Ranking geo-engineering schemes

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Geo-engineering proposals for mitigating climate change continue to proliferate without being tested. It is time to select and assess the most promising ideas according to efficacy, cost, all aspects of risk and, importantly, their rate of mitigation.

Propelling aerosols into the upper atmosphere or pumping carbon dioxide into the deep ocean are just two schemes that have been proposed to repair the Earth's climate through geo-engineering[1] (see Box 1). In the absence of adequate reductions in anthropogenic CO_2 emissions, geo-engineering has been put forward as the only remaining option that might fix our rapidly changing climate[2]. Because such schemes are planetary in scale[1], they are newsworthy and have long received widespread media attention[2,3]. Increasingly, the merits and drawbacks of at least testing the proposals are also prompting scientific debate[4]. Despite the surge in interest in old and new schemes[5], at present no geo-engineering proposal has been tested or even subjected to preliminary trials.

Although some proposals have been publicized for many years, little progress is evident[6] in ranking geo-engineering schemes since an initial comprehensive effort[7] 15 years ago. Appraising the relative merits of geo-engineering designs for a purposeful perturbation of the Earth system is essential: funds to investigate such proposals in detail are limited, and not all schemes can be put in place if we are to monitor the Earth system's response to each scheme with any confidence. The suggestions for geo-engineering are as diverse as they are controversial[1,7], and ranking them is not straightforward.

RE-EVALUATING EFFICACY AND COST

The rationale for any geo-engineering scheme must be based on its efficacy. Geo-engineering proposals are divided into two main groups. Some schemes propose to halt climate change by the storage of carbon where it cannot impact climate. Another class of schemes seeks to reduce the solar radiation that reaches the Earth's atmosphere, thereby compensating for the anthropogenic greenhouse effect[1,7]. Schemes based on carbon storage will also offset the effects of ocean acidification, whereas proposals to change radiative forcing do not combat changes in ocean chemistry.

Existing proposals have been evaluated using a range of approaches (Fig. 1), often starting out with over-optimistic claims on efficacy. For example, the proposed stratospheric injection of sulphur particles was expected to reverse the climate effects of rising atmospheric CO_2 concentrations completely[8]. This assessment of efficacy was based largely on the historical precedent of the atmospheric impact of the Pinatubo volcanic eruption, which suggested a large climate effect following an injection of sulphate particles into the stratosphere. Close scrutiny of this eruption has revealed that its climate impacts were complex and that additional causative mechanisms probably altered the climate at the time[9].

Similarly, the efficacy of Southern Ocean iron fertilization was based on a precedent in the geological past: the observed anti-correlation of dust supply and atmospheric CO_2 concentrations over millennia[10]. As for Pinatubo, other compelling candidate mechanisms, such as changes in ocean ventilation, have since emerged to explain altered climate conditions in the geological past, calling into question the schemes' mitigation efficacy[10]. Moreover, modelling studies based on better understanding of the Earth system now provide more realistic constraints on the potential carbon sequestration following ocean iron fertilization[11]. Hence, the efficacy of iron fertilization is probably less than one-third of that initially claimed[10]. Most other geo-engineering ideas lack precedents. As they are entirely based on theory and/or model simulations (Fig. 1), efficacy is even more uncertain, making any ranking efforts difficult.

Early cost assessments of geo-engineering schemes also require revision in the light of recent work. In the past 15 years, Earth system research pertinent to geo-engineering[4] has revealed many unknowns, including potentially expensive side-effects, that will increase these initial, over-simplistic cost estimates (Fig. 1). For example, model simulations of the global impact of decadal iron fertilization reported 'far-field' basin-scale effects, such as substantial reductions in the productivity of distant waters, driven by local removal of plant nutrients during fertilization[11]. And complex side-effects, for example on regional hydrological cycles, have been linked to stratospheric injection of sulphate particles from the Pinatubo eruption[12].

This possibility of unwanted side-effects must be factored into the cost of schemes (Fig. 1). In addition, unintended changes in the Earth system could, to an unknown degree, cancel out the mitigation of climate change driven by geo-engineering, causing a reduction in the estimated efficacy of a scheme and an increase in its cost.

FACETS OF RISK

Risk has long been included in classifications of geo-engineering schemes[6,7]. However, both the degree and categories of risk will vary widely when systems with differing complexity are perturbed: physicochemical engineering schemes, including the stratospheric projection of sulphur particles[8], differ greatly from geochemical carbon capture schemes[13] or biogeochemical ocean fertilization proposals[10,11]. Of course, other much greater risks, such as geopolitical, social and economic changes in response to climate changes from either greenhouse gas increases or geo-engineering[14], are even harder to assess and are not taken into account here.

An assessment of risks associated with geo-engineering proposals can be divided into broad groups according to their degree of predictability (Fig. 1). The first group, anticipated side-effects such as acid rain or ozone depletion resulting from stratospheric sulphur injection[2], can be quantified now, given reasonable effort. The second group, initially unanticipated side-effects (such as the decreased ocean productivity upon phosphate fertilization reported for a study of the Mediterranean Sea[15]) are not yet understood mechanistically — a necessary precursor to eventual prediction and quantification. Third, entirely unexpected side-effects of an unknown nature may become apparent only once a large-scale geo-engineering effort is already underway. Insight into the range and scale of potential side-effects is best gained from global-scale modelling. Simulations can probe the influences of the Earth system on large-scale perturbations, for example global ocean circulation[11]. These model studies point to the dangers inherent in scaling up the findings from any pilot study[10,11].

Additional risks are associated with both the implementation and verification of geo-engineering proposals. The degree of difficulty (and hence risk) in verification will vary between schemes (Fig. 1). For example, the ocean must be iron-fertilized continuously for decades to have any potential mitigation impact[11]. Such a sustained perturbation in a complex system will increase both the difficulty in verification and the period needed to achieve it. During implementation, the residence time of the agent of perturbation in the environment largely determines the magnitude and lifetime of detrimental side-effects. For example, atmospheric residence times of sulphate particles are relatively short (of the order of years[8]) whereas longer timescales (decades or longer[11]) are likely for iron added to oceanic regions. Finally, detrimental side-effects could linger if nonlinear effects of a geo-engineering scheme resulted in irreversible perturbation of the Earth system. Such effects urgently need to be anticipated, and assessed as far as possible.

TIME IS SHORT

Up to now, the relative merits of various geo-engineering schemes[1,7] have mainly been discussed in the context of risk and cost[6,7], with a few reports on individual schemes also looking at efficacy[10]. But restricting an evaluation to these three factors is of limited value. Two disparate recent studies, one using climate modelling to explore the implications of delaying climate mitigation[16], the other on designing a global response plan to confront climate change[17], suggest that relief from climate warming will be needed very soon. The timescale to advance each scheme from development to implementation to verification and hence mitigation is therefore of primary

Box 1 Geo-engineering schemes under discussion

Carbon burial. Long-term physical storage of atmospheric CO_2 under pressure, confined below the Earth's surface within selected structures such as disused aquifers[7,13]. Related approaches include deep-ocean carbon sequestration based on hydrate formation. Both have been debated since the early 1990s[7].

Geochemical carbon capture. Chemical transformation of carbon in CO_2 gas to either the dissolved phase (that is, to bicarbonate ions in sea water) or the solid phase (carbonation)[13] in the ocean or in brines, analogous to weathering of minerals that occur in nature. The method was first detailed in the early 1990s[7].

Atmospheric carbon capture. Direct capture of CO_2 in air masses by using some form of wind scrubbing with a chemical absorbent. The CO_2 is bound only lightly so that it can subsequently be released and transformed chemically before final storage[14]. Proposed schemes have advocated using medium-sized towers to carry out the wind scrubbing, or using the wind fields around turbines[14]. This idea has been around since the late 1990s[14].

Ocean fertilization. Continuous fertilization, over decades, of ocean waters that have a perennial excess of plant nutrients, in order to boost phytoplankton productivity and consequently increase the sequestration of atmospheric CO_2 into deep water[10]. Similar potential approaches include nitrogen fertilization of coastal waters (proposed in the late 1990s) or purposeful mixing of deep nutrient-rich waters into the surface ocean (proposed in 2007)[5] in the low-latitude ocean. Iron fertilization has been discussed since the early 1990s[7].

Stratospheric aerosols. Injection of sulphur particles into the upper stratosphere, using balloons or projectiles, which are there to form aerosols[2,8]. The aerosols alter the Earth's albedo and reflect a proportion of incoming sunlight back into space, mimicking the effect of a volcanic eruption[8]. This approach has been discussed since the early 1990s[7].

Cloud-whitening. Spraying of small seawater droplets from many wind-driven vessels into the turbulent boundary layer underlying marine clouds. The scheme is based on observations of the cumulative impact of ship exhausts in busy shipping lanes[19]. The droplets are thought to increase the reflectance or albedo in existing clouds. This idea was first communicated recently[19].

Sunshades in space. Launch of a very large number of sunshades, which will orbit the planet and redirect incoming sunlight in space[1,7]. The scheme was first mentioned in the early 1990s[7].

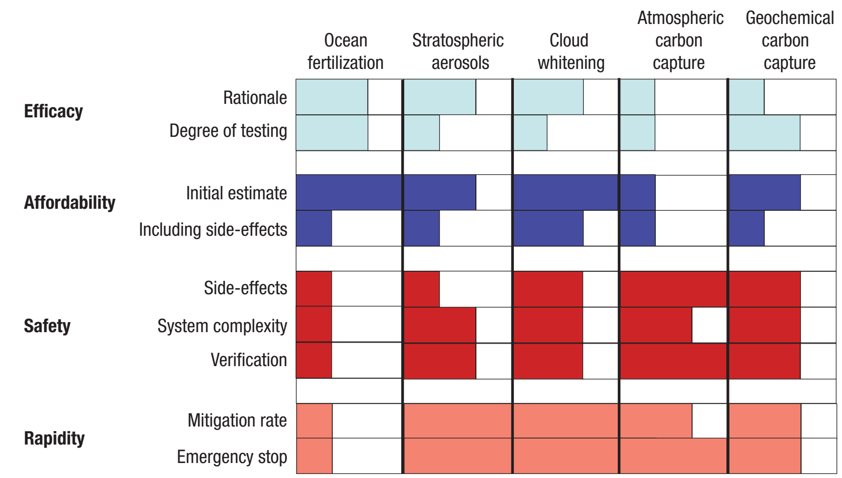

Figure 1 Comparison of aspects of five geo-engineering proposals. The schemes (see Box 1) span both carbon storage and reductions of solar radiation, and have been prominent in both the popular[2,3,20] and scientific[4,8] media. The figure highlights schematically some facets of the four criteria: efficacy, cost, risk and time. The assessment gives scores relative to other schemes. For each facet, more colour denotes a higher ranking. Efficacy is assessed in the first line according to the provenance of a scheme, with those based on historical precedents[8,10] rated higher than those derived from theory and/or models. The extent of testing is shown in the second line, with related observations from experiments[10,15] or pilot studies scoring higher than model simulations, which in turn rank above a proposal with accompanying technical details. The full degree of efficacy is too uncertain at present to depict as a facet in this inter-comparison and will need further research. Affordability is categorized as initial cost assessment from the designer of a scheme[3] in the upper line and a more realistic cost assessment including additional costs that come with a scheme's risks in the lower line. Safety provides an assessment of risk, which is related to known side-effects, with unknown side-effects represented here by system complexity (biogeochemical complexity[10,11] is larger than geochemical[13] complexity, which is larger than physicochemical[8] complexity) and the verification of both efficacy and side-effects. Other important but very uncertain aspects of risk, such as geopolitical and economic changes, require further research. Relevant aspects of time include the rate of climate mitigation in the top line (higher rates are better[18]), and the rapidity with which to halt any unanticipated deleterious effects, based on residence time of the agent of perturbation in the environment (shortest residence scores highest).

importance. If geo-engineering is to have a role in stabilizing our climate[18], we must apply metrics that incorporate efficacy, cost, risk and time in order to rank where future research effort is best focused.

The timescale for mitigation — and also that needed to halt detrimental side-effects of a failed geo-engineering scheme — could be used as a knock-out criterion for proposed schemes. A proposal that cannot bring sufficient benefits within the next few decades, and that cannot be arrested quickly (that is, within months to years, as claimed for cloud whitening[19]) if necessary, should not be considered further. Ocean iron fertilization is one example of this. Although its precedent — sustained fertilization in the geological past — strongly suggests a reduction in atmospheric CO_2 of up to 30 ppm, its mitigation timescale of millennia is not useful[10].

Time also affects the cost of geo-engineering approaches. Some costs will increase because of inflation, for example, during long-term implementation or verification. Other expenditures will decrease as technology improves, such as anticipated for carbon capture and storage[14]. Once time is fully taken into account, cost estimates can be compared meaningfully with costs associated with inaction on tackling climate change that are subject to the same time-dependent variations[17]. To assess efficacy, the rate of climate mitigation is more important than its magnitude[18]. All other properties being equal (efficacy, cost and risk), schemes that work in the short term are preferable over medium- to long-term ones.

SELECTED SCHEMES UNDER SCRUTINY

It is only by carefully estimating efficacy versus true cost that we can determine which schemes should be investigated further. At a time when most schemes have been proposed by either individuals or commercial companies, ranking the proposals according to objective criteria would improve the likelihood of securing research money from governments to investigate the most promising schemes further[20]. A transparent assessment should strive to increase public confidence in any selected tools, a prerequisite for tackling the difficult questions and complex issues raised by geopolitical, social and economic risks[14]. Such an assessment of all of the well-established proposals is urgently needed but so far entirely lacking[20].

Funding research into only a few promising schemes, according to such metrics, may lead to one or two relatively reliable mitigation options that can be placed in a 'climate-change toolbox'. In the near future, we must decide the relative importance of time, cost, risk and efficacy in tackling climate change if it is decided to press ahead with a geo-engineering approach. Of course, it could transpire after such an analysis that climate mitigation strategies with a very low risk but apparently higher costs, such as direct carbon capture and storage[14], are the best approach. As the costs of inaction[17] and of delaying the mitigation of climate change[16] are rising, an initial high investment — matched with a very low risk — may seem more and more reasonable.

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