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A Serious Look at Geoengineering

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Possible responses to the problem of anthropogenic climate change fall into three broad categories: abatement of human impacts by reducing the climate forcings, adaptation to reduce the impact of altered climate on human systems, and deliberate intervention in the climate system to change the effects of anthropogenic forcing—geoengineering. Recent reports from the *National Academy of Sciences* [1991] and the *Office of Technology Assessment* [1991] aimed to provide a comprehensive look at possible responses to climate change. While they included geoengineering options, they failed to consider them systematically. We present the beginnings of a more systematic analysis and urge a balanced research program on geoengineering.

We define geoengineering as actions taken with the primary goal of engineering (controlling by application of science) the climate system. Geoengineering is the deliberate manipulation of climate forcings intended to keep the climate in a desired state, in contrast to abatement, which reduces anthropogenic forcing.

Speculation about geoengineering dates to the beginning of the century when *Arrhenius* [1908] suggested that burning fossil fuels might help prevent the coming ice age. Some technical possibilities for geoengineering were summarized by *Dyson and Marland* [1979]. Since then, increased concern about climate change has generated more literature, but no systematic research program has emerged. For example, the OTA report has a cursory discription of two geoengineering options with no contextual discussion. The NAS report contains a more substantial review, although it has significant technical omissions. Neither provides a basis other than cost for comparing the options nor includes a discussion of the relationship between geoengineering and abatement.

We do not advocate geoengineering, but we offer these justifications for a more systematic evaluation of geoengineering options.

- Geoengineering may be needed if climate change is worse than we expect. That is, geoengineering could serve as fallback technology—one that puts an upper bound on the worst case, thereby allowing more confidence in pursuing other policy options.
- It seems very unlikely that world greenhouse gas (GHG) emissions can be kept below ~40% of 1990 levels—a prerequisite for averting climate change in the long term [*Houghton et al.*, 1990].

Doubt about the prospects for cooperative abatement of global GHG emissions is a pragmatic reason to consider geoengineering, whose implementation requires fewer cooperating actors than abatement. Thus, geoengineering fills a unique niche because of its potential to mitigate catastrophic climate change.

To act as a fallback strategy, geoengineering must be more certain of effect, faster to implement, or provide unlimited mitigation at fixed marginal cost. Our definition of "fallback strategy" is an extension of the term "backstop technology" used in energy systems analysis for a technology providing unlimited energy at fixed (usually high) marginal cost.

The existence of a fallback is critically important, as it allows more confidence in choosing a moderate response strategy. Moderate responses are difficult to implement when catastrophic consequences are possible from weak anthropogenic climate forcing. Fallback strategies permit moderate responses to be adopted with the knowledge that should these prove inadequate, an alternative mitigation option is available. We examine a range of geoengineering techniques to gauge their suitability as fallback strategies.

Examples of Geoengineering Techniques

Geoengineering affects climate by altering global energy fluxes through one of two strategies, either by increasing the amount of outgoing infrared radiation through reduction of GHGs, or by decreasing the amount of absorbed solar radiation through an increase in albedo.

Three examples of the first strategy, which remove CO_2 from the atmosphere, are direct deep-ocean disposal, ocean-surface fertilization, or afforestation. For the second strategy, we discuss albedo modification by placing solar shields in Earth-orbit, or by increasing aerosol concentrations. Our five cases are chosen to survey geoengineering's wide range of risks and costs. With the exception of direct ocean disposal and afforestation, these schemes have the theoretical potential to mitigate the full effect of anthro-

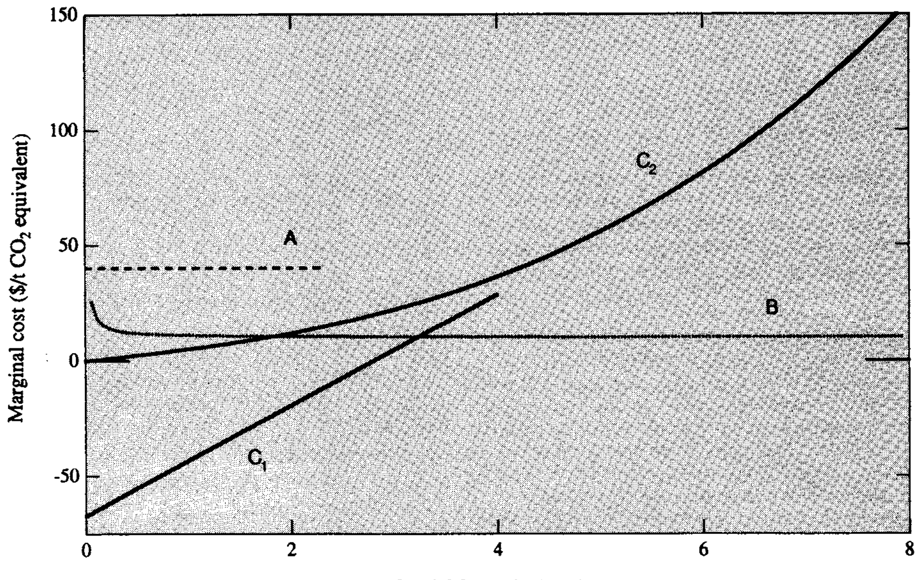

Fig. 1. Marginal cost of mitigation versus total mitigation for the United States. The lower axis is the total mitigation in Gt of CO_2 equivalent. The costs of geoengineering are given by two curves: A, CO_2 injection; and B, solar shields. Curves C, C_1, and C_2 represent a range of mitigation costs. CO_2 accounts for about half of the global-warming potential of U.S. emissions. Stabilizing GHG concentrations requires about a 60% emissions cut, for example, ~6 Gt CO_2 equivalent per year for the United States. The marginal cost of deep-ocean disposal of CO_2 (A) is taken from Golomb et al. *[1989]. Its application is limited to the total amount of CO_2 currently released by centralized facilities. The solar shield costs (B) are assumed to be $10/t with an initial capital cost of 10% of the full cost. The costs of abatement (C) are taken from the NAS report. The lower branch (C_1) is from the "technical costing method" and was generated using a linear fit to the midpoint data in Figure 11.1 of the NAS report. The upper branch (C_2) is from the "economic modeling method" (Figure Q.2) using a quadratic polynomial fit.*

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pogenic forcing of the mean radiative flux. Of course, restoring the radiative flux does not imply an unaltered climate.

Controlling Atmospheric CO_2: CO_2 may be removed from the atmosphere by transferring it to a different reservoir. For example, CO_2 from centralized power plants could be placed directly into the deep ocean or into abandoned wells by high-pressure injection. Alternatively, carbon may be transferred to the deep ocean by fertilization of the oceans' surface biota, or to the terrestrial biosphere by afforestation.

Direct Ocean Disposal: The scale of the anthropogenic flux of fossil carbon into the atmosphere has driven the atmosphere out of equilibrium with the ~60 times larger oceanic carbon reservoir. Injection of CO_2 directly into the ocean can accelerate the equilibration of the oceanic and atmospheric CO_2 concentrations, thus reducing the increase in atmospheric CO_2. CO_2 released into the ocean at depths below about 1 km forms a dilute supercritical mixture with sufficient density to sink to the deep ocean. Once on the ocean floor, CO_2 may form stable clathrates, or may mix with surrounding deep water, dissolving $CaCO_3$ to maintain the alkalinity.

Several studies have addressed the technical feasibility of capturing CO_2 from power stations and compressing it to the necessary ~150-bar pressure. The principle difficulty is the energy required to compress the CO_2, which is about one-third of the combustion energy. A plausible technology is to burn the fuel in pure oxygen, which balances the cost of producing the O_2 against the savings in separating the CO_2 from the steam of combustion gases. Retrofitting a coal-fired power plant to capture and compress CO_2 would decrease thermal efficiency from 35% to 25% and increase electricity cost from 4.6 to 8.3 ± 0.3¢/kW-hr [*Golomb et al.*, 1989], equivalent to a marginal mitigation cost of $42/t CO_2. These estimates include operating and capital costs, but ignore the cost of pipeline systems, which we estimate will increase the cost by about one-third.

Further research must move beyond the reasonably well-understood questions of CO_2 separation and compression. The fate of CO_2 injected into the ocean could be studied using modified versions of ocean circulation-chemistry models, for example, *Bacastow and Maier-Riemer* [1990]. A detailed study might concentrate on modeling a few representative locations such as the Japan trench. Economic issues could be addressed by developing a supply curve for implementation, taking into account the geographical distribution of power stations and ocean trenches, and the costs of high-pressure pipelines.

Ocean-Surface Fertilization: Carbon could be removed from the atmosphere by fertiliz-

Table 1. Summary Comparison of Geoengineering Options

Geoengineering Option	Mode of Action	Cost ($ per t CO_2 equivalent)	Risk: Side-Effects	Risk: Feasibility	Nontechnical Issues	References
Direct ocean disposal	CO_2 removal	15–30	Very low: damage to local benthic community.	High costs.	Equity: Like abatement all must bare costs.	*Golomb, NAS*
Ocean fertilization with phosphate	" "	1	Possible benefits: increased productivity higher up the food chain. Risk of eutrophication.	Very uncertain biology: can ecosystem shift off the current P:N ratio?	Equity and sovereignty: who pays and who gets the benefits (fish) if any?	*Broecker, Dyson*
Ocean fertilization with iron	" "	0.1–15	ditto	Very uncertain biology: is iron really limiting?	ditto	*NAS, OTA, NRC, Peng.*
Reforestation	Primary effect is CO_2 removal. Albedo decrease and increased atmospheric humidity may cause warming	3–10	Very low, but loss of key nutrients from soils and other effects could be significant in the long term.	Rate of C uptake by trees is still unclear.	Equity and sovereignty: who will provide the land for afforestation?	*NAS*
Solar shields	Albedo increase; equivalent to decrease of the solar constant.	0.25–2.5	Very low, but all albedo modifying options change climate.	Launch costs, space technology costs have very high uncertainty.	Security and equity: this may be weather control, who gets the rain?	*Sefritz, NAS*
Stratospheric SO_2	Albedo increase; will also cause stratospheric heating.	0.007	High: accelerated catalysis of CFC driven ozone depletion.	Residence times.	Equity: costs are so low that (who pays) is not an important issue Liability: ozone destruction.	*Broecker, NAS*
Stratospheric dust (inert)	" "	0.03–1	Risk of ozone depletion may be less than for SO_2.	Residence times, delivery system costs.	Ditto, except higher costs.	*NAS*
Tropospheric SO_2	Optical scattering *and* change in cloud optical properties	0.01–1	Low: we may already be mitigating the effect of anthropogenic GHGs.	Uncertainties in transport, optical properties, and cloud microphysics.	Equity	*NAS, Charlson*

ing the "biological pump," which maintains the disequilibrium in CO_2 concentration between the atmosphere and deep ocean [*Zaborsky*, 1990; *NAS*, 1991; *OTA*, 1991]. The net effect of biological activity in the ocean surface is to bind phosphorus, nitrogen, and carbon into organic detritus in a ratio of 1:15:130 (we are counting the C removed as $CaCO_3$) until all of the ultimate-limiting-nutrient, usually phosphorus, is exhausted. The detritus then falls to the deep ocean, providing the pumping action.

A simple interpretation of this ratio suggests that adding phosphate to the ocean surface should remove CO_2 from the atmosphere-ocean surface system in a molar ratio of ~130 to 1. Phosphate costs $25/ton, so if we ignore distribution and processing costs, the cost of CO_2 removed is ~$0.4/ton. World phosphate reserves are of the order of 100 Gt, so the process is not limited by lack of phosphate. Our first-order model of the biology ignores the phosphate-nitrate balance. Adding phosphate to the system without adding nitrate would only remove carbon in this ratio if the ecosystem shifted to favor nitrogen fixers.

In some areas of the southern oceans the ultimate limiting-nutrient may be iron, for which the molar ratio Fe:C in detritus is ~$1{:}10^4$, implying that iron may be an efficient fertilizer of ocean-surface biota [*Davies*, 1990]. This process may be particularly subject to dynamical constraints [*Peng and Broecker*, 1991], so it is surprising that only iron fertilization is discussed in the NAS and OTA reports. Should fertilization be successful it could decrease dissolved oxygen with consequent increased emissions of methane. Alternatively, the increase in primary productivity may produce higher yields from ocean fisheries.

Afforestation: Large-scale afforestation is the geoengineering option most thoroughly treated in the existing literature [*Dyson and Marland*, 1979; *NAS*, 1991; *OTA*, 1991]. Regularly harvested temperate forests capture atmospheric CO_2 at a rate of ~2 t/ha-yr; intensively cultivated forests of fast-growing trees can capture CO_2 3–5 times faster. If one-third of the current forested area (4×10^9 ha) was devoted to intensive sylviculture, then about 10 Gt/yr of CO_2 could be sequestered. In order to remove CO_2 continuously at this rate, it would be necessary to dispose of the trees so that their carbon could not return to the atmosphere, thus necessitating the removal of tree nutrients from the soil. Intensive fertilization would be required, and its production could be costly [*Dyson and Marland*, 1979]. A key problem, so far ignored, is the long-term effect of such tree farming on soils. Since it may be argued that soil degradation is a more serious problem than CO_2-induced climate change, this is a critical shortcoming of intensive sylviculture for carbon sequestration.

Albedo Modification: The primary effect of increasing GHGs can be offset by increasing the albedo to maintain the radiative balance. An albedo change of ~1.4% is needed to offset the effect of doubled CO_2. Even if albedo were changed to compensate for the effect of increased GHGs on globally averaged surface temperature, the climate would still be significantly altered due to the changed vertical and latitudinal distribution of atmospheric heating. The resulting reduction in stratospheric temperature and pole-to-equator gradient may significantly alter the climate. This issue is yet to be addressed in the geoengineering literature.

Space-Based Shields: The possibility of shielding the Earth with orbiting mirrors is the most technologically extravagant geoengineering scheme. We can estimate the costs by assuming they are dominated by the cost of lifting the required mass to orbit. The shields may be fabricated in orbit from aluminum micro-foil 0.1- to 0.5-μm thick. The angular size of individual shields as seen from Earth could be small enough not to cause noticeable modulation of sunlight. Detailed estimates of mass densities, including support structures, range from 1 to 10 g m^{-2} and can be found in the solar sail literature [*Drexler*, 1979]. Thus, the mass of a system required to reduce solar flux by 1.4% is $1–5 \times 10^{13}$ g. Current costs of launching payloads to Earth orbit are ~$25 g^{-1}; however, given economies of scale (which would certainly apply to this project!), it is argued that launch costs for unmanned packages of raw materials would be as low as ~$1 g^{-1}. Given these assumptions, the total system cost is ~$20 trillion.

Solar shields have clear advantages over other geoengineering options. The undesired side effects of the shields would certainly be both less significant and more predictable than for other albedo modification schemes. If the shields were steerable, their shadowing effect could be turned off at any time. Additionally, steerable shields could be used to direct radiation at specific areas, offering the possibility of weather control.

A key flaw in this scheme is that the shields would act like solar sails and be rapidly blown out of orbit by the sunlight they were designed to block. Simple dimensional analysis yields the perturbation time-scale in units of the orbital period, $S_0\rho^2/cg\sigma$, with solar constant S_0, sail mass density σ, and orbital radius in units of Earth's radius ρ (g and c as per usual). Our numerical experiments indicate that a sail with mass density of 1 g m^{-2} is lost from orbit in ~20 days (depending on the sail's orientation). The NAS study dismisses this problem, incorrectly stating that the orbits could be made stable by reorienting the mirrors. This problem was recognized by *Seifritz* [1989], who proposed using a single ~2000-km-radius shield at the Lagrange point between the Earth and Sun. Such a shield would be stable with weak active control and cost $1–$10 trillion. This implies a marginal cost of $2.5–$0.25 per ton of CO_2 equivilent. (The conversion of albedo modification costs to GHG reduction in CO_2-equivilent units is arbitrary. We used the NAS convention of 4000 Gt CO_2 mitigated by a 1% change in solar constant.)

Sulfate Aerosols: Aerosols may influence radiative fluxes either by optical scattering and reradiation, or indirectly by increasing the albedo and lifetime of clouds. It appears that anthropogenic sulfate aerosols may currently influence the global radiation budget by 1–2 Wm^{-2}, enough to compensate for the current forcing by anthropogenic GHGs [*Charlson et al.*, 1992]. Budyko was the first to suggest increasing the albedo by injecting SO_2 into the stratosphere where it would mimic the action of large volcanos on the climate. *Broecker* [1985] calculated that ~35×10^6 t/yr of SO_2 would be needed to counter the effect of doubled CO_2 concentration and that it could be lofted into the stratosphere by jet transports at a cost of ~$30 billion/year equivalent to a cost of $0.007/t CO_2. The increased acidity of precipitation from the upper atmosphere might be acceptable, as it amounts to only 10% of the current world SO_2 emissions. The most serious problem with this scheme may be the effect of the aerosols on atmospheric chemistry. The Antarctic ozone hole has clearly demonstrated the complexity of chemical kinetics in the stratosphere and the resulting susceptibility of ozone concentrations to trace contaminants. Albedo modification by tropospheric aerosols merits systematic study in light of new understanding [*Charlson et al.*, 1992] of their radiative effects.

Comparing the Options

Previous discussion of geoengineering has focused on issues of technical feasibility

Table 2. Costs Vs. Risks of Geoengineering Schemes

Risk of adverse effect	Cost		
	low	medium	high
low	—	reforestation	solar shields; direct ocean CO_2 injection
medium	SO_2 in troposphere; ocean fertilization-Fe	inert stratospheric aerosols; ocean fertilization-P	balloons in the stratosphere
high	SO_2 in stratosphere	—	—

Costs are from the same sources as Table 1. Risks are qualitative estimates informed by current knowledge. This kind of systematic comparison should be used in setting geoengineering research priorities.

and approximate cost. Many geoengineering schemes are sufficiently low in cost relative to abatement or adaptation that cost is unlikely to be the decisive factor in choices about implementation. Instead, issues of risk, politics, and ethics may prove more important; we summarize these in Table 1. Including other factors in an intercomparison of geoengineering schemes serves to differentiate the schemes and thus provides a basis for rationalizing the research program in the face of considerable uncertainty (Table 2). A sensible allocation of research resources dictates that work should be concentrated on answering questions with the greatest product of uncertainty and importance. For example, in the case of direct ocean disposal, further research should focus on the fate of the injected CO_2 rather than on refining our understanding of power plant design.

Important uncertainties in the political implications of geoengineering include *Sovereignty*: Who has the authority to deploy such a scheme? *Equity*: How are costs (direct and indirect) distributed relative to benefits? *Liability*: Creators of a geoengineering system will be blamed for an obvious failure. Would they be de facto libel for natural climate fluctuations? *Security*: Might geoengineering systems (for example, solar shields) be construed as offensive weapons? Even preliminary answers to these questions would better allow us to differentiate geoengineering schemes.

Questions about the advisability of geoengineering revolve around risk—risk of failure and risk of unintended side effects. The climate system is too poorly understood to allow quantitative assessment of risk, but we can construct some general heuristics for evaluating the risks of various options. If a geoengineering scheme works by imitating or amplifying a natural process, we can compare the magnitude of the engineered effect with the magnitude and fluctuations of the natural process and then assume that similar perturbations entail similar risks. For example, we estimate the magnitude of SO_2 released into the stratosphere as part of a geoengineering strategy and from a large volcano to be of similar scales. The quantity of phosphorous needed to increase oceanic uptake of CO_2 is roughly equal to the phosphorous reaching the ocean surface through upwelling. Hence, it may be reasonable to estimate the same magnitude of stratospheric ozone destruction in the former case and the same level of eutrophication of the water column in the latter case.

We can compare geoengineering with abatement by comparing the way the costs of reducing climate change scale with the degree of reduction demanded. Figure 1 makes this comparison. Although the values of these cost functions are uncertain by as much as an order of magnitude, there is much less doubt about their functional forms. Several recent studies suggest that small levels of abatement would have negative costs, that is, that conservation would save money. However, these studies do not consider reducing GHG emissions below about one-third of current levels because the costs become prohibitive. In contrast, many geoengineering options appear to have marginal costs which, while highly uncertain, are roughly independent of scale. In principle, the various cost curves could be used to derive an aggregate supply curve for climate stabilization. Current uncertainties make such an exercise impractical, but the result is clear—knowledge of geoengineering options puts an upper bound on the costs of climate change mitigation.

Conclusions

Current discussions of geoengineering are unsystematic and take insufficient account of prior results. The possibility of unpleasant suprises in the climate system justifies a more coherent (though not large) research program in order to define fallback options needed to make reasonable policy choices. A rational allocation of research priorities dictates that some resources be spent to study geoengineering unless nasty surprises are assigned a zero probability. Ignoring important ethical issues, we have demonstrated a need to examine geoengineering options more systematically.

A more systematic research program should focus on geoengineering schemes estimated to be low in both cost and risk. It should include more thorough and critical reviews of previous work. Nontechnical issues and risks need to be more carefully addressed in studying individual geoengineering schemes, and in allocating resources between different schemes in the face of uncertainty.

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