Geoengineering

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Introduction

Geoengineering is the intentional large-scale manipulation of the global environment. The term has usually been applied to proposals to manipulate the climate with the primary intention of reducing undesired climatic change caused by human influences. These geoengineering schemes seek to mitigate the effect of fossil-fuel combustion on the climate without abating fossil fuel use; for example, by placing shields in space to reduce the sunlight incident on the Earth.

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 counter the human impact on climate—geoengineering.

It is central to the common meaning of geoengineering that the environmental manipulation be deliberate, and be a primary goal rather than a side-effect. This distinction is at the heart of the substantial moral and legal concerns about geoengineering. For example, while it may be argued that modern agriculture constitutes geoengineering, the global-scale transformations of the nitrogen cycle it causes is a side-effect of food production, and is usually viewed differently from the deliberate modification of the global environment.

Explicit consideration of human modification of the global climate dates back at least to Arrhenius who was the first to analyze the role of CO_2 in regulating climate. In 1908 he suggested that warming resulting from fossil fuel combustion could increase food supply by allowing agriculture to extend northward (see bibliography).

Sporadic analysis of the potential for global climate modification continued through the first half of the century. The 1950s and ’60s saw increasing interest in the possibility of control of weather and climate for human benefit. Discussion of climate engineering as a means to counteract destructive human influences began in the 1970s at a time of increased concern about the negative effects of technological change.

Examples of Geoengineering Proposals

Proposals to engineer the climate may be usefully classified by their mode of action. Most proposals to mitigate climate change do so by altering global energy fluxes through one of two strategies: increasing the amount of outgoing infrared radiation through reduction of atmospheric CO_2, or decreasing the amount of absorbed solar radiation through an increase in albedo. The few proposals that fall outside this categorization typically involve modification of ocean currents (E.g., R.G. Johnson, "Climate Control Requires a Dam at the Strait of Gibraltar." EOS (78 (1997): 277-281). Although not considered further in this article, geoengineering has occasionally been proposed for non-climatic problems such as ozone depletion.

Albedo modification schemes aim to offset the effect of increasing CO_2 on the global radiative balance, and thus on average surface temperatures. An albedo change of ~1.5% is needed to offset the effect of doubled CO_2. Even if perfect compensation of the radiative balance could be achieved, the resulting climate would still be significantly altered. The climate changes would result from changed vertical and latitudinal distributions of atmospheric heating. In addition, the increase in CO_2 would have substantial effects on plant growth independent of its effect on climate. These effects cannot be offset by an increase in albedo.

The remainder of this section sketches five geoengineering schemes selected to survey the wide range of risk and cost involved. Table 1 summarizes various geoengineering schemes.

Stratospheric Aerosols

Aerosols influence radiative fluxes either directly by optical scattering and re-radiation, 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 Wm^{-2}—enough to counter much of the effect of increased CO_2. Budyko (see bibliography) was the first to suggest increasing the albedo by injecting SO_2 into the stratosphere where it would mimic the action of large volcanoes on the climate. The injection of about 10 teragrams per annum into the stratosphere would roughly counter the effect of doubled CO_2 on the global radiative balance. Several technologically straightforward alternatives exist for injecting the required sulfate into the stratosphere at a trivial cost compared to other methods of climate modification (see the NAS report in the bibliography).

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 dynamics in the stratosphere and the resulting susceptibility of ozone concentrations to aerosols. Recent elaborations of this scheme have focused on tailoring the scattering properties of the particles, and on choosing particles that might be chemically inert. Depending on the size of particles used, the aerosol layer might cause significant whitening of the daytime sky. Such whitening is one of the classic valuation problems posed by geoengineering: How much is a blue sky worth?

Space-Based Shields

The possibility of shielding the earth with orbiting mirrors is the most technologically extravagant geoengineering scheme. While expensive, it has clear advantages over other geoengineering options. Because solar shields effect a "clean" alteration of the solar constant, their side effects would be both less significant and more predictable than for other albedo modification schemes. Assuming that the shields were steerable, their effect could be eliminated at will. Additionally, steerable shields might be used to direct radiation at specific areas offering the possibility of weather control.

Most discussion of solar shields has assumed that they would be placed in low-earth orbit; however, such shields act as solar sails and would be rapidly pushed out of orbit by the sunlight they were designed to block. This problem was recognized by Seifritz (see bibliography) 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.

A rough estimate of the cost can be made by assuming that it is dominated by the cost of lifting the required mass to orbit. Detailed estimates of the minimum required mass densities can be found in the solar-sail literature. They range from 2 to 10 gm m^{-2} (including support structures). The mass of a system required to reduce solar flux by 1.5% is 1 to 5 teragrams. (N.B., a recent proposal aims to radically reduce the required mass by use of fine mesh with tailored optical scattering properties.) The current cost of launching payloads to orbit is about $20 per gram. However, given economies of scale—which would certainly apply here—it is argued that launch costs could be substantially lower.

Sequestration of CO_2 from fossil fuel combustion

The climatic impact of fossil energy use may be reduced by capturing the resulting carbon and sequestering it away from the atmosphere. Carbon can be captured from fossil fuels by separating CO_2 from products of combustion or by reforming the fuel to yield a hydrogen-enriched fuel stream for combustion and a carbon enriched stream for sequestration. The linked technologies of separation and sequestration are often called "carbon management." During the 1990's, a broad-based research program in carbon management has emerged, and has demonstrated substantial progress in the necessary technologies, and improved understanding of the potential for geologic and oceanic CO_2 sequestration. Driven by concerns over climatic change, large scale sequestration of CO_2 has already begun; Statoil of Norway is injecting CO_2 separated from natural gas into an aquifer beneath the North Sea. Other projects are planned, as are various pilot-scale sequestration experiments.

As carbon management emerges as a plausible near-term option for reducing CO_2 emissions, the degree to which it constitutes geoengineering is becoming controversial; with proponents contending that it is abatement, while opponents contend that it is geoengineering. In fact, carbon management occupies an ambiguous place in the conventional *abate/adapt/geoengineer* taxonomy outlined above. The term geoengineering was coined in the early 1970s by Marchetti who proposed that CO_2 from combustion could be disposed of in the ocean. Oceanic sequestration would constitute a deliberate intervention into the carbon cycle. Thus is seems reasonable to label it geoengineering. However, proposed "zero emission" power plants, that would emit nothing to the atmosphere and would sequester their CO_2 emissions in stable geological formations, may be seen as a novel form of mitigation.

A large body of recent engineering studies have addressed the technical feasibility of capturing CO_2 from power plants and compressing it for sequestration in the ocean or underground. The rough consensus of the studies is as follows.

- For new power stations, the amortized additional cost of CO_2 capture and sequestration would raise electricity prices by 30 to 150%, a cost that is less than the current costs of non-fossil alternative energy sources such as solar.
- The costs would be substantially higher for retrofitting existing power plants.
- Most costs arise from the separation of CO_2 from other exhaust gases, rather than from its compression and sequestration.

Carbon may also be captured from fossil fuels by reforming them to produce hydrogen and CO_2. If hydrogen was used as a primary energy carrier—a proposed route to large-scale decarbonization of the energy system—then the existing cost advantage of carbon management over non-fossil alternatives is augmented due to the technical advantages of thermochemical over electrochemical hydrogen production.

Carbon from fossil fuel combustion may be sequestered in geological formations or in the ocean. The options for geological sequestration may be summarized as follows. Three types of reservoirs have been seriously considered: depleted oil and gas fields (global capacity ~ 200-500 GtC), deep coal beds (~ 100-200 GtC), and deep saline aquifers (~ 10^2-10^3 GtC). Questions remain about the long-term stability of these reservoirs, particularly oil and gas fields. In the remainder of this section we will focus on oceanic sequestration because it most clearly constitutes geoengineering.

One may view CO_2-induced climate change as a problem of mismatched time-scales. It is due to the rate at which combustion of fossil fuels is transferring carbon from ancient terrestrial reservoirs into the comparatively small atmospheric reservoir. When CO_2 is emitted to the atmosphere, atmosphere-ocean equilibration transfers ~80% of it to the oceans with an exponential time-scale of ~300 yr. The atmospheric remaining CO_2 is removed on much longer time-scales. Injecting CO_2 into the deep ocean accelerates this equilibration, reducing peak atmospheric concentrations. The efficiency of equilibration depends on the location and depth of injection. For example, injection at ~700 m depth into the Kuroshio current off Japan would result in much the CO_2 being returned to the atmosphere in ~100 years, whereas injections that formed "lakes" of CO_2 in ocean trenches would more efficiently accelerate equilibration of the CO_2 with the deep-sea calcium carbonate reservoirs.

The dynamic nature of the marine carbon cycle precludes defining a unique static capacity, as may be done for geological sequestration. Depending on the increase in mean ocean acidity that is presumed acceptable, the capacity is of order ~10^3-10^4 Gigatons of Carbon (GtC), much larger than current anthropogenic emissions of ~ 6 GtC per year.

In considering the implications of oceanic sequestration one must note that—depending on the injection site—about 20% of the carbon returns to the atmosphere on the ~300 yr time-scale. Supplying the energy required for separating, compressing, and injecting the CO_2 required that more fossil fuel must be used than would be needed if the CO_2 was vented to the atmosphere. Thus, while oceanic sequestration can reduce the peak atmospheric concentration of CO_2 caused by the use of a given amount of fossil-derived energy, it increases the resulting atmospheric concentrations on time-scales greater than ~ 500 yr.

Ocean Surface Fertilization

Carbon could be removed from the atmosphere by fertilizing the "biological pump" which maintains the disequilibrium in CO_2 concentration between the atmosphere and deep ocean. 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 (this includes the carbon removed as $CaCO_3$) until all of the 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 ~130:1. This 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 limiting nutrient may be iron, for which the molar ratio Fe:C in detritus is ~1:10000, implying that iron may be a very efficient fertilizer of ocean-surface biota. This idea has received considerable attention and has stimulated some valuable research. Iron fertilization has been demonstrated *in situ*, but is not clear that sustained carbon removal is realizable.

Ocean fertilization would have significant side effects. For example, it might decrease dissolved oxygen with consequent increased emissions of methane—a greenhouse gas.

Afforestation

Large-scale forest management or afforestation for the purpose of removing atmospheric CO_2 is a form of geoengineering. (Note that this definition is unavoidably fuzzy; e.g., it may not be appropriate to consider afforestation for a mix of purposes as geoengineering.)

It appears that temperate-zone northern-hemisphere forests already capture a significant amount (~10 to 20%) of fossil fuel carbon. Uncertainty about the dynamics of carbon in forest ecosystems limits our ability to predict their response to climatic change and increasing CO_2; in particular, it is uncertain whether such changes would accelerate or reverse the sequestration of carbon in forests. Capturing a substantial fraction of fossil fuel carbon would require intensive management of forests on a very large scale. For example, fast growing forests of young trees can capture ~5 tons C/ha-yr under optimal conditions. To capture the full anthropogenic CO_2 emissions about 10^9 hectares would be required—roughly the current global area of managed forest. In order to capture carbon continuously at this rate it would be necessary to dispose of the trees so that their carbon could not return to the atmosphere. Fertilization would be required to replace the nutrients removed with the trees. Intensive forest management on this scale would have a substantial impact on forest ecosystems.

Evaluating Geoengineering

Most discussion of geoengineering has focused on assessments of technical feasibility and approximate cost. However, it is probable that issues of risk, politics, and ethics will prove more decisive factors in real choices about implementation. This is true both because of the strong negative reactions often provoked by most geoengineering proposals, and because many geoengineering schemes are inexpensive relative to abatement or adaptation.

Economics and Risk Analysis

Naive Cost Benefit Analysis

The simplest economic metric for geoengineering is to compute the "cost of mitigation"—the ratio of cost to the amount of mitigation effected (typically measured in dollars per ton of carbon emission mitigated). This measure permits comparison between geoengineering schemes and between geoengineering and the abatement of emissions. Table 1 includes the cost of mitigation for various schemes. The costs are highly uncertain. For albedo modification schemes additional uncertainty is introduced by the somewhat arbitrary conversion from albedo change to equivalent reduction in CO_2.

Examination of the cost of mitigation reveals that it varies by more than two orders of magnitude between various schemes, and that for some (e.g., stratospheric aerosols) the costs are very low compared to either abatement or adaptation. However, such direct cost comparisons have little meaning given the very large differences in the non-monetary aspects of these responses to climate change; e.g., risk of side effects, certainty of effect, and social distribution of cost.

Geoengineering as a Fallback Strategy

Focusing on the marginal cost of mitigation permits a more meaningful comparison between geoengineering and abatement. Although the cost of mitigation is uncertain, there is much less doubt about how the cost of mitigation scales with the degree of mitigation required. While econometric and technical methods for estimating the cost of moderate abatement differ radically, both agree that costs will rise steeply if we want to abate CO_2 emissions by more than 50%. In sharp contrast, some geoengineering schemes (e.g., albedo modification) have marginal costs that, while highly uncertain, are roughly independent of, and may even decrease with, the amount of mitigation effected. Other schemes (e.g., CO_2 sequestration) have marginal costs that are initially higher than abatement, but that rise more slowly. These relationships are illustrated in Figure 1.

Geoengineering may serve as a fallback strategy by putting an upper bound on the costs of mitigation should climate change be more severe than we expect. In this context a fallback strategy must either be more certain of effect, faster to implement, or provide unlimited mitigation at fixed marginal cost. Various geoengineering schemes meet each of these criteria. The notion of geoengineering as a fallback option provides a central—or perhaps the only—justification for taking large-scale geoengineering seriously. A fallback strategy permits more confidence in adopting a moderate response to the climate problem: without fallback options a moderate response is risky given the possibility of a strong climatic response to moderate levels of fossil-fuel combustion.

Risk Assessment

Questions about the advisability of geoengineering revolve around risk: risk of failure and risk of side effects. Climate prediction is too uncertain to allow quantitative assessment of risk. However, if a geoengineering scheme works by imitating a natural process, we can make a qualitative risk assessment by comparing the magnitude of the engineered effect with the magnitude and variability of the natural process, and then assume that similar perturbations entail similar results. For example, the amount of sulfate released into the stratosphere as part of a geoengineering scheme and the amount released by a large volcanic eruption are similar. We may estimate the magnitude of stratospheric ozone loss by analogy.

Even crude qualitative estimates of risk can give insight into the relative merits of various geoengineering schemes when considered in conjunction with other variables. Table 2 illustrates this with a comparison of risk and cost.

Political Considerations

The cardinal political reality of geoengineering is that unlike other responses to climate change (e.g., abatement or adaptation) geoengineering could be implemented by one or a few countries acting alone. Various political concerns arise from this fact with respect to security, sovereignty, and liability; they are briefly summarized below.

Some geoengineering schemes raise direct security concerns; solar shields, for example, might be used as offensive weapons. A more subtle but perhaps more important security concern arises from the growing links between environmental change and security. Whether or not they were actually responsible, the operators of a geoengineering project could be blamed for harmful climatic events that could plausibly be attributed—by an aggrieved party—to the geoengineering. Given the current political disputes arising from issues such as the depletion of fisheries and aquifers, it seems plausible that a unilateral geoengineering project could lead to significant political tension.

In general, international law has little bearing on geoengineering. However, Bodansky (1996) points out that several specific proposals may be covered by existing laws; for example, the fertilization of Antarctic waters would fall under the Antarctic Treaty System, and the use of space-based shields would fall under the Outer Space Treaty of 1967.

As in the current negotiations under the Framework Convention on Climate Change, geoengineering would raise questions of equity. In this case geoengineering might simplify the politics. As Tom Schelling (1996) pointed out, geoengineering "… totally transforms the greenhouse issue from an exceedingly complicated regulatory regime to a simple —not necessarily easy but simple—problem in international cost sharing."

One must note that not all geoengineering schemes are amenable to centralized implementation. For example, carbon management requires diffuse implementation at the manifold sources of fossil fuel combustion.

Ethics

Discussion of geoengineering commonly elicits strong negative reactions. Within the policy analysis community, for example, there has been vigorous debate about whether discussion of geoengineering should be included in public reports that outline possible responses to climate change. Fears have been voiced that its inclusion in such reports could influence policy makers to take it too seriously, and perhaps to defer action on abatement given knowledge of geoengineering as an alternative (see Schneider (1996) for discussion of the debate over geoengineering in the 1992 NAS panel). While these concerns are undoubtedly serious and substantive, it is difficult to disentangle their various roots and, in particular, to separate pragmatic from ethical concerns.

Many of the objections to geoengineering that are cited as "ethical" have an essentially pragmatic basis. Three common ones are:

- The slippery slope argument. If we choose geoengineering solutions to counter anthropogenic climate change, we open the door to future efforts to systematically alter the global environment to suit humans. This is a pragmatic argument, because in the future we will be a free as we are now to choose to what extent we wish to geoengineer. An ethical argument must define why such large-scale environmental manipulation is bad, and how it differs from what humanity is already doing.
- The kluge argument. Geoengineering is a 'technical fix', 'kluge', or 'end-of-pipe solution.' Rather than attacking the problems caused by fossil fuel combustion at their source, geoengineering aims to add new technology to counter their side-effects. Such solutions are commonly viewed as inherently undesirable—but not for ethical reasons.
- The unpredictability argument. Geoengineering entails 'messing with' a complex, poorly understood system: since we cannot reliably predict results its unethical to geoengineer. Because we are already perturbing the climate system with consequences that are unpredictable, this argument depends on the notion that intentional manipulation is inherently worse than manipulation that occurs as a side-effect.

One may analyze geoengineering using common ethical norms; for example, one could consider the effects of geoengineering on intergenerational equity, or on the rights of minorities (e.g., the inhabitants of low-lying countries). However, these modes of analysis say nothing unique about geoengineering, and could be applied in a similar manner to many other technological choices. Some people would argue that such analysis fails to address a particular ethical abhorrence they feel about geoengineering and that we should look for an ethical analysis that addresses geoengineering in particular; e.g., an environmental ethic.

The simplest formulations of environmental ethics proceed by extension of common ethical principles that apply between humans. A result is "animal rights" in one of its variants; e.g., Regan (The Case for Animal Rights, University of California Press, Berkeley 1983). Such formulations locate "rights" or "moral value" in individuals. When applied to a large-scale decision such as geoengineering, an ethical analysis based on individuals reduces to a problem of weighing conflicting rights or utility. As with analyses that are based on more traditional ethical norms, such analysis has no specific bearing on geoengineering. Alternative, and more controversial, formulations of environmental ethics locate moral value in systems of individuals, such as a species or a biotic community (see for example Callicott, In defense of the Land Ethic, SUNY press, Albany 1989). It is plausible that such a formulation of environmental ethics could more directly address the ethics of geoengineering.

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Geoengineering Scheme	COM[*]	Technical Uncertainties	Risk of Side Effects	Non-Technical Issues
Injection of CO_2 into the ocean.	30-80	Costs are much better known than for other geoengineering schemes. Moderate uncertainty about fate of CO_2 in ocean.	Low risk. Possibility of damage to local benthic community.	Like abatement this scheme is local with costs associated with each source. Potential legal and political concerns over oceanic disposal.
Injection of CO_2 underground.	30-80	Cost are know as for CO_2 in ocean; less uncertainty about geologic than oceanic storage.	Very low risk.	Is geologic disposal of CO_2 geoengineering or a method of emissions abatement?
Ocean fertilization with phosphate	1-3	Uncertain biology: can ecosystem change its P:N utilization ratio?	Moderate risk. Possible oxygen depletion may cause methane release. Changed mix of ocean biota.	Legal concerns: Law of the Sea, Antarctic Treaty. Liability concerns arising from effect on fisheries; N.B. fisheries might be improved.
Ocean fertilization with iron	0.3-3	Uncertain biology: when is iron really limiting?	As above.	As above.
Intensive forestry to capture carbon in harvested trees.	3-100	Uncertainty about rate of carbon accumulation, particularly under changing climatic conditions.	Low risk. Intensive cultivation will impact soils and biodiversity.	Political questions: how to divide costs? Whose land is used?
Solar shields to generate an increase in the Earth's albedo.	10-100	Costs are large and highly uncertain. Uncertainty dominated by launch costs.	Very low risk. However, albedo increase does not exactly counter the effect of increased CO_2.	Security, equity and liability if system used for weather control.
Stratospheric SO_2 to increase albedo by direct optical scattering.	<< 1	Uncertain lifetime of stratospheric aerosols.	High risk. Effect on ozone depletion uncertain. Albedo increase is not equivalent to CO_2 mitigation.	Liability: ozone destruction.
Tropospheric SO_2 to increase albedo by direct and indirect effects.	< 1	Substantial uncertainties regarding, aerosol transport and their effect on cloud optical properties.	Moderate risk: unintentional mitigation of the effect of CO_2 already in progress.	Liability and sovereignty because the distribution of tropospheric aerosols strongly effects regional climate.

Table 1. Summary comparison of geoengineering options. (*) Cost of Mitigation (COM) is in dollars per ton of CO_2 emissions mitigated. While based on current literature, the estimates of risk and cost are the authors alone.

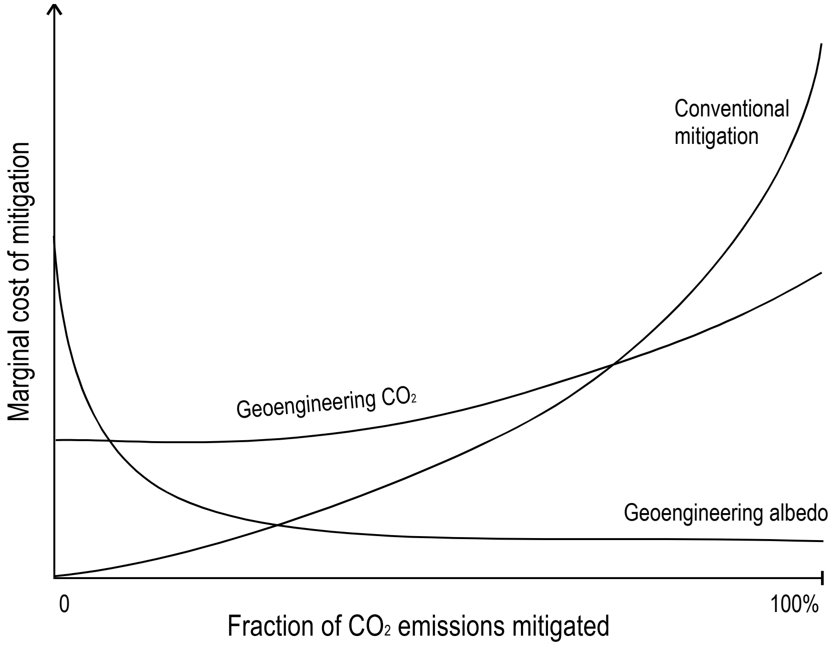

Figure 1. Schematic comparison between modes of mitigation. Conventional mitigation means any method other than geoengineering; e.g., conservation, fuel switching, or use of non-fossil energy sources. Albedo modification schemes (e.g., solar shields) have high initial capital costs, but can provide essentially unlimited mitigation at fixed marginal cost. Geoengineering by disposal of CO_2 costs more than conventional mitigation for small amounts of mitigation, but less than conventional mitigation if we require mitigation of all CO_2 emissions.

Risk	Cost		
	low	medium	high
low	—	Intensive forestry for carbon sequestration	Solar shields CO_2 disposal
medium	Tropospheric SO_2 Ocean fertilization with iron	Inert stratospheric aerosols Ocean fertilization with phosphate	Balloons in the stratosphere
high	Stratospheric SO_2	—	—

Table 2. Costs *vs* risks of geoengineering schemes. Cost and risk estimates are qualitative estimates informed by current knowledge. This kind of systematic inter-comparison is useful in setting geoengineering research priorities.