GAO REPORT RELEASE

Climate Engineering: Technical Status, Future Directions, and Potential Responses

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Wilson Center
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October 12, 2011
Washington, D.C.

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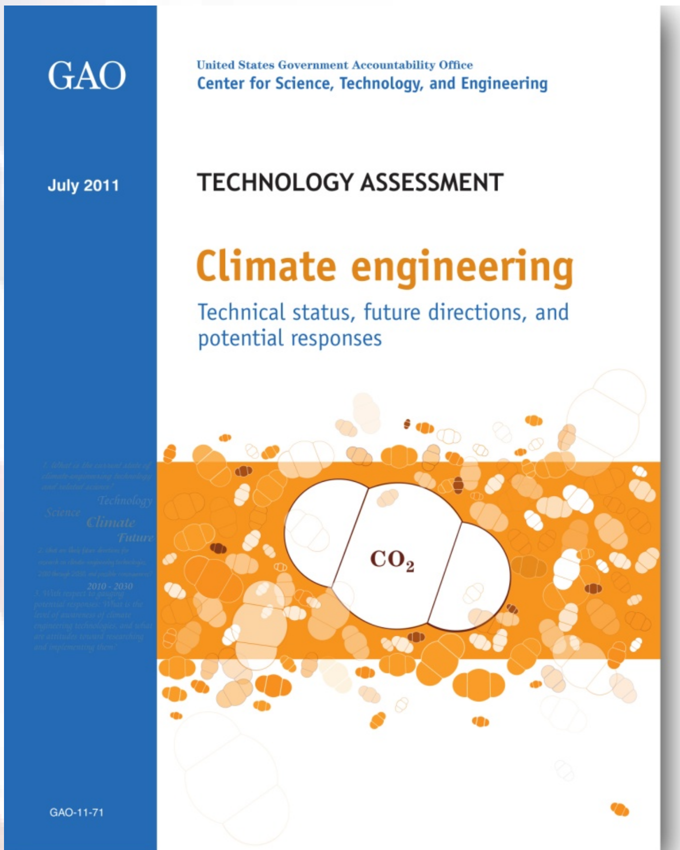
Ranking Member of the House Committee on Science, Space, and Technology Requests Technology Assessment of Climate Engineering



3 Major Areas of Examination

(1) Current state of climate engineering science and technology

(2) Experts' views of the future of U.S. climate engineering research

(3) Potential public responses to climate engineering

Complements Earlier GAO Study

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

(GAO-10-903 September 23, 2010)

Interactive Animation: Depiction of the Global Carbon Cycle Changes Over Time

Depiction of the Global Carbon Cycle Changes Over Time

Animation to GAO-11-71

Climate Engineering:

Technical Status, Future Directions, and Potential Responses

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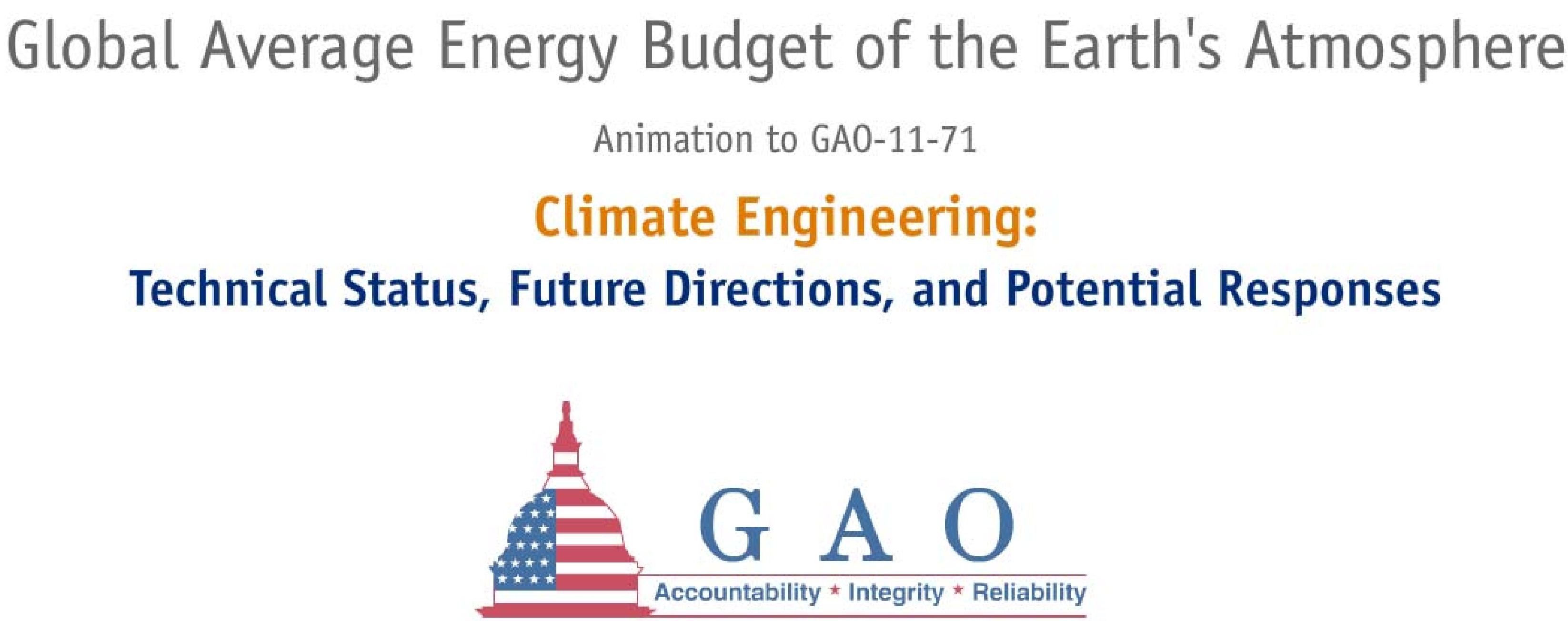
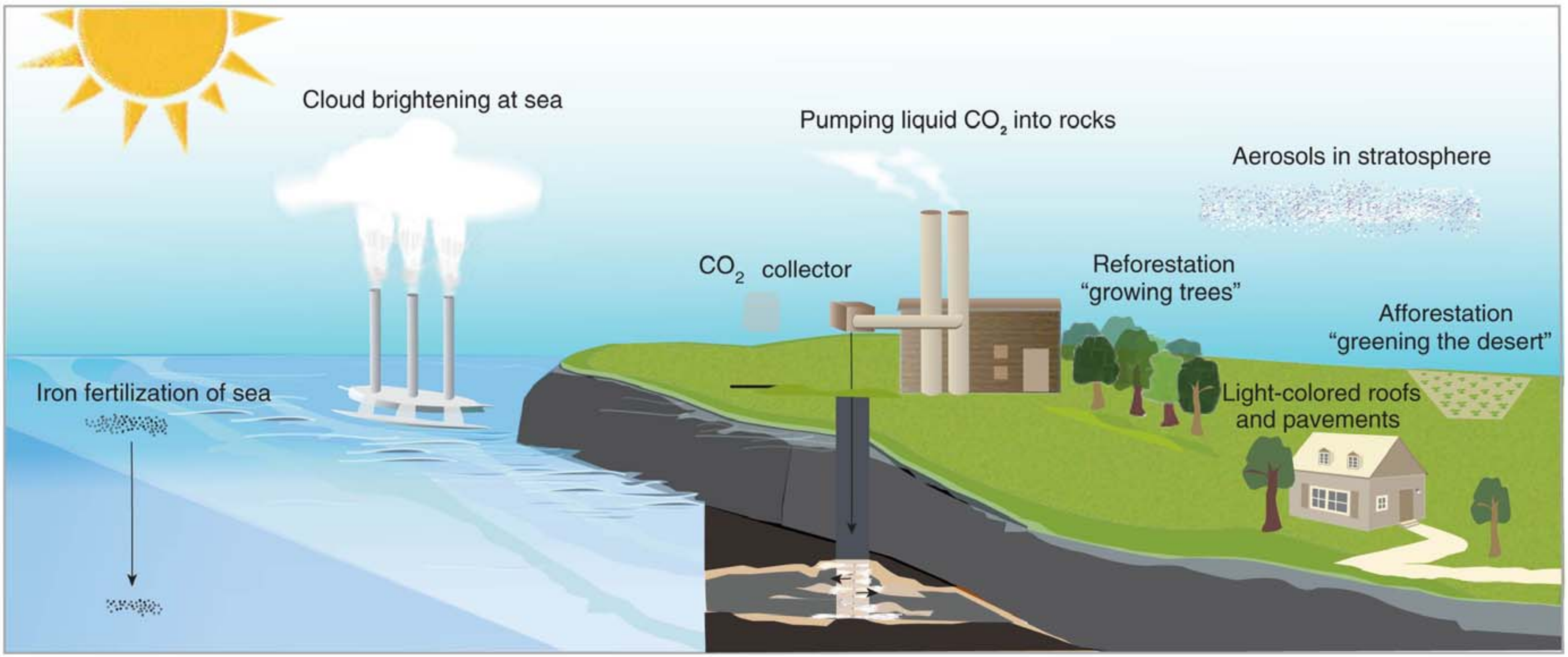
Interactive Animation: Global Average Energy Budget of Earth’s Atmosphere



Technology Assessment of Climate Engineering Research



Source: GAO.

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Technology Assessment Integrates Information Toward Anticipatory Governance

Technology Evaluation *(physical scientists, engineers, economists)*

Eliciting Views of the Future through Scenarios *(social scientists, foresight methodologists, economists, engineers)*

Assessment of Public Perceptions *(survey methodologists, social scientists)*

Climate Engineering: What GAO found

Emerging technologies, which include carbon dioxide removal (CDR) and solar radiation management (SRM)

- are not now viable options (currently immature; potential consequences)
- may be difficult to develop because of current gaps in climate data, models

Future directions—expert views

- advocates of conducting research immediately see urgency or express “insurance” view
- opponents cite major risks or say not needed
- advocates emphasize risk management in future research
- advocates also envision future federal effort with specific features

Potential responses

- public not currently familiar with climate engineering
- open to research but concerned about safety

Emerging Technologies: immature and challenged by current information gaps

- Currently not viable options
  - immature (on a “technology readiness scale” of 1-9, most rated at level 2)
  - effectiveness is uncertain, although some technologies are seen as “potentially fully effective” in countering anticipated warming
  - may face challenges re: effectiveness, cost factors, and potential consequence

- May be potentially difficult to develop because of current gaps in climate data, models

Technology	Maturity[a]	Potential effectiveness[b]	Cost factors[c]	Potential consequences[d]
Direct air capture of CO_2 with geologic sequestration	**Low (TRL 3):** • Basic principles understood and reported • System concept formulated • Experimental proof of concept demonstrated with a prototype unit in a laboratory environment • Models of CO_2 injection and transport developed and used for risk analysis and for simulating fate of injected CO_2 • Basic technological components not demonstrated as working together • No plans or prototypes for large-scale industrial implementation • Geological sequestration of CO_2 is more mature but not practiced on a scale to potentially affect climate	**Not rated:** • No "obvious limit" to the amount of CO_2 reduction by year 2100 • Could theoretically counter all global anthropogenic CO_2 emissions at 33 gigatons per year • Large energy penalty: net increase in CO_2 emissions if fossil fuel used (electricity from fossil fuels would release more CO_2 than an air capture unit would remove) • Uncertainty around technical scalability	• Viability may depend on nature and extent of a carbon market • Process energy requirements for currently inefficient technologies for directly separating CO_2 from air in very dilute concentration • Transportation and logistics for sequestration of captured CO_2 • Construction and management of geologic CO_2 sequestration sites (e.g., CO_2 injection, measuring, monitoring, and verification) • Greatly varied estimates in the scientific literature: $27 to $630 or more per ton of CO_2 removed (excluding transportation, sequestration, and other costs)	• Aspects associated with handling process materials or chemicals • May have sequestration risks such as potential for CO_2 to escape from underground storage in the event of reservoir fracture or fissure from built-up pressure

Table 3.1 Selected CDR technologies, continues on next page

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Technology	Maturity[a]	Potential effectiveness[b]	Cost factors[c]	Potential consequences[d]
Bioenergy with CO_2 capture and sequestration	**Low (TRL 2):** • Basic principles understood and reported • System concept formulated • No experimental demonstration of proof of concept (no laboratory scale experiments that indicate CO_2 reducing potential) • Emerging technology leverages what is known about CO_2 capture and geologic sequestration	**Low to medium:** • Maximum ability to reduce atmospheric CO_2: 50–150 ppm by 2100 • Net carbon negative under ideal conditions • Depends on plant productivity and land area cultivated	• Viability may depend on nature and extent of a carbon market • Value of land in other uses • Potentially large land area for growing and harvesting biomass • Type of biomass feedstock (e.g., switchgrass) • Process energy requirements for bioenergy production (e.g., pyrolysis) • Construction and management of geologic CO_2 sequestration sites (e.g., CO_2 injection, measuring, monitoring, and verification) • Transportation and logistics for sequestering captured CO_2 • Greatly varied estimates in the scientific literature: \$150–\$500 per ton of CO_2 removed (excluding transportation and sequestration costs)	• Potential land-use trade-offs; related impacts on food prices, water resources, fertilizer use • CO_2 sequestration risks same as direct air capture

Table 3.1 Selected CDR technologies, continues on next page

Technology	Maturity[a]	Potential effectiveness[b]	Cost factors[c]	Potential consequences[d]
Biochar and biomass methods	**Low (TRL 2):** • Basic principles understood and reported • System concept formulated • Proof of concept shown in modeling and experimental results demonstrating its CO_2 capturing ability–but CO_2 sequestration aspects uncertain • Not practiced on a scale to affect climate. No plans or prototypes for large-scale implementation • Substantial uncertainties about capacity to reduce net emissions of CO_2	**Low:** • Maximum ability to reduce atmospheric CO_2: 10–50 ppm by 2100 • Maximum annual sustainable reduction: 1–2 gigatons CO_2-C equivalent of CO_2, CH_4, and N_2O • Net carbon negative under ideal conditions (comparable to bioenergy with CO_2 capture and sequestration)	• Viability may depend on nature and extent of a carbon market • Soil fertility outcomes • Type of pyrolysis feedstock and related factors • Process energy requirements for bioenergy production (e.g., pyrolysis) • Greatly varied estimates in the scientific literature: \$2–\$62 per ton of CO_2 removed	• Potential land-use trade-offs • Long-term effects on soil uncertain • Health and safety of pyrolysis and biochar handling • Local benefits to soil enhance crop yield

Table 3.1 Selected CDR technologies, continues on next page

Technology	Maturity[a]	Potential effectiveness[b]	Cost factors[c]	Potential consequences[d]
Land-use management (reforestation, afforestation, or reductions in deforestation)	**Low (TRL 2):** • Basic principles understood and reported • Techniques well established • System concept formulated and estimates of its carbon mitigation potential reported based on modeling studies • No experimental demonstration or proof of systemwide concept of CO_2 capture and sequestration by land-use activities • Not practiced on a scale to affect climate. No plans for large-scale implementation	**Low to medium:** • Potential removal of 1.3–13.8 gigatons CO_2 annually • 0.4–14.2 metric tons of CO_2 sequestered per acre per year • Possible rerelease of sequestered CO_2	• Viability may depend on nature and extent of a carbon market • Value of land in other uses • Potentially large land area for growing or preserving forests • Type of flora planted or preserved • Natural resource requirements for maintenance and management of forests (e.g., water) • Measuring, monitoring, and verification	• Potential land-use trade-offs • Possible cobenefits such as reduced water runoff
Enhanced weathering	**Low (TRL 2):** • Basic principles understood and reported • System concept formulated • No experimental demonstration of proof of system-wide concept • Not practiced on a scale to affect climate. No plans or prototypes for large-scale implementation	**Not rated:** • Limited studies in literature • Some estimates based on models but varied conclusions about levels of effectiveness	• Viability may depend on nature and extent of a carbon market • Design and implementation of silicate-based weathering scheme, including distribution and delivery of material • Mining and transportation of silicate rock, and logistics • Greatly varied estimates in the scientific literature: \$4–\$100 per ton of CO_2 removed	• Potentially undesirable environmental and other consequences from large-scale mining and transportation

Table 3.1 Selected CDR technologies, continues on next page

Technology	Maturity[a]	Potential effectiveness[b]	Cost factors[c]	Potential consequences[d]
Ocean fertilization	**Low (TRL 2):** • Basic principles understood and reported • System concept formulated • Limited small-scale field experiments conducted but results unclear • Published research mainly theoretical • Not practiced on a scale to affect climate. No plans or prototypes for large-scale implementation	**Low:** • Maximum ability to reduce atmospheric CO_2: 10–30 ppm by 2100 • Scientific uncertainty surrounding (1) duration of carbon sequestered in the ocean, (2) how ecological impacts might limit effectiveness, and (3) how often iron would need to be added • Outcomes from limited experiments not understood or well documented	• Viability may depend on nature and extent of a carbon market • Design and implementation of ocean fertilization scheme, including distribution and delivery of material • Mining and transportation of iron ore, and logistics • Greatly varied estimates in the scientific literature: \$8–\$80 per ton of CO_2 removed	• Ecological effect on ocean not well understood • Risk of algal blooms causing anoxic zones in the ocean

Table 3.1 Selected CDR technologies: Their maturity and a summary of available information. Source: GAO.

[a] In this report, we considered each technology's maturity in terms of its readiness for application in a system designed to address global climate change. To do this, we used technology readiness levels (TRL), a standard tool that some federal agencies use to assess the maturity of emerging technologies. We characterized technologies with TRL scores lower than 6 as "immature" (section 8.1). The TRL rating methodology considers the maturity level of the whole integrated system rather than individual components of a particular technology.

[b] We assessed potential effectiveness by considering the qualitative judgments of the Royal Society and reported estimates of two quantitative measures: (1) maximum ability to reduce the atmospheric CO_2 (ppm) projected for 2100 and (2) annual capacity to remove CO_2 from Earth's atmosphere (gigatons of CO_2 or CO_2-C equivalent per year). Additionally, we reviewed scientific literature with respect to these measures of effectiveness and for assessments indicating the feasibility of implementing CDR technologies on a global scale to achieve a net reduction of atmospheric CO_2 concentration. A technology was not assigned an overall qualitative rating when there were substantial uncertainties in the literature about its effectiveness (see section 8.1).

[c] Cost factors are resources a system uses to remove CO_2 from the atmosphere and store it. Some of the studies we reviewed indicated possible cost levels, which we provide here for illustration. We did not evaluate this information independently.

[d] Includes potential consequences, risks, and cobenefits.

Technology	Maturity[a]	Potential effectiveness[b]	Cost factors[c]	Potential consequences[d]
Stratospheric aerosols	**Low (TRL 1):** • Basic principles understood and reported • No system concept proposed	**Potentially fully effective:** • Aerosols must be continuously replaced	• Design, fabrication, testing, acquisition, and deployment of aerosol delivery scheme, including distribution and delivery mechanisms, fabrication of aerosol dispersal equipment, and all associated infrastructure • Literature-based estimates vary significantly: \$35 billion to \$65 billion in the first year; \$13 billion to \$25 billion in operating cost each year thereafter	• Little change in global average annual precipitation • Disruption of Asian and African summer monsoons with accompanying reduction in precipitation • Delayed ozone layer recovery in southern hemisphere and about a 30-year delay in recovery of Antarctic ozone hole • Scattering interference with terrestrial astronomy • Efficiency of solar-collector power plants reduced by increased diffuse radiation
Marine cloud brightening	**Low (TRL 2):** • Basic principles understood and reported • System concept proposed • Proof of concept not demonstrated	**Potentially fully effective:** • Model-dependent estimates of effectiveness vary • Clouds must be continuously brightened	• Design, fabrication, testing, acquisition, and deployment of a fleet of 1,500 wind-driven spray vessels • Fleet infrastructure and operation • Estimates in the scientific literature vary significantly at \$42 million for development, \$47 million for production tooling, \$2.3 billion to \$4.7 billion for 1,500-vessel fleet acquisition	• Small changes in global average temperature, regional temperatures, and global precipitation • Large regional changes in precipitation, evaporation, and runoff; both precipitation and runoff increase, and the net result might not "dry out" the continents

Table 3.2 Selected SRM technologies, continues on next page

Technology	Maturity[a]	Potential effectiveness[b]	Cost factors[c]	Potential consequences[d]
Scatterers or reflectors in space • Earth orbit • Deep space	**Low (TRL 2):** • Basic principles understood and reported • System concepts proposed, but proof of concept not demonstrated	**Potentially fully effective:** • Spacecraft's limited lifetime	• Design, fabrication, testing, acquisition, and deployment of a fleet of millions to trillions of reflecting or scattering spacecraft • Launch vehicle • Infrastructure and operation • Estimates in the scientific literature vary significantly: an estimate of $1.3 trillion and an estimate of less than $5 trillion	**Earth-orbit technologies:** • A cool band in the tropics with unknown effects on ocean currents, temperature, precipitation, and wind • A multitude of bright "stars" in the morning and evening that would interfere with terrestrial astronomy **Deep-space technologies:** • Annual average tropical temperatures a little cooler • Annual average higher latitude temperatures a little warmer • Small reduction of annual global precipitation
Terrestrial reflectivity • Deserts • Flora • Urban or settled areas	**Low (Up to TRL 2):** • Basic principles understood and reported • One technology proposed a system concept but without demonstrated proof of concept	**Potential effectiveness of 0.21 (urban areas) to more than 57 percent (deserts)** • Sustainability issues: maintaining reflectivity and missing information on reflective flora	• Design, fabrication, testing, acquisition, and deployment of reflective material or flora • Infrastructure and maintenance • Estimates in the scientific literature to maintain reflectivity vary greatly from $78 billion (urban areas) to $3 trillion per year (deserts)	• Cool deserts might change large-scale patterns of atmospheric circulation • Reflective crops would probably not significantly affect global average temperature but might reduce regional summer temperatures • Reflective urban areas would probably not affect global average temperature but might reduce air-conditioning costs

Table 3.2 Selected SRM technologies: Their maturity and a summary of available information. Source: GAO.

[a] In this report, we considered each technology's maturity in terms of its readiness for application in a system designed to address global climate change. To do this, we used technology readiness levels (TRL), a standard tool that some federal agencies use to assess the maturity of emerging technologies. We characterized technologies with TRL scores lower than 6 as "immature" (see section 8.1). The TRL rating methodology considers the maturity level of the whole integrated system rather than individual components of a particular technology.

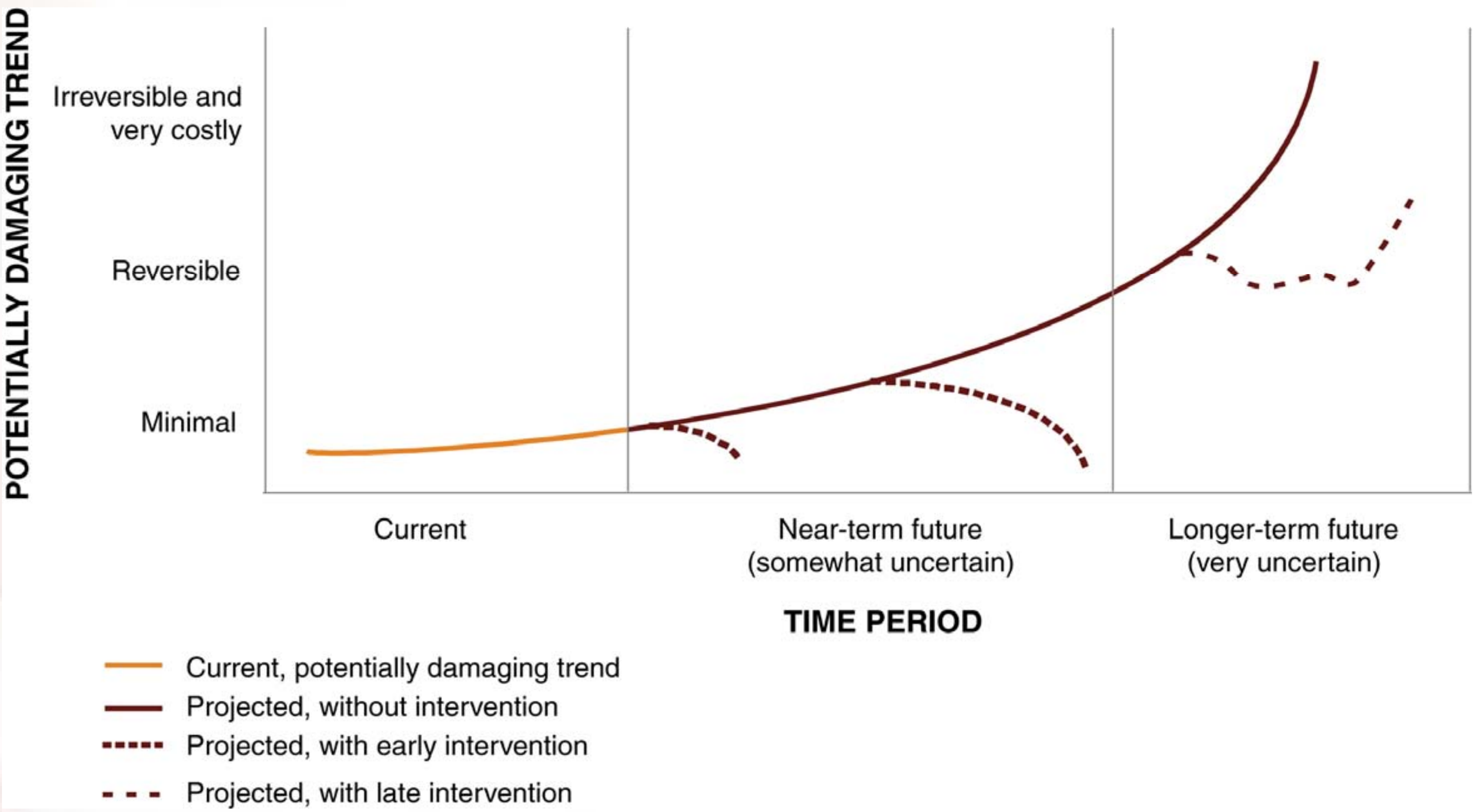
[b] We assessed potential effectiveness in terms of a technology's potential ability to counteract global warming caused by doubling the preindustrial CO_2 concentration.

[c] Cost factors are resources a system uses to counteract global warming caused by doubled preindustrial atmospheric CO_2 concentration, or for technologies that are potentially not fully effective, resources required to counteract global warming to the maximum extent possible. Some of the studies we reviewed indicate possible cost levels, which we provide here for illustration. We did not evaluate this information independently.

[d] Includes potential consequences, risks, and cobenefits.

Future Directions: experts* advocating research now—saw research as urgent or as "insurance" against worst climate scenarios

*the majority of those we consulted.



Source: Adapted from D. Rejeski, "S&T Challenges in the 21st Century: Strategy and Tempo," in A.Teich et al (eds.) *AAAS Science and Technology Policy Yearbook 2003.*

Future Directions: experts advocating research now anticipated risks and ways to address them

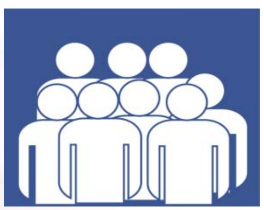
Anticipated a need to address risks

- by balancing benefits and risks (in decision-making)
- by using varied strategies to *manage* risks--whether
  1. from the research itself, e.g., manage by applying an "IRB" concept, or
  2. from deployed technologies developed from research, e.g., manage by developing norms for deployment decisions

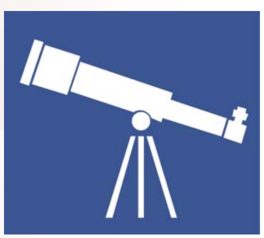
Future Directions: experts advocating research now also envisioned a federal effort

envisioned a federal research effort that would…

have an international focus



engage the public and national leaders



include a foresight component

Future Directions: but certain experts flagged alternative possible futures

These experts saw future technologies or efforts to develop them (or both) as

- negatively impacting future precipitation, the environment, populations in vulnerable countries; cause famine, mass deaths, and international conflict…or otherwise "backfire"
- undermining future emissions reduction efforts: *"leaders faced with the choice of…unilateral reductions in…emissions and the illusion of a techno-fix, [will] go for the latter"*--or
- not being needed in future because (1) climate change will not be of a magnitude to require intervention or (2) other approaches will prove sufficient, e.g., "building ecosystem… resilience"

Potential Responses: public likely to express concern about the potential for harm from climate engineering

- Majority of public is not yet familiar with climate engineering
- When provided information about climate engineering technologies, 50 percent or more of the public, across a range of demographic groups, express concern about the potential for harm from climate engineering technologies
- Public concern about the potential for harm is greater for technologies identified by experts as having risk of serious negative consequences

Potential Responses: public likely to be open to research on climate engineering, despite concern about potential for harm

- About 65 percent of the public, exposed to the same type of information as our survey, is likely to be open to research on climate engineering

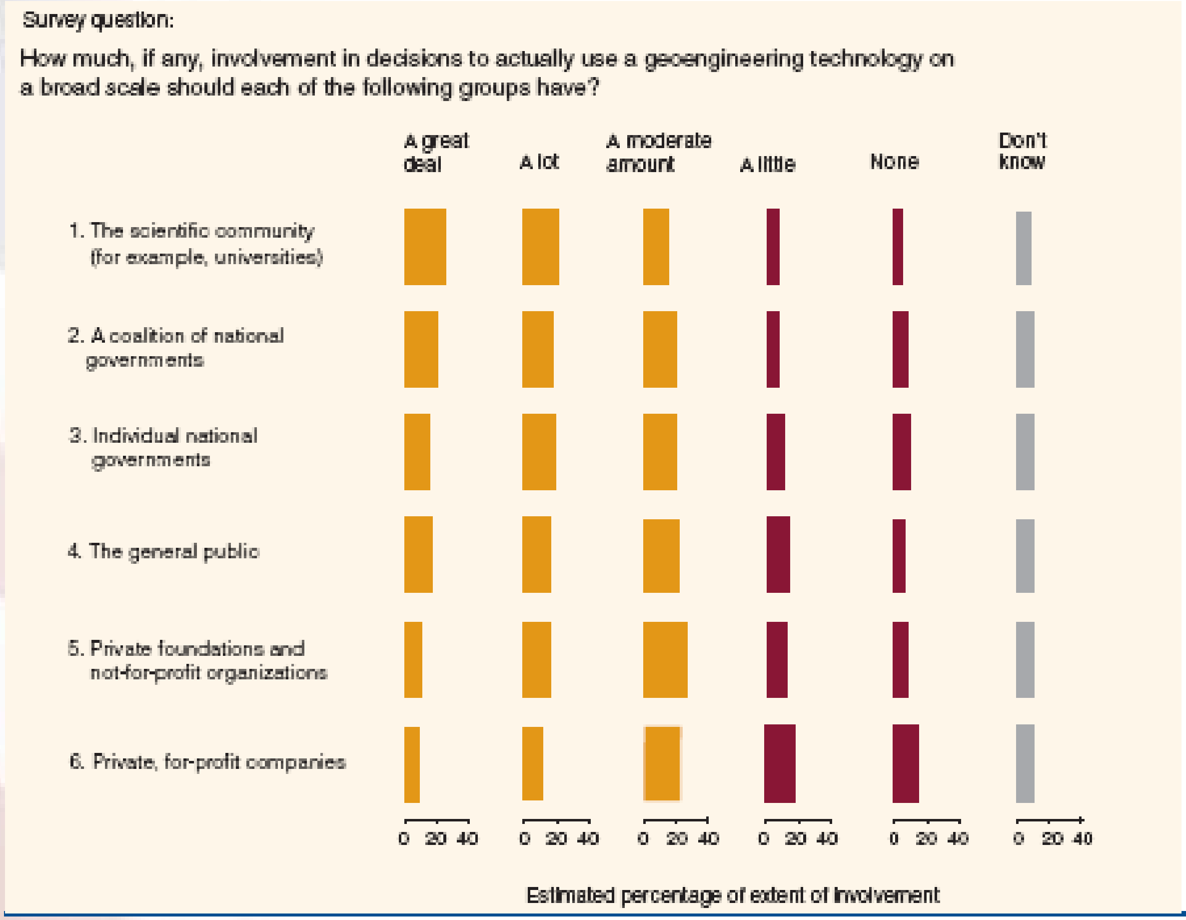
- Research may be seen as way to assess the safety and effectiveness of climate engineering—in the words of one survey respondent:

  "*Since the outcome is uncertain, more research needs to be done to find out how much of any one thing is enough or too much.*"

Potential Responses: public expresses stronger support for reducing CO_2 emissions; relying more on alternative energy sources

- About 75 percent of the public support
  - developing more fuel-efficient cars, power plants, and manufacturing processes to reduce carbon dioxide emissions
  - encouraging businesses to reduce their carbon dioxide emissions
  - relying more on solar and wind power
- About 50 percent of the public support
  - developing geoengineering technologies that could cool the climate or absorb carbon dioxide from the atmosphere

Potential Responses: public likely to support involvement of the scientific community; national/international governments in decision-making on use of technology



In the words of one survey respondent:

> ***"national governments, along with the scientific community, should determine under what circumstances it would be okay to actually use geoengineering technologies."***

GAO Technology Assessment Reports

TECHNOLOGY ASSESSMENT: Using Biometrics for Border Security, GAO-03-174, November 14, 2002

TECHNOLOGY ASSESSMENT: Cybersecurity for Critical Infrastructure Protection, GAO-04-321, May 28, 2004

TECHNOLOGY ASSESSMENT: Protecting Structures and Improving Communications during Wildland Fires, GAO-05-380, April 26, 2005

TECHNOLOGY ASSESSMENT: Securing the Transport of Cargo Containers, GAO-06-68SU, January 14, 2006 [Classification: For Official Use Only]

TECHNOLOGY ASSESSMENT: Explosives Detection Technology to Protect Passenger Rail, GAO-10-898, July 28, 2010

TECHNOLOGY ASSESSMENT: Climate Engineering—Technical Status, Current Perspectives, and Future Prospects, GAO-11-71, July 28, 2011

TECHNOLOGY ASSESSMENT: Neutron Detectors—Alternatives to Using Helium-3, GAO-11-753, September 29, 2011 [Currently issued under restriction]

THANK YOU

For further questions, please contact me at:

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