRC and Royal Society have identified geoengineering as one of several potential tools to limit the impact and consequences of climate change. However, these bodies have stated that geoengineering is a potential complement to, rather than a substitute for, sharp reductions in greenhouse gas emissions. While the NRC and Royal Society have identified geoengineering as a potential tool, what role geoengineering might play in a domestic and international response strategy will likely be shaped by resolving unanswered scientific questions surrounding the technical feasibility, unintended consequences, effectiveness, cost, and risks associated with each approach. Answers to these questions will also inform the public debate concerning whether geoengineering is an acceptable response given the ethical and social implications of deliberate interventions in the earth's climate system. The federal government is already engaging in research that could help address some of the uncertainties surrounding geoengineering and inform policy decisions about research priorities. While agencies identified about $100.9 million in research funding relevant to geoengineering in fiscal years 2009 and 2010, federal officials also said that a substantial portion of the existing federal climate change and earth science research could be relevant to understanding geoengineering—roughly $2 billion in requested budget authority for 2010 alone. However, because there is no coordinated federal geoengineering strategy, it is difficult to determine the extent of relevant research. At present, while some agencies are sharing information on two geoengineering approaches to inform negotiations relevant to international regulation of ocean dumping and address barriers to geological sequestration as a mitigation strategy, agencies generally are not collecting and sharing information more broadly on research relevant to other geoengineering approaches. Without a definition of geoengineering for agencies to use, and without coordination among agencies to identify the full extent of available research efforts relevant to geoengineering as well as to identify research priorities, policymakers and agency officials may lack sufficient information to leverage existing research resources to their full benefit. In turn, this lack of information may hinder policy decisions and governance at the domestic and international level. Even if policymakers decide that geoengineering should not be pursued domestically, knowledge of geoengineering approaches and their potential effects will be essential to inform international negotiations regarding other countries' consideration of, or actions related to, geoengineering research and deployment.

Recommendation

GAO recommends that the appropriate entities within the Executive Office of the President (EOP), such as the Office of Science and Technology Policy (OSTP), in consultation with relevant federal agencies, develop a clear, defined, and coordinated approach to geoengineering research in the context of a federal strategy to address climate change that (1) defines geoengineering for federal agencies; (2) leverages existing resources by having federal agencies collect information and coordinate federal research related to geoengineering in a transparent manner; and if the administration decides to establish a formal geoengineering research program, (3) sets clear research priorities to inform decision-making and future governance efforts.

Agency Comments and Our Evaluation

We provided a draft of this report to the Office of Science and Technology Policy (OSTP) within the Executive Office of the President (EOP) for review and comment. OSTP also circulated the report to the 13 participating USGCRP agencies. In response to the draft, OSTP, the Council on Environmental Quality, U.S. Department of Agriculture (USDA), Department of State (State), National Oceanic and Atmospheric Administration (NOAA), and National Science Foundation (NSF) neither agreed nor disagreed with our findings and recommendation; rather, they provided technical and other comments, which we incorporated as appropriate. General comments and our response are summarized below.

In their comments, USDA, NSF, and OSTP raised various concerns about how geoengineering should be defined. For example, OSTP and USDA cited concerns that the definition used in this report is too broad because it overlaps with certain land-based practices, such as biological sequestration of CO_2 in forests, that are considered to be emissions reduction practices—also referred to as mitigation. In particular, USDA commented that applying such a broad definition to USDA's portfolio of research would lead to a great deal of confusion. In contrast, NSF raised concerns that the definition used in the report was not broad enough, and should include techniques that reduce CO_2 emissions. For the purposes of this report, we used the Royal Society study's definition and descriptions of geoengineering approaches because this study was the most comprehensive review of geoengineering science available at the time of our request. Other scientific organizations, such as the National Research Council (NRC), the American Meteorological Society, and the American

Geophysical Union have also either reported on or issued position statements regarding geoengineering, and used a similarly broad definition. However, as we note in the report, discussions about how to define geoengineering and what activities should be considered geoengineering remain active. Variations in agencies' interpretation of our data request, as well as the comments noted above, support our recommendation that additional clarity and guidance regarding the federal approach to geoengineering is needed, and that further discussion of what types of activities should be included in a federal operational definition of geoengineering may be warranted. Accordingly, we recommended that the appropriate entities within the EOP consult with the relevant federal agencies to develop a clear, defined, and coordinated approach to geoengineering research in the context of a federal strategy to address climate change.

Additionally, NOAA and NSF noted that because the global nature of climate change requires an international response, international coordination and collaboration would be important for geoengineering activities and oversight efforts. As we noted in our report, the applicability of international agreements to geoengineering remains unclear; however, parties to three agreements have issued decisions regarding the agreements' applicability to ocean fertilization and sub-seabed geological sequestration. Furthermore, the legal experts we spoke with generally agreed that some type of regulation of geoengineering field research is necessary in the near future, particularly for those approaches where large-scale experiments could have transboundary impacts. According to these experts, any framework governing research should include several elements, such as transparency, coordination, flexibility, a review process for experiments, the use of environmental risk thresholds, and an emphasis on modeling prior to field studies.

NOAA emphasized the importance of fully understanding unintended consequences and risks associated with geoengineering approaches. In particular, NOAA commented that sufficient resources should be directed specifically towards identifying possible unintended consequences and risks. As we note in the report, relevant studies indicate that there are additional environmental risks and trade-offs associated with both CDR and SRM approaches. Furthermore, our discussions with experts and review of relevant studies identified unintended consequences associated with geoengineering approaches as a key uncertainty requiring further study.

In addition to these comments, CEQ, OSTP, and the agencies provided technical changes and corrections which we incorporated where appropriate.

As agreed with your office, unless you publicly announce the contents of this report earlier, we plan no further distribution until 30 days from the report date. At that time, we will send copies of this report to the appropriate congressional committees, the Office of Science and Technology Policy within the Executive Office of the President, and other interested parties. In addition, the report will be available at no charge on GAO's Web site at http://www.gao.gov.

If you or your staff members have any questions about this report, please contact Frank Rusco at (202) 512-3841 or ruscof@gao.gov, or John Stephenson at (202) 512-3841 or stephensonj@gao.gov. Contact points for our Offices of Congressional Relations and Public Affairs may be found on the last page of this report. GAO staff who made key contributions to this report are listed in Appendix V.

Sincerely yours,

Frank Rusco
Director, Natural Resources and Environment

John B. Stephenson
Director, Natural Resources and Environment

Appendix I: Scope and Methodology

This report examines (1) the general state of the science regarding geoengineering approaches and their potential effects; (2) the extent to which the federal government is sponsoring or participating in geoengineering research or deployment; and (3) the views of legal experts and federal officials about the extent to which federal laws and international agreements apply to geoengineering activities, and associated challenges, if any, to geoengineering governance.

To determine the general state of the science regarding geoengineering approaches and their potential effects, we summarized the results of semi-structured interviews with scientific and policy experts as well as the findings from relevant literature. First, we identified 95 potential experts based on five criteria indicating recognition from their peers as geoengineering experts. These criteria included having (1) presented at the Asilomar International Conference on Climate Intervention Technologies, (2) presented at the geoengineering panels held at the American Association for the Advancement of Science 2010 Annual Meeting, (3) served as a witness at one of the three hearings on geoengineering held by the House Science and Technology Committee, (4) recommendations from other recognized experts that we had interviewed during our work for the March testimony for the committee,[1] and (5) participating in smaller panels or working groups that specifically focused on geoengineering. To identify the most active experts in the field, we scored the experts from the initial list based on their participation in the five previously noted activities. Based on this process, we selected the 10 highest-scoring experts and contacted them for interviews. We selected 10 experts to ensure we could collect a range of views from experts associated with academia, nongovernmental organizations, and government. To assess potential conflicts of interest, we asked the 10 experts to submit a conflict of interest form. These forms included questions about potential financial or other interests that might bias an expert's opinions related to the state of geoengineering science. We conducted a content analysis to summarize expert responses and grouped responses into overall themes. The views expressed by experts do not necessarily represent the views of GAO. Not all of the experts provided their views on all issues. In addition to gathering expert views, we selected and reviewed collaborative peer-reviewed studies that addressed geoengineering, such as the National Research Council's *Advancing the Science of Climate Change* study as well as the Royal Society's study

[1] GAO-10-546T

Geoengineering and the climate: Science, governance and uncertainty.[2] To corroborate the factual information provided to us by our experts, we utilized these collaborative reports as well as select articles from peer-reviewed journals to support specific key details from the interviews.

To determine the extent to which the federal government is sponsoring or participating in geoengineering research or deployment, we obtained and analyzed data on relevant activities from the 13 agencies participating in the U.S. Global Change Research Program (USGCRP) through July 2010.[3] We selected these agencies because the USGCRP is the interagency entity that coordinates and integrates federal research on global environmental changes, such as climate change, and their implications for society. To help officials identify relevant activities, we provided them with a data collection instrument that defined geoengineering and described proposed geoengineering approaches, based on the Royal Society study (see appendix III). We used the Royal Society study definition and descriptions because it was the most comprehensive review of geoengineering science available at the time of our request. The data collection instrument also included some examples of potentially relevant activities based on our work for the March testimony for the committee. We then asked officials to identify federal activities during fiscal years 2009 and 2010 that were relevant to the definition and description we provided. Because the federal government does not have a formal policy on geoengineering that defines what activities constitute geoengineering or asks agencies to track this information, we relied on agency officials' professional judgment to identify relevant activities. As part of their response, we requested information that included a description of the activity, the dates of the work, whether it was a grant or conducted within a government lab, and funds obligated. We analyzed the responses and removed 12 activities that did not appear related to geoengineering based on the definition we

[2]The Royal Society is the United Kingdom's national academy of sciences.

[3]USGCRP-participating agencies are the Departments of Agriculture (USDA), Commerce, Defense (DOD), Energy (DOE), Interior, Health and Human Services, State, and Transportation; and the U.S. Agency for International Development, the Environmental Protection Agency (EPA), the National Aeronautics and Space Administration (NASA), the National Science Foundation (NSF), and the Smithsonian Institution.

provided.[4] We then categorized the remaining activities into three broad types: (1) activities related to conventional carbon mitigation efforts that are directly applicable to a proposed geoengineering approach, although not designated as such; (2) activities related to improving basic scientific understanding of earth systems, processes, or technologies that could be applied generally to geoengineering; and (3) activities designed specifically to address a proposed geoengineering approach that does not overlap with a conventional carbon mitigation strategy. We sent the results of our analysis and categorization of agency-reported activities to each agency for their review and verification in July 2010. Specifically, we asked agency officials to ensure that the data were complete and accurate, and that our categorization of the data was appropriate. Each agency verified our analysis. In addition, we met with officials and staff from interagency bodies coordinating federal responses to climate change, including the Office of Science and Technology Policy (OSTP), Council on Environmental Quality (CEQ), and USGCRP, as well as the Department of Energy (DOE), which coordinates the Climate Change Technology Program—a multiagency research and development program for climate change technology. We assessed the reliability of the data and found the data to be sufficiently reliable for the purposes of this report.

To determine the views of legal experts and federal officials about the extent to which federal laws and international agreements apply to geoengineering activities and identify governance challenges, if any, we summarized the results of our interviews with experts and federal officials as well as the findings from relevant literature. First, we identified 23 potential experts based on three criteria indicating recognition from their peers as legal experts knowledgeable about geoengineering. These criteria included having (1) participated in panels or working groups that specifically focused on geoengineering, (2) recommendations from other experts that we had interviewed during our work for the March testimony for the committee, and (3) published one or more articles related to geoengineering. To identify the most active experts in the field, we scored

[4]These 12 activities were (1) investigating green roof behavior in dense urban environments, (2) developing membrane technology for hydrogen purification, (3) converting municipal solid wastes to liquid fuel, (4) developing technology for generating hydrocarbon fuels using solar energy and CO_2, (5) water desalinization project using solar energy, (6) internationally collaborating with China to foster emissions mitigation research, (7) developing technology to facilitate the conversion of methane gas to liquid fuel, and five activities to develop technologies related to biofuels. Based on their description, we determined that these 12 activities did not appear relevant to identified CDR or SRM approaches.

each expert from the initial list based on the three criteria noted above. Based on this process, we selected the 8 highest scoring experts and contacted them for interviews. We selected 8 experts because the scoring process created a natural break between the 8 highest scoring experts and the remaining experts. To assess potential conflicts of interest, we asked each expert to submit a conflict of interest form. These forms included questions about potential financial or other interests that might bias an expert's opinions related to the applicability of federal laws and international agreements to geoengineering. We conducted a content analysis to summarize expert responses and grouped responses into overall themes. The views expressed by experts do not necessarily represent the views of GAO. Not all of the experts provided their views on all issues. We also met with federal officials from the Environmental Protection Agency (EPA) and the Department of State (State) to collect their views on the applicability of domestic laws and international agreements to geoengineering, and governance challenges, if any. In addition to gathering experts' and federal officials' views, we selected and reviewed collaborative reports that addressed geoengineering governance, such as the Royal Society's study *Geoengineering and the climate: Science, governance and uncertainty*, and the United Kingdom House of Commons Science and Technology Committee report *The Regulation of Geoengineering*, among others.[5] To corroborate the legal information provided to us by our experts, we utilized these collaborative reports as well as select articles from relevant journals to support specific key details from the interviews.

We conducted this performance audit from December 2009 through September 2010 in accordance with generally accepted government auditing standards. Those standards require that we plan and perform the audit to obtain sufficient, appropriate evidence to provide a reasonable basis for our findings and conclusions based on our audit objectives. We believe that the evidence obtained provides a reasonable basis for our findings and conclusions based on our audit objectives.

[5]House of Commons Science and Technology Committee, *The Regulation of Geoengineering: Fifth Report of Session 2009-10* (London, United Kingdom, Mar. 18, 2010).

Appendix II: Geoengineering Experts Selected for This Review

We identified and selected scientific and policy experts to provide their views on the general state of the science regarding geoengineering approaches and their potential effects. We also identified and selected legal experts to provide their views on the applicability of federal laws and international agreements to geoengineering, and associated challenges, if any, to geoengineering governance. This appendix lists the experts we selected and contacted for interviews. In two cases, experts we contacted did not participate in our review, either due to schedule conflicts or because they did not respond to our request.

Scientific and Policy Experts

Scott Barrett, Columbia University
Ken Caldeira, Carnegie Institution of Washington
James Fleming, Colby College
Michael MacCracken, Climate Institute
Philip Rasch, Pacific Northwest National Laboratory, Department of Energy
Alan Robock, Rutgers University
John Shepherd, University of Southampton, United Kingdom (did not participate)
David Keith, University of Calgary, Canada
M. Granger Morgan, Carnegie Mellon University
Margaret Leinen, Climate Response Fund

Legal Experts

Daniel Bodansky, Arizona State University
Dale Jamieson, New York University
Edward (Ted) Parson, University of Michigan (did not participate)
David Victor, University of California-San Diego
Catherine Redgwell, University College London, United Kingdom
Albert Lin, University of California-Davis
David Freestone, George Washington University
Stephen Seidel, Pew Center on Global Climate Change

Appendix III: Geoengineering Description Provided To USGCRP Agencies

To help federal officials identify relevant activities, we provided them with a data collection instrument that defined geoengineering and described proposed geoengineering approaches, as outlined below. The definition and descriptions were based on the Royal Society study—which was the most authoritative review of geoengineering at the time of our data request. This appendix reflects the language and more technical descriptions we provided to the agencies and, as such, will not be an exact match to the more generalized language used to describe these approaches in the background section of this report. We have provided additional explanations of some scientific terms in footnotes to the text. These footnotes were not part of the data collection instrument sent to the agencies.

Definition of Geoengineering

Deliberate, large-scale interventions in the earth's climate system to diminish climate change or its impacts

Description of Geoengineering Approaches

Carbon dioxide removal approaches:

1. Biological carbon removal / sequestration—enhancing the natural abilities of the earth's biological systems to capture and sequester carbon

   Land-based examples:

   - Large-scale afforestation / reforestation / land-use changes to maximize carbon sequestration in soil or biomass
   - Biomass energy with carbon dioxide (CO_2) capture and sequestration (BECS)
   - Biomass sequestration and burial / biochar

   Ocean-based examples:

   - Ocean fertilization with limiting nutrients, such as iron, to stimulate phytoplankton growth and increase CO_2 removal from the atmosphere
   - Enhancing upwelling of nutrient-rich deep sea water to the surface to stimulate phytoplankton growth

2. Physical carbon removal / sequestration—physically enhancing the natural abilities of the earth's systems to capture and sequester carbon

   Land-based examples:

   - Capture of CO_2 from ambient air (air capture) via industrial atmospheric CO_2 scrubber devices and either using the captured CO_2 or sequestering it in underground formations (Note: Although we are excluding funding for "carbon capture and storage" research and projects from this data call since it is an emissions reduction rather than geoengineering strategy, we are interested in capturing federal dollars directed towards research of the storage of CO_2 in underground formations, because it is an important component of this particular geoengineering approach.)

   Ocean-based examples:

   - Altering ocean overturning circulation patterns to increase the rate that atmospheric CO_2 is transferred to the deep sea

3. Chemical carbon removal / sequestration—chemically enhancing the natural abilities of the earth's systems to capture and sequester carbon

   Land-based examples:

   - Enhanced weathering of carbonate or silicate rocks to accelerate the absorption of CO_2 on the earth's surface or underground

   - Accelerating carbon sequestration in soils by spreading ground silicate minerals on fields

   - Pumping reactant CO_2 gas into underground olivine and basalt formations to form carbonates in-situ

   Ocean-based examples:

   - Enhancing the alkalinity of the ocean by grinding, dispersing, and dissolving limestone, silicates, or calcium hydroxide

Solar radiation management approaches:

1. Increasing planet surface albedo[1]—increasing the albedo of the planet by making the surface of the planet more reflective

   Examples:

   - Brightening buildings and painting roofs white
   - Planting lands with more reflective vegetation or engineering more reflective variants of existing vegetation
   - Increasing reflectivity of desert regions
   - Increasing reflectivity of oceanic regions

2. Cloud albedo enhancement—increasing the planetary albedo by producing additional cloud cover and thickening clouds over oceanic regions

   Example:

   - Brightening marine clouds by spraying seawater to increase the number of cloud condensation nuclei[2] available

3. Stratospheric aerosol injection—increasing the albedo of the planet by injecting reflective aerosol particles into the atmosphere

   Examples:

   - Injecting sulfate aerosols into the stratosphere to reflect incoming solar radiation

[1]Albedo is the fraction of solar radiation reflected by a surface or object, often expressed as a percentage. Snow-covered surfaces have a high albedo, the surface albedo of soils ranges from high to low, and vegetation-covered surfaces and oceans have a low albedo. The earth's planetary albedo varies mainly through varying cloudiness, snow, ice, leaf area, and land cover changes.

[2]Cloud condensation nuclei are small particles in the air that become surfaces on which water vapor can condense and form cloud droplets. Sources of cloud condensation nuclei can be both natural and human-caused. Natural sources of cloud condensation nuclei include volcanic dust, sea spray salt, and bacteria. Humans also release unnatural chemicals into the air from the burning of fossil fuels and from industrial sources.

- Injecting other reflective aerosols into the stratosphere to reflect incoming solar radiation

4. Space-based techniques for reducing incoming solar radiation—reducing the amount of solar radiation that reaches the planet or adjusting the nature of that radiation to a type that is less likely to be absorbed by the earth's climate system

   Examples:

   - Placing a large refracting lens at the L1 orbit position[3]

   - Launching trillions of small reflecting disks into near-earth orbit

Other greenhouse gas removal approaches:

5. Techniques to remove other greenhouse gases such as methane, nitrous oxide, chlorofluorocarbons, or others from the atmosphere

[3]The L1 orbit position is the point between the earth and sun where the gravitational attractions of the two bodies are equal.

Appendix IV: Data from USGCRP Agencies on Geoengineering-Related Activities

In response to our data collection instrument, the 13 agencies participating in the USGCRP reported the following research activities relevant to geoengineering. Our request was limited to activities funded during fiscal years 2009 and 2010; however, in some cases, reported activities were initiated prior to fiscal year 2009 and continued beyond fiscal year 2010, as noted in the "Dates of research" column in tables 5, 6, and 7. To be consistent with the tables in the report, the activities are organized by agency and geoengineering approach. According to agency officials, none of the activities listed below received funding in the American Recovery and Reinvestment Act of 2009.[1] The Departments of Health and Human Services and State, as well as the U.S. Agency for International Development, the National Aeronautics and Space Administration, and the Smithsonian Institution, all reported no relevant activities during fiscal years 2009 and 2010.

Table 5: Reported Mitigation-Related Research Relevant to Geoengineering, by USGCRP Agency and Related Geoengineering Approach, Fiscal Years 2009 and 2010

(In dollars)

Department/ Agency	Activity description	Dates of research	Type of research (grant or in-house)[a]	Sponsoring federal program or laboratory	Reported funding[b]	Fiscal year	Related geoengineering approach
Department of Agriculture (USDA)	Research to quantify the effects of amending soils with biochar on crop productivity, soil quality, carbon sequestration, and water quality	2008-2011	Nonfunded cooperative agreement	Agricultural Research Service	$2,800,000	2010	CDR - biological carbon removal/ sequestration
	Research to evaluate soil carbon sequestration in existing and alternative agricultural systems	2007-2010	In-house	Agricultural Research Service	11,100,000	2010	CDR - biological carbon removal/ sequestration
Department of Energy (DOE)	Study investigating large-scale biological removal/ sequestration of carbon dioxide	2009-2010	In-house	Oak Ridge National Laboratory	350,000	2010	CDR - biological carbon removal/ sequestration

[1]Pub. L. No. 111-5 (2009).

Department/ Agency	Activity description	Dates of research	Type of research (grant or in-house)[a]	Sponsoring federal program or laboratory	Reported funding[b]	Fiscal year	Related geoengineering approach
DOE	Research to identify, understand, and predict the fundamental physical, chemical, biological, and genetic processes controlling carbon sequestration in terrestrial ecosystems	2000-present	Mixed — grant and national laboratories	Office of Science (Biological and Environmental Research)	4,728,000	2010	CDR - biological carbon removal/ sequestration
	Advanced carbon sequestration systems	2009	In-house	Savannah River National Laboratory	50,000	2009	CDR - physical carbon removal/ sequestration
	Regional Partnership Program activities related to geological sequestration of carbon dioxide	2010	Grant	Work performed by Savannah River National Laboratory on behalf of the Office of Fossil Energy	139,000	2010	CDR - physical carbon removal/ sequestration
	Regional Partnership Program activities related to geological sequestration of carbon dioxide	2009-2010	In-house	Los Alamos National Laboratory	770,000	2009	CDR - physical carbon removal/ sequestration
	Measurement and detection of carbon dioxide at geological sequestration sites	2008-2010	In-house	Los Alamos National Laboratory	900,000	2009	CDR - physical carbon removal/ sequestration
					900,000	2010	
	Modeling of geological sequestration of carbon dioxide	2008-2010	In-house	Los Alamos National Laboratory	2,000,000	2009	CDR - physical carbon removal/ sequestration
					2,000,000	2010	

Department/ Agency	Activity description	Dates of research	Type of research (grant or in-house)[a]	Sponsoring federal program or laboratory	Reported funding[b]	Fiscal year	Related geoengineering approach
Department of the Interior	An assessment to compare existing biological sequestration resources to estimates of hypothetical biological sequestration in potential or historical vegetation and soils	2010	In-house	U.S. Geological Survey Office of Global Change Programs	290,000	2010	CDR - biological carbon removal/ sequestration
	A range of projects related to carbon dioxide balance, sequestration, and fluxes in soils and ecosystems, including mechanistic understanding, regionalization of site data, and modeling	2009-2012	In-house	U.S. Geological Survey Office of Global Change Programs	2,362,408	2010	CDR - biological carbon removal/ sequestration
	Methodology development for a national assessment of biological sequestration resources that remove and store carbon dioxide in vegetation, soils, and sediments	2009-2012	In-house	U.S. Geological Survey Office of Global Change Programs	5,000,000	2010	CDR - biological carbon removal/ sequestration
	Development of best management practices for geologic sequestration of carbon dioxide in sub-seabed formations	2010-2013	Broad agency announcement	Bureau of Ocean Energy Management, Regulation, and Enforcement	250,000 - 500,000	2010	CDR - physical carbon removal/ sequestration

Department/ Agency	Activity description	Dates of research	Type of research (grant or in-house)[a]	Sponsoring federal program or laboratory	Reported funding[b]	Fiscal year	Related geoengineering approach
Interior	Methodology development for a national assessment of geological sequestration resources for storage of carbon dioxide in oil and gas reservoirs and saline formations	2009-2012	In-house	U.S. Geological Survey Office of Global Change Programs	5,000,000	2010	CDR - physical carbon removal/ sequestration
Department of Transportation	Pilot program to determine economic and policy implications of biological carbon sequestration (carbon offsets) in highway right-of-way	2008-2011	In-house	Federal Highway Administration	150,000	2009	CDR - biological carbon removal/ sequestration
					100,000	2010	
Environmental Protection Agency (EPA)	Research, in coordination with USDA and other land management agencies, to address the environmental effects of biological sequestration (carbon offsets)	2009-2011	In-house	Office of Research and Development	300,000[c]	2010	CDR - biological carbon removal/ sequestration
	Research to understand how various carbon dioxide capture technologies could impact pollution control systems and their effluent streams, which could improve understanding of how contaminants present could adversely impact transport, injection, and long-term storage of carbon dioxide	2010-2011	In-house	Office of Research and Development	500,000[c]	2010	CDR - physical carbon removal/ sequestration

Department/ Agency	Activity description	Dates of research	Type of research (grant or in-house)[a]	Sponsoring federal program or laboratory	Reported funding[b]	Fiscal year	Related geoengineering approach
EPA	Research to assess the risks of underground injection of carbon dioxide	2009-2011	In-house	Office of Research and Development	1,900,000[c]	2009	CDR - physical carbon removal/ sequestration
					2,900,000[c]	2010	
	Grants to research the design, modeling, and monitoring of the geological sequestration of carbon dioxide to safeguard sources of drinking water	2009-2011	Grant	Office of Research and Development	4,700,000[c]	2009	CDR - physical carbon removal/ sequestration
					1,000,000[c]	2010	
National Science Foundation (NSF)	Ten year regional field experiment to improve understanding of biological sequestration of carbon dioxide in northern hemisphere forests; the research will quantify the amounts of carbon stored in overstory trees, forest floor, and soil over the next decade	2008-2012	Grant (only 2 of 5 years funding shown)	Division of Environmental Biology	71,385	2009	CDR - biological carbon removal/ sequestration
					70,790	2010	
	Research to determine whether waste materials that contain significant amounts of alkaline minerals can safely and permanently store carbon dioxide via the carbonation process	2009	Grant	Directorate of Engineering	33,793	2009	CDR - chemical carbon removal/ sequestration

Department/ Agency	Activity description	Dates of research	Type of research (grant or in-house)[a]	Sponsoring federal program or laboratory	Reported funding[b]	Fiscal year	Related geoengineering approach
NSF	Research to develop safe and permanent sequestration of carbon dioxide using techniques that mimic natural rock weathering processes, such as carbonation	2009-2011	Grant	Directorate of Engineering	300,033	2009	CDR - chemical carbon removal/ sequestration
	Research to evolve an economically viable coal and biomass fed energy plant that generates electricity while capturing a significant portion of carbon dioxide and coproduces hydrogen for future fuel cell applications	2009-2010	Grant	Directorate of Engineering	99,738	2009	CDR - physical carbon removal/ sequestration
					99,647	2010	
	Numerical investigation into aquifer carbon sequestration efficiency and potential leakage subsequent to injection of carbon dioxide	2009-2010	Grant	Directorate of Geosciences	262,416	2009	CDR - physical carbon removal/ sequestration
	Modeling project to evaluate the long-term sequestration of carbon dioxide in saline aquifers	2008-2011	Grant	Directorate of Mathematical and Physical Sciences	350,000	2009	CDR - physical carbon removal/ sequestration
	Research into methods to enhance geological sequestration of carbon dioxide using hydrofracturing techniques	2010-2012	Grant (pending)	Directorate of Geosciences	374,600	2010	CDR - physical carbon removal/ sequestration

Department/ Agency	Activity description	Dates of research	Type of research (grant or in-house)[a]	Sponsoring federal program or laboratory	Reported funding[b]	Fiscal year	Related geoengineering approach
NSF	Demonstration project of a novel low cost and low energy-consuming capture technology to remove carbon dioxide from flue gas of post-combustion coal-fired power plants	2009-2010	Grant	Directorate of Engineering	499,998	2009	CDR - physical carbon removal/ sequestration
	Project to develop a deep underground laboratory for carbon dioxide sequestration experimentation, as well as several modeling projects that are exploring issues such as the impacts of underground fluid injection and uncertainty in sequestration models	2009 - 2012	A set of collaborative grants and an interagency transfer	Directorate of Engineering	1,000,000[d]	2009	CDR - physical carbon removal/ sequestration
					1,000,000[d]	2010	

Source: GAO analysis of the agencies' responses to our data collection instrument, which provided a definition and description of geoengineering to officials. The data collection instrument also included some examples of potentially relevant activities based on our work for our March testimony on geoengineering.

Note: We collected data on agency activities through July 2010. Accordingly, additional activities relevant to geoengineering may receive funding during fiscal year 2010.

[a]For the purposes of this table, grant refers to an award provided to an external institution, and in-house refers to work performed by the reporting agency.

[b]Unless otherwise noted, reported funding represents dollars obligated to the activity for the noted fiscal years as reported by federal agencies.

[c]Reported funding represents enacted budget authority rather than obligations.

[d]For this project, NSF reported funded obligations of $2,000,000 during fiscal years 2009 and 2010, with approximately $1,000,000 obligated during each of these years.

Table 6: Reported Fundamental Scientific Research Activities Relevant to Geoengineering, by USGCRP Agency and Related Geoengineering Approach, Fiscal Years 2009 and 2010

(In dollars)

Department/ Agency	Activity description	Dates of research	Type of research (grant or in-house)[a]	Sponsoring federal program or laboratory	Reported funding[b]	Fiscal year	Related geoengineering approach
Department of Commerce (Commerce)	Subcontinental scale detection of contributions of biological emissions and sequestration of greenhouse gases on atmospheric composition	Global emphasis since 1968; North American focus 1990 - present	Long-term monitoring — mainly in-house; some grants	National Oceanic and Atmospheric Administration's (NOAA) Office of Atmospheric and Oceanic Research	$12,900,000	2009	CDR - biological carbon removal/ sequestration
					12,900,000	2010	
	Comprehensive Earth System Modeling to support research on the carbon cycle, climate system processes, and interfaces between atmospheric chemistry and climate	2000-present	In-house	NOAA's Geophysical Fluid Dynamics Laboratory	7,920,000	2009	CDR - general, SRM - general
					7,920,000	2010	
Department of Defense	Seed grant to study methods of removing methane and nitrous oxide greenhouse gases from the atmosphere using enzymes	2010	Grant	Defense Advanced Research Projects Agency	250,000	2010	Other greenhouse gas removal approaches
National Science Foundation (NSF)	Research to develop and commercialize a new catalyst to improve the process for removing tar from gasified biomass; this research will improve the efficiency and reduce cost associated with the production of energy, liquid fuels, or other chemicals from gasified biomass	2009-2011	Grant	Directorate of Engineering	508,000	2009	CDR - biological carbon removal/ sequestration

Department/ Agency	Activity description	Dates of research	Type of research (grant or in-house)[a]	Sponsoring federal program or laboratory	Reported funding[b]	Fiscal year	Related geoengineering approach
NSF	Research to examine a new porous material for use in separating carbon dioxide from mixtures with carbon monoxide and methane	2010	Grant	Directorate of Engineering	75,381	2010	CDR - physical carbon removal/ sequestration
	Research to design and synthesize next-generation multifunctional, porous materials for the separation of carbon dioxide and methane, among other applications	2009-2013	Grant (2 of 5 years funding shown)	Directorate of Engineering	79,626	2009	CDR - physical carbon removal/ sequestration
					75,723	2010	
	Research to improve gas separation membranes	2009-2013	Grant (2 of 5 years funding shown)	Directorate of Engineering	85,485	2009	CDR - physical carbon removal/ sequestration
					78,285	2010	
	Research to test methods to electrochemically reduce oxygen and atmospheric carbon dioxide to carbonate for various applications, including carbon sequestration	2010	Grant	Directorate of Engineering	97,721	2010	CDR - physical carbon removal/ sequestration
	Project to commercialize a new gas separation product that separates the components of air to increase its oxygen content for natural gas and carbon dioxide sequestration applications	2009	Grant	Directorate of Engineering	149,996	2009	CDR - physical carbon removal/ sequestration

Department/ Agency	Activity description	Dates of research	Type of research (grant or in-house)[a]	Sponsoring federal program or laboratory	Reported funding[b]	Fiscal year	Related geoengineering approach
NSF	A technology transfer project to test the feasibility of producing lightweight building materials from fly ash using water supersaturated with air and carbon dioxide, which will sequester carbon dioxide	2009	Grant	Directorate of Engineering	150,000	2009	CDR - physical carbon removal/ sequestration
	Research into methane and carbon dioxide hydrate systems to study in part, the potential for gas storage in artificial hydrate form	2009-2011	Grant (2 of 3 years funding shown)	Directorate of Engineering	204,120	2009	CDR - physical carbon removal/ sequestration
					50,000	2010	
	Research to design, fabricate, and test mixed matrix membranes for gas separations, including carbon dioxide, methane, nitrogen, and oxygen	2009-2011	Grant	Directorate of Engineering	299,999	2009	CDR - physical carbon removal/ sequestration
	Research into gas separation membranes for carbon dioxide and methane, for natural gas applications	2009-2010	Grant	Directorate of Engineering	330,000	2009	CDR - physical carbon removal/ sequestration
	Research to quantify different types of gas transport in materials made to separate gases, such as carbon dioxide, methane, and nitrogen	2009-2013	Grant	Directorate of Engineering	400,000	2009	CDR - physical carbon removal/ sequestration

Department/ Agency	Activity description	Dates of research	Type of research (grant or in-house)[a]	Sponsoring federal program or laboratory	Reported funding[b]	Fiscal year	Related geoengineering approach
NSF	Research into gas separation membranes for separating hydrocarbons from methane and hydrogen, for natural gas applications	2010	Grant	Directorate of Engineering	150,000	2010	Other greenhouse gas removal approaches

Source: GAO analysis of the agencies' responses to our data collection instrument, which provided a definition and description of geoengineering to officials. The data collection instrument also included some examples of potentially relevant activities based on our work for our March testimony on geoengineering.

Note: We collected data on agency activities through July 2010. Accordingly, additional activities relevant to geoengineering may receive funding during fiscal year 2010.

[a]For the purposes of this table, grant refers to an award provided to an external institution, and in-house refers to work performed by the reporting agency.

[b]Unless otherwise noted, reported funding represents dollars obligated to the activity for the noted fiscal years as reported by federal agencies.

Table 7: Reported Direct Geoengineering Research by USGCRP Agency and Related Geoengineering Approach, Fiscal Years 2009 and 2010

(In dollars)

Department/ Agency	Activity description	Dates of research	Type of research (grant or in-house)[a]	Sponsoring federal program or laboratory	Reported funding[b]	Fiscal year	Related geoengineering approach
Department of Commerce (Commerce)	Research examining the possible implications of aerosol-based geoengineering proposals for the peak power output of large solar-power-generating plants	2008-2009	In-house	NOAA's Earth System Research Laboratory, Chemical Sciences Division	$45,000	2009	SRM - stratospheric aerosol injection
	Research examining the possible climate implications (beyond temperature) of geoengineering proposals that limit incoming solar radiation	2008-2009	In-house	NOAA's Earth System Research Laboratory, Chemical Sciences Division	25,000	2009	SRM - multiple approaches
Department of Energy (DOE)	Contribution to American Physical Society's review of the status of technologies and concepts to physically remove carbon dioxide from the air (direct air capture)	2009-2010	Grant	Office of Policy, Climate Change Technology Program, and Office of Fossil Energy	50,000	2009	CDR - physical carbon removal/ sequestration
	Study to perform systems analysis and cost estimates for large-scale, direct, physical capture of carbon dioxide from the air (direct air capture)	2009	In-house	Lawrence Livermore National Laboratory	243,000	2009	CDR - physical carbon removal/ sequestration
	Study investigating the unintended consequences of climate change response strategies, including geoengineering	2009-2010	In-house	Sandia National Laboratory	100,000	2009	Multiple CDR and SRM approaches
					70,000	2010	

Department/ Agency	Activity description	Dates of research	Type of research (grant or in-house)[a]	Sponsoring federal program or laboratory	Reported funding[b]	Fiscal year	Related geoengineering approach
DOE	Modeling studies related to two types of SRM: cloud-brightening and stratospheric aerosol injection	2009-2010	Grant	Work performed by Pacific Northwest National Laboratory on behalf of University of Calgary, Canada	266,000	Total funding 2009 and 2010	SRM - cloud albedo enhancement, stratospheric aerosols
National Science Foundation (NSF)	Research examining the effect of iron to carbon ratios in food on marine copepods, which will shed light on potential environmental impacts of ocean iron fertilization	2010-2013	Grant	Directorate of Geosciences	473,904	2010	CDR - biological carbon removal/ sequestration
	Collaborative modeling research project studying the impacts of plausible scenarios of stratospheric aerosol injection and a space-based SRM method	2008-2011	Grant	Directorate of Geosciences	221,558	2009	SRM - stratospheric aerosol injection, space-based techniques
					183,265	2010	
	Research investigating the moral challenges of solar radiation management	2010-2011	Grant	Directorate of Social, Behavioral, and Economic Sciences	208,551	2010	SRM - multiple approaches

Source: GAO analysis of the agencies' responses to our data collection instrument, which provided a definition and description of geoengineering to officials. The data collection instrument also included some examples of potentially relevant activities based on our work for our March testimony on geoengineering.

Note: We collected data on agency activities through July 2010. Accordingly, additional activities relevant to geoengineering may receive funding during fiscal year 2010.

[a]For the purposes of this table, grant refers to an award provided to an external institution, and in-house refers to work performed by the reporting agency.

[b]Unless otherwise noted, reported funding represents dollars obligated to the activity for the noted fiscal years as reported by federal agencies.

Appendix V: GAO Contacts and Staff Acknowledgments

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