studies and their use as a vital part of building a sustainable future. ❐

Michael Carbajales-Dale[1]***, *Charles J. Barnhart*[2], *Adam R. Brandt*[1] *and Sally M. Benson*[1,2] *are at* [1]*Department of Energy Resources Engineering, Stanford University, Stanford, California 94305, USA.* [2]*Global Climate and Energy Project, Stanford University, Stanford, California 94305, USA.*
**e-mail: mikdale@stanford.edu*

References

1. Hall, C. A., Cleveland, C. J. & Kaufmann, R. *Energy and Resource Quality: The Ecology of the Economic Process* (John Wiley and Sons, 1986).
2. Cleveland, C. J. *Energy* **30,** 769–782 (2005).
3. Brandt, A. R. *Sustainability* **3,** 1833–1854 (2011).
4. Barnhart, C. J., Dale, M., Brandt, A. R. & Benson, S. M. *Energ. Environ. Sci.* **6,** 2804–2810 (2013).
5. Dale, M. & Benson, S. M. *Environ. Sci. Technol.* **47,** 3482–3489 (2013).
6. Carbajales-Dale, M., Barnhart, C. J. & Benson, S. M. *Energ. Environ. Sci.* **7,** 1538–1544 (2014).
7. Kümmel, R. *Energy* **7,** 189–203 (1982).
8. Sorrell, S. *Sustainability* **2,** 1784–1809 (2010).
9. Ayres, R. U. & Warr, B. *The Economic Growth Engine: How Energy and Work Drive Material Prosperity* (Edward Elgar Publishing, 2010).
10. US Energy Information Administration *International Energy Statistics* (EIA, 2012); http://www.eia.gov/countries/data.cfm
11. IPCC *Climate Change 2007: Synthesis Report* (eds Pachauri, R. K. & Reisinger, A.) (Cambridge Univ. Press, 2007).
12. Brandt, A. R., Englander, J. & Bharadwaj, S. *Energy* **55,** 693–702 (2013).
13. Dale, M., Krumdieck, S. & Bodger, P. *Energy Policy* **39,** 7095–7102 (2011).
14. El-Houjeiri, H. M., Brandt, A. R. & Duffy, J. E. *Environ. Sci. Technol.* **47,** 5998–6006 (2013).
15. Zhai, P. *et al. Energ. Environ. Sci.* **6,** 2380–2389 (2013).
16. Barnhart, C. J. & Benson, S. M. *Energ. Environ. Sci.* **6,** 1083–1092 (2013).
17. Gerdes, J. Solar energy storage about to take off in Germany and California. *Forbes* (18 July 2013); http://onforb.es/18ninCv
18. Huettner, D. A. *Science* **192,** 101–104 (1976).
19. Meadows, D. H. *et al. Indicators and Information Systems for Sustainable Development* (Sustainability Institute Hartland, 1998).

Acknowledgements

This work was made possible through funding from the Global Climate and Energy Project (GCEP), Stanford University (http://gcep.stanford.edu), and the Institute for Integrated Economic Research (http://www.iier.ch). Thanks also to M. Shwartz at GCEP for helpful editorial comments.

COMMENTARY:

Climate engineering reconsidered

Scott Barrett, Timothy M. Lenton, Antony Millner, Alessandro Tavoni, Stephen Carpenter, John M. Anderies, F. Stuart Chapin III, Anne-Sophie Crépin, Gretchen Daily, Paul Ehrlich, Carl Folke, Victor Galaz, Terry Hughes, Nils Kautsky, Eric F. Lambin, Rosamond Naylor, Karine Nyborg, Stephen Polasky, Marten Scheffer, James Wilen, Anastasios Xepapadeas and Aart de Zeeuw

Stratospheric injection of sulphate aerosols has been advocated as an emergency geoengineering measure to tackle dangerous climate change, or as a stop-gap until atmospheric carbon dioxide levels are reduced. But it may not prove to be the game-changer that some imagine.

In the 1992 Framework Convention on Climate Change, virtually every country agreed to stabilize concentrations of greenhouse gases (GHGs) in the atmosphere at a level that would avoid dangerous climate change. Since then, however, international cooperation in limiting emissions has been ineffectual and concentrations have continued to rise. Recently, there has been more discussion of limiting climate change by geoengineering, a term taken here to be synonymous with solar radiation management, through the injection of sulphate aerosols in the stratosphere. The technique is even mentioned in the Intergovernmental Panel on Climate Change's 2013 Summary for Policymakers[1].

Two powerful arguments have been made for using geoengineering: as an emergency measure[2] and as a stop-gap[3]. We analyse both proposals from two perspectives: (1) effectiveness — would the use of geoengineering achieve the stated goal? (2) political feasibility — is there a reasonable prospect that the international political system would allow geoengineering to be used to achieve the stated goal? Our main conclusion is that, when the use of geoengineering is politically feasible, the intervention may not be effective; and that, when the use of geoengineering might be effective, its deployment may not be politically feasible. On careful reflection, geoengineering may not prove to be the game-changer some people expect it to be.

The effects of geoengineering

Among the many options for 'global dimming' aimed at limiting global warming, the simplest involves putting sulphate aerosols in the stratosphere to scatter sunlight[4]. This form of geoengineering could reduce temperature in the lower atmosphere quickly. It would also be relatively inexpensive to deploy and could be done unilaterally, without the need for international cooperation. Ironically, however, this is one of geoengineering's problems: its use might harm some countries (for example, by altering the monsoons) even if it were expected to help others. Geoengineering, particularly the use of stratospheric aerosols, poses a challenge for governance.

Of all the arguments against geoengineering, perhaps the one most frequently advanced is that knowledge of geoengineering's ability to cool the climate will reduce the incentive to cut emissions[5]. However, theory and laboratory experiments suggest that the failure to cut emissions can be explained by free-rider problems, including those associated with uncertainty about the true threshold for dangerous climate change[6]. Belief that geoengineering could serve as a cheap and quick fix might further dampen the incentive to cut emissions, but it doesn't seem probable that this belief will, by itself, cause concentrations to exceed dangerous levels. In any event, knowledge of geoengineering cannot be erased.

It is important to understand that geoengineering cannot be used to preserve today's climate. Sunlight scattering would act on shortwave radiation, and GHGs affect long-wave radiation. In theory, atmospheric aerosol injection could be used to limit mean global temperature change to a specific level, such as 2 °C, even as concentrations continue to increase. However, it could not be used to limit changes in temperature and precipitation independently[7]. Moreover, no matter how geoengineering might be targeted, it could not preserve the spatial distribution of either temperature or precipitation, let alone the historical pattern of ocean circulation[7]. Finally, geoengineering would have environmental effects unrelated to the climate. Some of these, such as stratospheric ozone depletion[2], are reasonably well understood, but geoengineering might have other currently unknown effects.

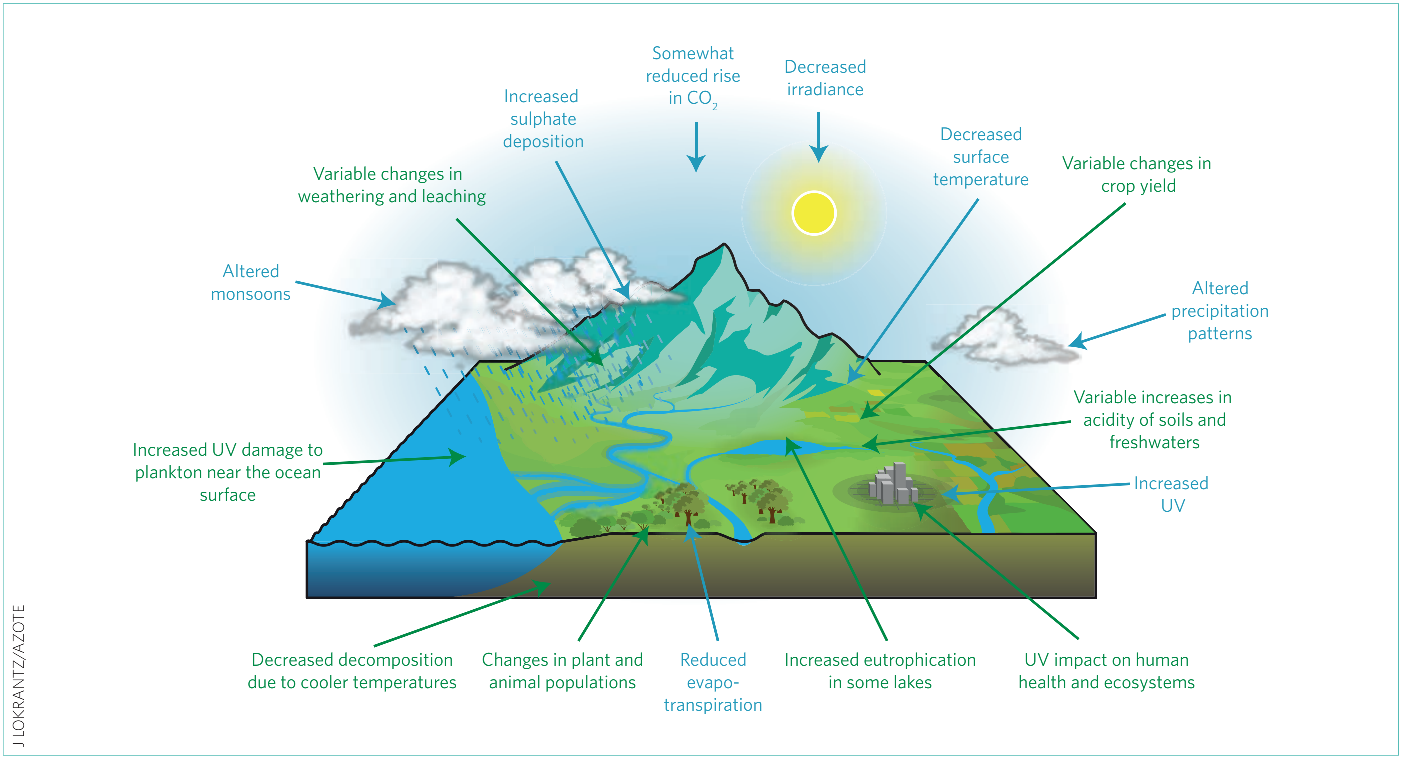
A climate disturbed by elevated CO_2 concentrations and geoengineering would be very different from the current climate (Fig. 1). The behaviour of human societies in this altered environment will also matter. For example, although the combination of CO_2 fertilization and global dimming might increase agricultural yields for certain crops on a global scale[8], the local effects will probably be highly variable, with uncertain implications for land-use change, crop selection, and food prices.

Averting disaster

Would geoengineering be useful as a last resort? The idea seems comforting, but what kind of emergency could be prevented or alleviated by geoengineering? Stratospheric injection of sulphate aerosols would cool surface air temperatures quickly, but if the West Antarctic ice sheet were to disintegrate, the cause would presumably be oceanic, rather than atmospheric warming and it would take centuries for geoengineering to reverse the process leading to this catastrophic collapse[9]. Sunlight scattering would also be ineffective in addressing polar climate emergencies, not least because it cannot directly or quickly affect temperature during the polar winter[10]. Geoengineering could probably help to reduce melting of the Greenland ice sheet[11] and rises in sea level, but these are slow processes that might be better addressed by adaptation, which can also be done unilaterally but without creating significant new risks or arousing geopolitical tensions.

A related problem is the timing of deployment. If countries waited too long before intervening, some geophysical processes might prove impossible to reverse. Early warning signals could help to avert some catastrophes[12]. However, early warnings might be unreliable or come too late to allow geoengineering to avoid catastrophic climate change[13]. A case could be made for using geoengineering prior to any warning signs, to avoid crossing an approaching but uncertain climate tipping point. However, doing so would introduce new dangers (Fig. 1), and it is not clear that the reduction in climate change hazards would justify the risks associated with geoengineering. It is also not clear that countries would approve the use of geoengineering as a precautionary approach to addressing climate change.

The temptation to use geoengineering to address a regional emergency, such as an altered monsoon, might be harder to resist. However, geoengineering could not be counted on to prevent every regional climate crisis. For example, it probably could not prevent Amazonian forest die-back due to drought conditions. Moreover, countries that expect to be harmed by geoengineering would surely act to prevent it from being used. They might offer assistance to the countries contemplating the use of geoengineering, in exchange for these countries agreeing to refrain from deployment. They might also threaten trade



J LOKRANTZ/AZOTE

Figure 1 | The ecological effects of solar radiation management using sulphate aerosols. The schematic shows change in the drivers of ecosystem responses (blue) that are probable to arise from the use of sulphate aerosols, compared with not using sulphate aerosols, given current trends of increasing greenhouse gas concentrations, and the probable ecosystem responses (green). Drivers that are probable to change include temperature, precipitation, irradiance, monsoons and sulphate deposition[16]. Ecosystem responses will be complex, with implications for food production, freshwater supplies, soil and water chemistry, and human health. They will also be spatially variable, creating both winners and losers, and uncertain, possibly causing large changes in ecosystems and in the availability of resources.

Table1 | Evaluation of criteria for use of solar radiation management using sulphate aerosols for key scenarios.

Scenario	Criteria for deployment effectiveness	Political feasibility
Global emergency	Low for ocean warming and the West Antarctic ice sheet, but higher for Greenland ice sheet and for sea-level rise	Relatively high, but perhaps less preferred than adaptation
Regional emergency	Perhaps high for altered monsoon, but low for Amazonian die-back	Low, as probable to induce retaliatory response
Stop gap	Low due to weakened incentives to cut emissions	Fear of addiction may undermine consensus

sanctions, a military response, or the use of counter-geoengineering — the injection of particles designed to warm rather than to cool the Earth. Geoengineering might prove more acceptable if, by agreement, any 'losers' were to be compensated for their losses. However, attributing particular changes to geoengineering rather than to natural variation would be difficult, if not impossible[14].

Buying time

Should geoengineering be used as a stop-gap? If so, the idea would be to deploy stratospheric aerosol injection soon, initially at a low level, and then to turn it up gradually over time, with the goal of limiting temperature change while more effort is put into abating emissions and developing new technologies for reducing emissions[3]. Once concentrations return to a 'safe' level, geoengineering could be scaled back and eventually stopped. This approach would limit the risk of climate change while also limiting the risk posed by geoengineering. However, the assumption that countries will overcome free-rider incentives when geoengineering is used, despite having failed to do so when geoengineering was not used, seems implausible. Therefore, the proposal to use geoengineering as a stop-gap lacks credibility.

Indeed, it seems at least probable that, rather than scale back the use of geoengineering, countries might instead choose to adapt to the combined effects of both climate change and geoengineering. Liming might be used to protect sensitive coral ecosystems from future ocean acidification. Commercially important fish species might be engineered to withstand warmer ocean temperatures[15]. Crops might be engineered to benefit both from higher CO_2 concentrations and from the more diffused light created by sunlight scattering. Use of one form of geoengineering might only beget the use of a multiple of other forms of 'nature engineering'.

If geoengineering were used over a number of decades, and GHG concentrations continued to rise, turning geoengineering off abruptly would cause rapid climate change[1]. It seems more probable, however, that countries will someday cut the amount of reflective aerosols currently emitted by fossil fuel burning, causing regional temperatures to rise. In this situation, the ability of sunlight scattering to lower temperatures rapidly could be an advantage. The bigger risk to using geoengineering, we believe, is not that countries will turn it off abruptly but that, having begun to use it, they will continue to use it and may even become addicted to it.

Thinking again

Analysis of the possible use of solar radiation management in plausible scenarios (Table 1) suggests that, when its use is politically feasible, geoengineering may not be effective; and that, when its use might be effective, its deployment may not be politically feasible. The many problems with geoengineering — its inability to address every climate emergency, the risks associated with its use, the geopolitical problems that would be triggered by its use, and the prospect of its use becoming addictive — suggest that contemplation of geoengineering does little to diminish the need to address the root causes of climate change. If anything, the prospect of geoengineering should strengthen resolve to tackle climate change by limiting atmospheric concentrations of GHGs. ❐

Scott Barrett[1], Timothy M. Lenton[2], Antony Millner[3], Alessandro Tavoni[3], Stephen Carpenter[4], John M. Anderies[5], F. Stuart Chapin III[6], Anne-Sophie Crépin[7,9], Gretchen Daily[8], Paul Ehrlich[8], Carl Folke[7,9], Victor Galaz[9], Terry Hughes[10], Nils Kautsky[11], Eric F. Lambin[12], Rosamond Naylor[13], Karine Nyborg[14], Stephen Polasky[15], Marten Scheffer[16], James Wilen[17], Anastasios Xepapadeas[18] and Aart de Zeeuw[19] are at the [1]School of International and Public Affairs, Columbia University, New York, New York 10027, USA, [2]College of Life and Environmental Sciences, University of Exeter, Exeter EX4 4QE, UK, [3]Grantham Research Institute on Climate Change and the Environment, London School of Economics, London WC2A 2AE, UK, [4]Center for Limnology, University of Wisconsin, Madison, Wisconsin 53706, USA, [5]School of Sustainability, Arizona State University, Tempe, Arizona 85287, USA, [6]Institute of Arctic Biology, University of Alaska Fairbanks, Fairbanks, Alaska 99775, USA, [7]Beijer Institute of Ecological Economics, Royal Swedish Academy of Sciences, SE104 05 Stockholm, Sweden, [8]Department of Biology, Stanford University, Stanford, CA 94305, USA, [9]Stockholm Resilience Centre, Stockholm University, SE-106 91 Stockholm, Sweden, [10]Australian Research Council (ARC) Centre of Excellence for Coral Reef Studies, James Cook University, Townsville, QLD 4811, Australia, [11]Department of Ecology, Environment and Plant Sciences, Stockholm University, SE-106 91 Stockholm, Sweden, [12]Department of Geography, University of Louvain, B-1348 Louvain-la-Neuve, Belgium, [13]Department of Environmental Earth System Science, Stanford University, Stanford, California 94304, USA, [14]Department of Economics, University of Oslo, 0317 Oslo, Norway, [15]Department of Applied Economics, University of Minnesota, St. Paul, Minnesota 55108, USA, [16]Department of Environmental Sciences, Wageningen University, NL-6700 AA Wageningen, Netherlands, [17]Department of Agricultural and Resource Economics, University of California, Davis, California 95616, USA, [18]Department of International and European Economic Studies, Athens University of Economics and Business, GR10434 Athens, Greece, [19]Department of Economics, Tilburg University, 5000 LE Tilburg, Netherlands.*

**e-mail: sb3116@columbia.edu*

References

1. IPCC Summary for Policymakers in *Climate Change 2013: The Physical Science Basis* (eds Stocker, T. F. *et al.*) (Cambridge Univ. Press, 2013).
2. Crutzen, P. J. *Climatic Change* **77,** 211–219 (2006).
3. Keith, D. W. *A Case for Climate Engineering* (Boston Review Books, 2013).
4. Vaughan, N. E. & Lenton, T. M. *Climatic Change* **109,** 745–790 (2011).
5. Robock, A. *Bull. Atomos. Sci.* **64,** 14–18 (2008).
6. Barrett, S. & Dannenberg, A. *Proc. Natl Acad. Sci. USA* **109,** 17372–17376 (2012).
7. Irvine, P. J., Sriver, R. L. & Keller, K. *Nature Clim. Change* **2,** 97–100 (2012).
8. Pongratz, J., Lobell, D. B., Cao, L. & Caldeira, K. *Nature Clim. Change* **2,** 101–105 (2012).
9. Gillett, N. P., Arora, V. K., Zickfeld, K., Marshall, S. J. & Merryfield, W. J. *Nature Geosci.* **4,** 83–87 (2011).
10. McCusker, K. E., Battisti, D. S. & Bitz, C. M. *J. Clim.* **25,** 3096–3116 (2012).
11. Irvine, P. J., Lunt, D. J., Stone, E. J. & Ridgwell, A. *Environ. Res. Lett.* **4,** http://dx.doi.org/10.1088/1748-9326/4/4/045109 (2009).
12. Scheffer, M. *et al. Science* **338,** 344–348 (2012).
13. Lenton, T. M. *Nature Clim. Change* **1,** 201–209 (2011).
14. Seidel, D. J., Feingold, G., Jacobson, A. R. & Loeb, N. *Nature Clim.Change* **4,** 93–98 (2014).
15. Rau, G. H., MacLeod, E. L. & Hoegh-Guldberg, O. *Nature Clim. Change* **2,** 720–724 (2012).
16. Kravitz, B. *et al. J. Geophys. Res. Atmos.* **118,** 8320–8332 (2013).

Acknowledgments

The Beijer Institute of Ecological Economics and the Global Economic Dynamics and the Biosphere program, both of the Royal Swedish Academy of Sciences, supported the authors' collaboration.