An interdisciplinary assessment of climate engineering strategies

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Mitigating further anthropogenic changes to the global climate will require reducing greenhouse-gas emissions ("abatement"), or else removing carbon dioxide from the atmosphere and/or diminishing solar input ("climate engineering"). Here, we develop and apply criteria to measure technical, economic, ecological, institutional, and ethical dimensions of, and public acceptance for, climate engineering strategies; provide a relative rating for each dimension; and offer a new interdisciplinary framework for comparing abatement and climate engineering options. While abatement remains the most desirable policy, certain climate engineering strategies, including forest and soil management for carbon sequestration, merit broad-scale application. Other proposed strategies, such as biochar production and geological carbon capture and storage, are rated somewhat lower, but deserve further research and development. Hence, fertilization of the oceans and solar radiation management, although cost-effective, received the lowest ratings on most criteria. We conclude that although abatement should remain the central climate-change response, some low-risk, cost-effective climate engineering approaches should be applied as complement strategies. The framework presented here aims to guide and prioritize further research and development, leading to improved entry in climate engineering strategies.

In a nutshell:

- A better understanding of greenhouse-gas emissions should aim the focus of climate-change policy.
- Given their associated uncertainties and risks, climate engineering strategies best serve as core plans to abate emissions.
- We provide a framework to assess climate engineering strategies and determine their performance in considering criteria such as cost-effectiveness, ecological risk, and institutional capacity.
- These strategies are evaluated and ranked according to six criteria (Figure 1), with abatement (as opposed to no action taken) as a basis for comparison, this framework includes a broader array of criteria than that of previous assessments, and each criterion is addressed in terms of the best available literature. This multi-attribute trade-off approach does not apply weights to the criteria, but instead employs a collaborative approach to produce numerical scores for each criterion and strategy (Figure 1, Table 1). Here, we (1) focus on feasible strategies to mitigate anthropogenic climate change; (2) provide a coherent interdisciplinary discussion to assist international-level decision makers in selecting strategies best suited to their institutional strengths, and evaluating risks and benefits; and (3) encourage analysts to

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propose alterations to the assessment methodology, to conduct further research, and ultimately to improve management and implementation of climate engineering.

In our assessment, some strategies pose substantial multidimensional challenges, whereas others offer feasible options for abatement. We briefly introduce the strategies, and then apply the six criteria.

**Strategies**

This section describes abatement and climate engineering strategies, focusing on the maximum potential effect (i.e., C sequestration or cooling effects) of each. Underdeveloped strategies (e.g., accelerated weathering of rock) are described but not analyzed further.

**Abatement**

Carbon abatement reduces GHG emissions through means such as energy efficiency, conservation, and fuel switching. To illustrate, Pacala and Socolow (2004) identified several CO₂ reduction methods equivalent to offsetting 1 gigaton of C per year (G T C yr⁻¹), including doubling vehicle fuel economy (efficiency), reducing vehicle use by one-half (conservation), or switching vehicle fuels from petroleum to biomass (fuel switching).

Consensus estimates suggest that abatement could theoretically reduce GHG emissions by 1-9 G T C yr⁻¹ by 2030 (IEA 2011). To put this into perspective, human activity adds ~9 G T C yr⁻¹ to the 800 G T already present in the atmosphere (IPCC 2007). Forest regrowth and dissolution of CO₂ into oceans remove ~5 G T C yr⁻¹ from the atmosphere, but this uptake is projected to diminish over time, leaving at least 4 G T C yr⁻¹ to abate, sequester, or cancel out (Cox et al. 2000).

**Biological C sequestration**

These strategies are based on the photosynthetic activity of living organisms and on storage of organic C in plants and soils. Several approaches have received considerable attention. First, reducing deforestation and promoting forest growth globally could sequester an estimated 1.3 G T C yr⁻¹ in biomass, with deforestation currently contributing >1 G T C yr⁻¹ to the atmosphere (IPCC 2007). Forest regrowth and dissolution of CO₂ into oceans remove >5 G T C yr⁻¹ from the atmosphere, but this uptake is projected to diminish over time, leaving at least 4 G T C yr⁻¹ to abate, sequester, or cancel out (Cox et al. 2000).

**Abiotic C sequestration**

Strategies include carbon capture and storage (CCS) from point sources and diffuse sources, and accelerated weathering of rock. Point-source CCS involves CO₂ emitted from industrial coal and natural gas burned in power plants and sequestered in geological formations on land or in the ocean. Abiotic CCS currently stores on the order of 5-6 G T C yr⁻¹, but has the potential to reach 1-4 G T C yr⁻¹, or up to 345 G T C total over time (IPCC 2007; Herzog 2011). Capture of CO₂ from an industrial source (as a diffuse source) would sequester CO₂ from the atmosphere, but is currently in practice because of high costs and compliance with existing regulations. In contrast, weathering of rock would sequester CO₂ in stable carbonates through chemical reaction with metal oxide residues.
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oxides, but energy requirements make this unfeasible with current technologies (Anderson and Newell 2004). Thus, subsequent sections analyze only point-source CCS.

Solar radiation management (SRM)

These efforts aim to reduce solar energetic input to Earth, where it turns into radiant heat, by increasing albedo (reflectance). Proposed methods include stratospheric aerosols, marine cloud brightening via increased water droplet concentration, outer-atmosphere reflectors, and whitening of surfaces in cities, oceans, and deserts (GAO 2011). The projected cooling potential of combined SRM strategies is slightly higher than the predicted effects of forest management C sequestration (WebTable 1).

Application of criteria

Technical potential

Technical potential here refers to the technological feasibility of implementing a strategy, the potential for increasing total C storage, and the duration of C storage.

The technical potential for abatement is extremely high, because efficiency, conservation, and fuel switching have all been tested and developed much more extensively than climate engineering strategies. To be effective, abatement efforts must be sustained in perpetuity.

Forest management and regrowth present few technological obstacles. However, availability of suitable land and constraints in land management, and plant or plantation life spans limit the duration of aboveground C storage. Less is known about how to implement soil management for large-scale, long-term C storage, which depends on highly uncertain effects of ecosystem properties, land-use history, and organic tissue chemistry (Schmidt et al. 2011). For biochar, although efficient combustion technology is available, resistance to decomposition over the long term is likely to vary across sites, depending on properties such as microbial activity and soil mineralogy (Cusack et al. 2013; Gurwick et al. 2013). Widespread application of biochar to soils, as well as availability of biomass inputs for production, present technical challenges. Although ocean fertilization

Table 1. Interdisciplinary framework to assess climate engineering strategies

<table>
<thead>
<tr>
<th>Category</th>
<th>Technical potential</th>
<th>Cost effectiveness</th>
<th>Ecological risk</th>
<th>Other criteria</th>
<th>Institutional capacity</th>
<th>Public acceptance</th>
<th>Scope of ethical concerns</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) Carbon sequestration potential</td>
<td>(a) Cost per ton CO₂ reduction equivalent</td>
<td>(a) Physical and chemical side effects on ecosystems</td>
<td>(a) Locus of decision making</td>
<td>(a) Perceived risks and costs</td>
<td>(a) Governance</td>
<td>(b) Trust</td>
<td>(b) Responsibility for consequences</td>
</tr>
<tr>
<td>(b) Global cooling potential</td>
<td>(b) Cost uncertainty</td>
<td>(b) Biological effects on organisms</td>
<td>(b) Distribution of benefits/risks</td>
<td>(b) Time scale</td>
<td>(c) Fairness</td>
<td>(c) Burdens of action</td>
<td></td>
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<tr>
<td>(c) Likely duration of sequestration effectiveness (years)</td>
<td>(c) Potential feedbacks to warming</td>
<td>(c) Perceived “naturalness”</td>
<td>(d) Observability of option</td>
<td>(d) Acceptability of risk</td>
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<td>(d) Life-cycle assessment (energy required to initiate)</td>
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<td>(e) Weighing options</td>
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<td></td>
<td>(f) Moral failure to abate</td>
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applies to be technically simple, requiring only distribution of CO₂ inhaled (de Baar et al. 2005). The effectiveness depends on algal cells sinking into the deep ocean. Field studies have shown that not only a small percentage of the CO₂ from fertilized algal blooms (< 25%) sinks to the deep ocean (de Baar et al. 2005), but a large fraction of that remains in the bloom (Landry et al. 2000).

Point-source CCS is well developed and has been used successfully for several decades in the oil and gas industry. However, there are concerns about the possibility of leakage of CO₂ from storage reservoirs. Leakage could seriously compromise the strategy’s long-term effectiveness. Achieving a long-term climate benefit as low as 1.0 mm decade⁻¹ requires leakage rates from storage sites less than 1 % per thousand years (Shaffer 2010). While some offshore marine locations may offer lower risks of leakage, one estimate suggests an additional technical challenge.

All SRM strategies would require not only further research and development but also continual maintenance for long-term effectiveness. Space-based reflection presents extreme management challenges. Ground-whitening solutions are limited by the relatively small area that could be lightened. Marine cloud brightening presents technological challenges for continual suspension of water droplets. This leaves stratospheric aerosols as the most technically viable option, although questions about appropriate particle size and duration remain; subsequent discussion of SRM focuses on this strategy.

Cost-effectiveness

The cost-effectiveness of climate engineering strategies is framed here as marginal costs, or dollars spent to reduce CO₂ emissions (or the equivalent in terms of avoided climate warming) by one tonne of CO₂.

For abatement, the costs range from $20–200 per ton of CO₂ (IPCC 2001; Steem 2007) but vary widely by technology, sector, region, time scale, and magnitude. Faster, deeper cuts impose higher marginal costs. For example, one US estimate for abatement is $15 per ton for a 10% reduction in CO₂, but over $120 per ton for 50% reduction (Mulford et al. 2011).

Carbon engineering proposals often promise low costs relative to abatement (Bazett et al. 2008). Nevertheless, estimates are subject to considerable uncertainty and are often presented as a single cost, ignoring marginal costs. Regarding biological sequestration, abatement is a management challenge. Carbon sequestration in soils (Bala et al. 2007) may promote cloud formation and may alter climated e patterns, potentially producing additional GHGs via off-gassing, and reducing regional water availability. Establishing forests in previously unforested areas may also alter weather patterns due to surface roughness and transpiration of water to the atmosphere from trees (Baier et al. 2007). Soil management and carbon-rich grasses grown on marginal, unforested lands that are unsuitable for agriculture (Costanza 1980).

Ocean fertilization is often portrayed as the cheapest strategy, potentially costing only a few dollars per ton of CO₂, equivalent to some strategies (Shepherd et al. 2009). Yet to sustain lower temperature, SRM would require perpetual maintenance that would most likely lead to higher costs and increased management challenges. Given the risk of sudden warming if the strategy were abandoned, these costs would be incurred indefinitely.

Ecological risk

Ecological risk is the potential for loss of ecosystem function, biodiversity, and/or ecosystem interactions, and overall threat to the integrity of the global biosphere. A abatement poses little ecological risk, although these risks may vary from energy-saving materials (eg mercury in compact fluorescent bulbs) to the effects of land-use changes associated with alternative fuels (Costanza 1980). Forest and soil management appear to be ecologically attractive options because they are linked to ecosystem restoration, but these are geographical concerns. Foreexample, increasing forest cover in snow-covered, high-latitude regions could contribute to warming by darkening the Earth’s surface. However, this effect could be offset by changes in surface reflectance elsewhere. A more pressing concern is that sequestration on degraded lands may require fertilization and, to a lesser extent, producing additional GHGs via off-gassing, and reducing regional water availability. Establishing forests in previously unforested areas might also alter weather patterns due to surface roughness and transpiration of water to the atmosphere. SRM would require perpetual maintenance that would most likely lead to higher costs and increasing management challenges. Given the risk of sudden warming if the strategy were abandoned, these costs would be incurred indefinitely.
CCS methods are associated with the risk of accidental leakage of concentrated liquid CO₂, which depletes oxygen and can lead to anoxia if the gas reaches high concentrations in nearby areas (Kling et al. 1987). Injection of CO₂ underground also has the potential to cause small earthquakes (Zoback and Copley 2012). Storage of CO₂ in the deep ocean could lead to extreme ocean acidification and high levels of dissolved CO₂ in the water column (Shaffer 2010), affecting marine animals and marine ecosystems.

SRM carries ecological risks of uncertain but potentially severe magnitude and duration. The risks associated with intervening in global atmospheric systems are extremely high, since a single intervention can cause multiple non-linear feedbacks to weather and climate patterns over multiple time scales (Hansen et al. 2007). Furthermore, by focusing solely on temperature, SRM fails to address other issues associated with rising CO₂ in the atmosphere, such as ocean acidification.

Institutional capacity

The term institution here refers to a system of rights, rules, and decision-making procedures for a climate engineering option (Young et al. 2008). Institutional capacity is the ability of these systems to effectively govern a climate engineering approach. Five primary characteristics of any given engineering strategy influence the capacity to govern it: (1) the number of decision-makers needed for plan enforcement; (2) distribution of risks and benefits, which determine stakeholders and influence consensus-building; (3) uncertainty regarding the possible harms and benefits of an engineering strategy, which inform how adaptive an institution must be; (4) the homogeneity or inhomogeneity of a climate engineering option across the planet, which can require different institutions and institutional capacity; and (5) the option’s ability to be seen or measured, which influences ease of monitoring and enforcement (Dietz et al. 2007). Prominent discussions of institutional rules have focused on managing research and results, using informed consent, and creating institutional review boards (Kintisch 2010).

One of the biggest challenges for climate engineering is that each strategy varies greatly in the characteristics described above; therefore the optimal decision-making procedures, rules, and rights also vary greatly. The range in scale, in the nature of risks and uncertainties, and in the ease of difficulty of enforcement suggests that a polycentric system is the best approach. Components of such a system could be managed and enforced by specific countries, which have varying degrees of capacity from local to international and from regional to global. A basin could be achieved through a variety of policy mechanisms, including C pricing, cap-and-trade, technology standards, and incentive programs; organizations could verify decreased energy use through energy monitoring systems. However, fragility of relevant markets and a diversity of decision-making processes pose major challenges to the implementation of abatement and management (Barn et al. 2012). For instance, there is the problem of split incentives, where those who invest in efficient technologies (e.g., multifamily building owners) do not always benefit from the savings (e.g., lower energy bills for tenants). Market policies may address some of these challenges. Energy efficiency policies have historically been implemented at local and national levels, engaging efforts such as the Super-efficient Equipment and Appliance Deployment Initiative's Global Energy Efficiency Standards, labeling, and procurement to coordinate action between non-governmental organizations and industrialized and developing nations to coordinate a "global asset transformation action".

Regarding biotic sequestration options, forest and soil management appear considerably easier to govern than other engineering strategies. They can be undertaken nationally and managed at local levels, pose low risk of harm, yield benefits in the aggregate, and are easier to enforce. Forest and soil management, however, would require long-term monitoring and international cooperation to be effective on a global scale.

Ocean fertilization presents greater challenges because it would require us to place in international waters, the stakeholders are less obvious, the risks of harm are extremely high, and there is great uncertainty regarding C sequestration benefits. Corporations tested this strategy in the absence of regulation until 2008, when the UN Convention on Biological Diversity placed a moratorium on large-scale commercial ocean fertilization (Tollefson 2008). Recent rogue ocean fertilization events have placed the effectiveness of this moratorium in question (Fountain 2012) and highlight the need for international cooperation.

A biotic C storage option presents complex institutional challenges, in particular the need for long-term monitoring to prevent CO₂ leakage into the atmosphere from underground reservoirs. CCS can be undertaken at the local level by a small number of decision-makers and is currently regulated in the US at the federal level by the Environmental Protection Agency. It is associated with milder and uncertain risks of ecological damage that would be relatively localized, so governing institutions should engage local stakeholders.

SRM is extremely challenging to govern. It poses potentially large-scale risks to the climate system, yet could be put into action by only a few decision-makers. Risks and benefits are distributed differentially worldwide, depending on changes in weather patterns. SRM governance would entail consistent monitoring to integrate new information and maintain agreed-upon targets, and would require restraining and coordinating actions.

Public acceptance

The public acceptance criterion assesses whether citizens will embrace, tolerate, or resist a given strategy. Relevant factors include: (1) perceptions of favorable
benefits; (2) costs and risks; (3) knowledge and trust of the technology; (4) trust in the actors in play among the strategy; (5) fairness in decision making; and (6) equitable distribution of costs and benefits (Kuijts et al. 2012). Because public awareness of climate engineering strategies is minimal (Sharp et al. 2009; GAO 2011; Mercer et al. 2011), it is difficult to assess public opinion, and thus estimate of public acceptance remains preliminary (M alone et al. 2010). Current research relies on surveys, qualitative interviews, and focus groups wherein researchers first explain a strategy and then elicit opinions from participants. This approach may provide a baseline for acceptance, but public perceptions can change with exposure to different types of information (Stephens et al. 2009) and public consultation (Temesy et al. 2010).

When discussing abatement, members of the public are likely to be more supportive of subsidies for efficient technologies, less supportive of technology-forcing standards (ie required to achieve an emissions limit), and least supportive of taxes on CO2 emissions (Dietz et al. 2007). Support tends to be lowest for the abatement policies that are most likely to be effective (eg C pricing). Policy-makers’ perceptions of such public resistance tend to prevent enactment of stringent abatement policies (Hartzell-Nichols 2012). Abatement also raises environmental concerns, including the distribution of social costs, but these are relatively minor as compared to those associated with climate engineering approaches.

Among climate engineering strategies, forest and soil management have the lowest risk of unintended consequences, which minimise the above-described concerns.

Scope of ethical concerns

Climate change presents a moral dilemma involving issues of justice, the value of human nature, and obligations to future generations (Gardiner 2011). Similarly, climate engineering poses complex moral questions (Preston 2012). Key ethical concerns include: (1) who should govern; (2) burden-sharing and distribution of costs; (3) levels of acceptable risk; (4) weighing options against alternatives; (5) responsibility for harm; and (6) background costs given the lack of effective abatement efforts to date. Climate engineering policies and research that fail to address these issues pose ethical risks (Tuana et al. 2010). In general, climate interventions should have predictable consequences and should not violate well-founded ethical principles (Jimerson 1996). They must be shown to be safe before being entertained (Shepherd et al. 2009), although standards of proof and safety remain an open debate (Hartzell-Nichols 2012). Abatement also raises some ethical concerns associated with the distribution of social costs, but these are relatively minor as compared to those associated with climate engineering approaches.

Among climate engineering strategies, forest and soil management have the lowest risk of unintended consequences, which minimise the above-described concerns. This approach therefore generates the least ethical concern, followed by biochar and geological CCS. Ocean fertilisation and deep-sea CCS entail substantial risks of unintended consequences, including ecological effects and CO2 leakage. SRM presents a particularly extreme and ethically challenging case. To be ethical, such a scale of climate engineering may require worldwide consent (Preston 2012). A key ethical concern is the potential for irreversible changes and major harm to consequences (Corner and Padgen 2010), as SRM might.

Conclusions

The climate engineering strategies assessed here raise complex questions and considerable uncertainties. Nevertheless, this review points to some meaningful conclusions. In light of their limitations and risks, climate engineering approaches would best serve as a complement to—rather than replacement for—abatement, and the latter should remain a focus of climate change policy for the foreseeable future.

Climate engineering efforts should focus first on low-risk strategies, including measures to enhance reliable and well-tried technologies, to reduce costs, to avoid ecological risks, ease of governance, wide public acceptance, and few moral concerns. The focus on SRM applied here gives the most positive ratings to forest and soil management for CO2 storage—more than other strategies such as biochar and geological CCS (Figure 3). Yet biochar application to
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Institutional Capacity, and ethical concerns.

Institutions, and public perceptions associated with all strategies – including abatement – are continually changing. As with many past environmental problems, there might be a largely engineered solution for climate change. Yet historical experience suggests an answer would emerge from an evolution of technologies, institutions, and public behaviors than from a single technical fix (Fanz 1996).

Acknowledgements


References


review of biochar research, with a focus on its stability in situ and its use as a climate change mitigation strategy. PLoS ONE 8: e75922.


