Beyond Climate Control: 'Opening up' Propositions for Geoengineering Governance

Rob Bellamy

Climate Geoengineering Governance Working Paper Series: 011.

Published online 27 May 2014

Climate Geoengineering Governance (CCG)

Climate Geoengineering Governance (http://geoengineering-governance-research.org) is a research project which aims to provide a timely basis for the governance of geoengineering through robust research on the ethical, legal, social and political implications of a range of geoengineering approaches. It is funded by the Economic and Social Research Council (ESRC) and the Arts and Humanities Research Council (AHRC) - grant ES/J007730/1

CGG Working Papers

The CGG Working Paper series is designed to give a first public airing to a wide range of papers broadly related to the project's themes. Papers published in this series may be, but are not necessarily, early outputs from the project team; equally they may be from other authors, and reflect different perspectives and different issues from those directly pursued by the project itself. The aim is to promote vigorous and informed debate, in a spirit of pluralism.

What the working papers have in common is that they will all be at an early stage of development, prior to full publication. Comment and response, at any level of detail, is therefore doubly welcome. Please send all responses in the first instance to the authors themselves - each paper contains a correspondence address. We will be looking for opportunities to use the website or other project activities to give a wider airing to any dialogues and debates that develop around a paper or issue.

About the Author

Rob Bellamy (rob.bellamy@insis.ox.ac.uk) is a James Martin Research Fellow at the Institute of Science, Innovation and Society at the University of Oxford. His research interests include technology assessment, risk perception and public participation. In the CGG project, he is working with Steve Rayner and Javier Lezaun on public engagement with geoengineering governance.

Beyond Climate Control: 'Opening up' Propositions for Geoengineering Governance

Rob Bellamy

Institute for Science, Innovation and Society, University of Oxford

Abstract

Growing scientific and political interest in climate 'geoengineering' proposals and recent controversies relating to their experimentation have prompted efforts to responsibly govern the proposals before they can be deployed. Yet, many of the assessments that support geoengineering governance considerations are narrowly framed and show little reflexivity, ultimately 'closing down' around particular courses of action. This article explores the governance implications of the first effort to overcome these significant and pervasive limitations and 'open up' geoengineering appraisal. A radically different view of option performance has given rise to five propositions, not only for geoengineering governance, but for climate response governance at large. These propositions argue that (1) the sociotechnical imaginaries driving purposes and innovation need to gain foresight; (2) governance needs context from alternative options for tackling climate change; (3) performance should be robust within and across diverse framings; (4) mitigation and adaptation are the priority for presently making robust decisions; and (5) governance should open up before closing down through 'clumsiness'. These propositions offer a reflective and reflexive framework for the appraisal and governance of

geoengineering in the context of alternative options for tackling climate change.

1. Climate Geoengineering Governance

Deliberate, large-scale interventions in the Earth's climate system have been proposed to counter anthropogenic climate change. Notwithstanding the long and chequered history of their antecedents (Fleming, 2010), these climate 'geoengineering' proposals have recently emerged as a third category of possible responses to climate change alongside reducing greenhouse gas emissions ('mitigation') and reducing the impacts of climate change ('adaptation'). Indeed, it is the ostensible insufficiency of mitigation efforts to avoid 'dangerous' climate change (e.g. Crutzen, 2006), and of adaptive capacities to cope with a possible climate 'emergency' (e.g. Blackstock *et al.*, 2009), that has fuelled much of the interest in geoengineering. The term 'geoengineering' encompasses a disparate range of technology proposals that can be broadly divided into two types that seek to rectify those insufficiencies. The first type, 'carbon geoengineering', consists of proposals that seek to remove and sequester carbon dioxide from the atmosphere. The second type, 'solar geoengineering', consists of proposals that seek to reflect a fraction of sunlight away from the Earth.

Assessments of carbon geoengineering proposals have commonly found that they would be slow in their effect and expensive, but pose relatively few uncertainties and risks (Vaughan & Lenton, 2011). On the other hand, assessments of solar geoengineering proposals have commonly found that they would be fast in their effect and inexpensive, but pose greater uncertainties and risks. However, the issues raised by geoengineering are not limited to technical considerations, but also include social and ethical concerns (Corner & Pidgeon, 2010). Indeed, in its landmark report on *Geoengineering the Climate*, the UK's Royal Society concluded that 'The acceptability of geoengineering will be determined as much by social, legal and political issues as by scientific and technical factors' and that 'serious and complex governance issues [would] need to be resolved if geoengineering is ever to become an acceptable method for moderating climate change' (2009: ix). The Society went on to recommend the development and implementation of frameworks for governing geoengineering research and development, and, if necessary, for eventual deployment.

Three broad approaches to governing geoengineering exist: through a multilateral organisation such as the United Nations; through a consortium of states; or by lone states unilaterally (Virgoe, 2009). A growing number of commentators have supported the case for governing geoengineering multilaterally through the UN Framework Convention on Climate Change (Lin, 2009; Honegger *et al.*, 2012; Zürn & Schäfer, 2013). This approach is advocated with particular fervour in relation to transboundary solar geoengineering proposals such as stratospheric aerosol injection (Barrett, 2008). Indeed, the supposedly fast and cheap qualities of these sorts of proposals have sparked concerns over possible unilateral actions. Yet, without widespread international support, unilateral action or a blanket moratorium consistent with the precautionary principle could be more likely to occur than multilateral decision making (Bodansky, 1996). Others have dismissed fears of unilateral actions as misplaced, suggesting that international dynamics would build pressures that lead to cooperation (Horton, 2011). A consortium-led approach could therefore be possible and has even been advocated to avoid the lack of progress experienced in the UNFCCC negotiations (Benedick, 2011). Some have suggested that regional differences in geoengineering effects would create strategic incentives to ensure that these consortia were as small as possible (Ricke *et al.*, 2013).

A number of controversies relating to geoengineering experimentation such as the UK's Stratospheric Particle Injection for Climate Engineering (SPICE) project, the LOHAFEX (Iron Fertilisation Experiment) trial (Strong *et al.*, 2009) and the 'rogue' iron fertilisation of the Haida Salmon Restoration Corporation (Tollefson, 2012), have recently directed governance concerns towards research as much as deployment. A number of commentators have recommended that research into geoengineering take place under the auspices of the Intergovernmental Panel on Climate Change (IPCC) (Honegger *et al.*, 2012; Zürn & Schäfer, 2013), and in particular with regard to solar geoengineering (Barrett, 2008). Others, however, have observed that the 'consensus science' model of the IPCC could overlook improbable but important geoengineering impacts (Victor, 2008). A number of novel international institutions have also been proposed, including an International Climate Engineering Agency to coordinate and disseminate research (Zürn & Schäfer, 2013), and an International Climate Engineering Research Review and Coordination Boards to coordinate geoengineering field experiments (Morrow *et al.*, 2009). Others have rejected self-regulation in favour of government authority and proposed a moratorium on large-scale geoengineering experiments, but proposed experimentation thresholds below which small-scale tests might be permitted to take place (Parson & Keith, 2013).

The disparate proposals that reside under 'geoengineering', however, effectively preclude the adoption of a single model for their governance. Important demarcations can be drawn between different proposals that in turn pose different regulatory implications. These can be drawn between carbon and solar geoengineering proposals in that the former may largely be regulated through existing or extended legal instruments (Royal Society, 2009; Reynolds, 2011). For example, ocean iron fertilisation, a carbon geoengineering proposal, was identified as being governable through the London Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (IMO, 2007) and has since been re-ratified (IMO, 2013). By contrast, governance pertaining to solar geoengineering has been deemed to be largely lacking (SRMGI, 2011). The jurisdictions within which geoengineering proposals may operate is another key line of distinction (Humphreys, 2011). 'Territorial' proposals, such as biochar and urban albedo enhancement, may be governed within the sovereign territory of states (whilst potentially requiring internationally collective action); whereas 'commons' proposals, such as iron fertilisation and stratospheric aerosol injection, may require international agreements. There is hence the need for geoengineering governance to be sufficiently flexible to accommodate proposals under these, and other, regulatory demarcations.

Ambitions to govern geoengineering are frustrated by a much more fundamental difficulty, however: the 'technology control dilemma' (Collingridge, 1980). This dilemma observes that whilst it would be ideal to implement governance architecture in advance of significant research and development in order to guard against an emerging technology's harmful impacts, those impacts cannot be sufficiently known until that significant development has taken place. At that point, the ability to control or change a technology's innovation trajectory becomes increasingly problematic. Much as with accommodating the governance requirements of the disparate proposals under 'geoengineering', flexibility is critical to overcoming the technology control dilemma. It is with flexibility between alternative courses of action in mind that the influential 'Oxford Principles' for geoengineering governance have been proposed

(Rayner *et al.*, 2013). This set of high-level principles argues for (1) geoengineering to be regulated as a public good; (2) public participation in geoengineering decision making; (3) disclosure of geoengineering research and open publication of results; (4) independent assessment of impacts; and (5) governance before deployment. The UK Government (2010) and the House of Commons Select Committee on Science and Technology (2010) have since established that 'While some aspects of the suggested five key principles need further development, they provide a sound foundation for developing future regulation' (*ibid*: 35).

Most recently Science and Technology Studies scholars have experimented with applying a framework for responsible innovation to geoengineering governance that would seek to manage its responsible emergence (or non-emergence) in society. Four dimensions of responsible innovation have emerged from an analysis of societal concerns raised across 17 public engagements with emerging technologies since 2005 (Macnaghten & Chilvers, 2013), including one with geoengineering (NERC, 2010): anticipation, reflexivity, inclusion and responsiveness (Owen *et al.*, 2013). These dimensions uphold existing calls for foresight of possible intended and unintended impacts (Ravetz, 1997); institutional reflexivity (Wynne, 1993); 'opening up' to diversity and deliberation (Stirling, 2008); and anticipatory governance (Barben *et al.*, 2008). Indeed, the proposed framework was partly developed during efforts to instil notions of responsibility into an early geoengineering research project: SPICE (Stilgoe *et al.*, 2013). As part of the testbed for a delivery mechanism for stratospheric aerosol injection a technique for building responsiveness called stage-gating (Cooper, 1990) was employed to ensure that criteria for responsible innovation were met at critical stages during research and development. As a result of the technique, the testbed was at first postponed to allow for sufficient public engagement (Macnaghten & Owen, 2011), but was later postponed indefinitely after a conflict of interest emerged concerning a patent application by one of the project investigators (Cressey, 2012).

The SPICE project study in responsiveness is one of a small but growing number of studies that have sought to support the responsible innovation of geoengineering. In response to the need for more sufficient public engagement highlighted as part of the same project, other research went on to engage publics with the SPICE testbed using deliberative workshops (Pidgeon *et al.*, 2013). Participants in that study displayed a 'reluctant acceptance' (Bickerstaff *et al.*, 2008) of the geoengineering research but stressed the need for international governance to shape future research and development. Separately, others have also engaged publics with solar geoengineering using deliberative focus groups (Macnaghten & Szerszynski, 2013). Five conditions for the public acceptance of solar geoengineering emerged from these groups that demand confidence in: (1) climate science as a reliable guide to policy; (2) the ability of research to anticipate side effects; (3) the ability of research to demonstrate efficacy; (4) effective governance; and (5) the capacity of democracy to accommodate solar geoengineering. After raising doubts as to the attainability of these conditions, further consideration has concluded that solar geoengineering and democracy 'won't mix' (Szerszynski *et al.*, 2013). This conclusion, however, is built upon a particular conception of participatory democracy (Heyward & Rayner, 2013). Others still have engaged publics with geoengineering more broadly using deliberative workshops that have determined 'naturalness' to be a key but complex determinant of public acceptance of geoengineering (Corner *et al.*, 2013).

Most recently research into the responsible innovation of geoengineering has sought to respond to the emergent 'closing down' in the framing of appraisals that seek to support governance considerations (Bellamy *et al.*, 2012). This Deliberative Mapping of Geoengineering (DMG) sought to ‘open up’ appraisal to alternative options for responding to climate change with diverse experts and stakeholders as well as publics (Bellamy *et al.*, 2013; Bellamy *et al.*, submitted). This article explores the unique implications of opening up geoengineering appraisal in the DMG for the governance and responsible innovation of geoengineering. It begins by introducing the origins of the project, before then exploring its implications through five propositions for geoengineering governance. The article then concludes by summarising posing several key recommendations for future research and policy.

2. Deliberative Mapping of Geoengineering

Appraisals of geoengineering have begun in earnest to provide policy makers around the world with crucial decision support. A recent critical analysis of these appraisals, however, has revealed three significant and pervasive limitations (Bellamy *et al.*, 2012) relating to their use of framings in ‘closing down’ policy alternatives (Stirling, 2008) that risk premature entrenchment (Collingridge, 1980), path-dependency (David, 2001), and lock-in to particular options and future pathways (Arthur, 1989). Such activity can lead to conflict between divergent perspectives, as has already been witnessed with other previously emerging technologies such as nuclear energy and genetically modified crops. The first of these is that geoengineering proposals have been appraised in ‘contextual isolation’ of alternative options for tackling climate change. Two dominant problem definitions have been adopted: ‘insufficient mitigation’ efforts and the risk of a ‘climate emergency’;

which, taken together, marginalise legitimate mitigation and adaptation alternatives to geoengineering. As a consequence, the appraisals have consequently focussed on assessing single geoengineering proposals (e.g. Keith *et al.*, 2005; Lampitt *et al.*, 2008; Robock *et al.*, 2009) or performing internal comparisons between geoengineering proposals (e.g. Keith, 2000; Irvine & Ridgwell, 2009; Vaughan & Lenton, 2011).

The second limitation is that geoengineering appraisals have adopted narrow methodological framings that have inadequately responded to the 'post-normal' (Funtowicz & Ravetz, 1993) scientific context in which they reside. Methods of appraisal have largely taken the form of reductive 'expert-analytic' approaches such as computer modelling (e.g. Irvine *et al.*, 2011), cost-benefit analysis (e.g. Goes *et al.*, 2011), expert review (e.g. Russell *et al.*, 2012) and multi-criteria analysis (e.g. Boyd, 2008), that treat the issue as one of simple 'risk' rather than one of indeterminate uncertainty, ambiguity or ignorance (Wynne, 1992; Stirling *et al.*, 2007). Whilst these methods have undoubtedly offered important insights into technical issues, they focus on narrowly framed criteria that overlook broader political, social, and ethical concerns. They have furthermore excluded the 'extended peer communities' of wider stakeholders and publics that are vital for navigating the high stakes and uncertainties of post-normal science. Of the few studies that have engaged in wider participation, however, most have continued to treat geoengineering in contextual isolation (e.g. NERC, 2010; Mercer *et al.*, 2011; Wright *et al.*, 2014); and whilst others have adopted broader framings, they have not treated alternative options symmetrically (Corner *et al.*, 2013; Macnaghten & Szerszynski, 2013; Pidgeon *et al.*, 2013).

The third limitation is that appraisals of geoengineering have demonstrated very little reflexivity in their acknowledgment of the framings that condition their outcomes. Ultimately, this has led to many of the appraisals prematurely ‘closing down’ on and prescribing ostensibly preferable proposals, the foremost of which being stratospheric aerosol injection. The Royal Society’s (2009) multi-criteria assessment provides a valuable illustration of this through its selection and elevation of particular criteria. Its appraisal utilised just four technical criteria: effectiveness, affordability, timeliness, and safety; of which the former two were selected to be given normative priority on the two axes of the conveying figure. Under this configuration, stratospheric aerosol injection performed the most highly, but this is the output from just one of six possible permutations (Bellamy, 2013). This need for reflexivity, joined by imperatives for diverse framings and participation, compels a particular suite of methodological responses in appraisal design (Stirling *et al.*, 2007). One of these methods is Deliberative Mapping.

Deliberative Mapping is an analytic-deliberative multi-criteria option appraisal process that engages with diverse experts and stakeholders (specialists) and members of the public (citizens) in the assessment of complex and uncertain issues, such as geoengineering (Davies *et al.*, 2003; Burgess *et al.*, 2004; Burgess *et al.*, 2007). It combines the strengths of the expert-analytic Multi-Criteria Mapping (MCM) (Stirling, 1997) with those of the participatory-deliberative Stakeholder Decision Analysis (SDA) (Burgess *et al.*, 1988), generating quantitative assessments of option performance and qualitative explorations of the reasonings that underpin such judgements. It is distinctive in that it is the only method that invites specialists and citizens to participate in the same appraisal process. This consistency allows for direct comparisons of convergence and divergence between different group perspectives of those participating in the process. The DMG took place during the summer and autumn of 2012 with twelve diverse specialists and thirteen diverse citizens in the first effort to open up geoengineering appraisal in the context of alterative options for responding to climate change.

3. Propositions for Climate Governance

In 'opening up' geoengineering appraisal to diverse framings for the first time the DMG revealed several radically different findings to those of other assessments (Bellamy *et al.*, 2013; Bellamy *et al.*, submitted). These included (1) a significant expansion of appraisal criteria 'depth', or of the diversity of alternative criteria that pertain to an ostensibly discrete criterion such as 'efficacy'; (2) lessons from appraising geoengineering under a broader problem definition, against alternative options for tackling climate change; (3) a significant expansion of appraisal criteria 'range', or the diversity of alternative criteria at large, such as the inclusion of more 'social' criteria in addition to more 'technical' criteria; (4) a very different view of option performance, with geoengineering proposals consistently outperformed by mitigation alternatives; and (5) lessons from the overall approach taken in opening up geoengineering appraisal. These findings pose correspondingly different implications for geoengineering governance, that unlike other proposed governance recommendations have emerged from an extensive process of reflection and reflexivity (Stirling, 2006). Each of the following propositions are thus not only for geoengineering governance, but for climate response governance at large. Given the focus of this article, however, these propositions will be discussed with particular attention to geoengineering.

3.1 Gain sociotechnical foresight

'Collectively imagined forms of social life and social order reflected in the design and fulfilment of scientific and/or technological projects' (Jasanoff & Kim, 2009: 120) constitute important influences on the relationship of prospective sciences and technologies such as geoengineering to political power. Such 'sociotechnical imaginaries' of the futures within which geoengineering might reside were revealed through the appraisal criteria developed during the DMG. Each of the groups of criteria elicited illustrates different aspects of these imagined futures. As the force behind envisaged purposes of geoengineering, the efficacy criteria group demands particular consideration here with respect to its construction of the geoengineering imaginary. In expanding the depth of efficacy criteria beyond those employed in previous assessments, five different sociotechnical imaginaries for geoengineering emerge from thirteen unique efficacy criteria developed in the project.

One of the most dominant sociotechnical imaginaries is one that maps directly upon one of the two dominant problem definitions identified as having framed other geoengineering appraisals (Bellamy *et al.*, 2012): the 'insufficient mitigation' frame. Assessing the extent to which options for responding to climate change may stabilise atmospheric CO_2 concentration and reduce greenhouse gas emissions or atmospheric concentrations illuminates an imagined future where geoengineering efforts may **supplement mitigation** in order to avoid dangerous climate change. Such an imaginary is not unorthodox nor is it greatly contested amongst scientists and stakeholders alike, with it increasingly understood that 'dangerous' climate change beyond 2°C may not be avoided without the use of (carbon) geoengineering (McLaren, 2012). Indeed, at least two carbon geoengineering proposals (large-scale afforestation and bio-energy with carbon sequestration) already form integral parts of the representative concentration pathway scenarios used for the IPCC's Fifth Assessment Report (see van Vuuren *et al.*, 2011).

Seeking the reduction of climate change impacts and in their entirety reveals an imagined future where geoengineering may **supplement adaptation** to climate change. This imaginary extends that of supplementing mitigation efforts, capturing the view that no one of the three main categories of response will be sufficient to respond to climate change on their own. Indeed, some have called for a unified Mitigation, Adaptation and Geoengineering ('MAG') approach to climate policy (IMechE, 2009). There is, however, an imagined future in which mitigation and adaptation would be wholly ineffectual. Concern with the climatic response time of options for responding to climate change illuminates a future of urgency in which a **climate emergency** which may only be overcome with (solar) geoengineering. Of course, this is also the second of the two dominant problem definitions identified as having framed other geoengineering appraisals (Bellamy *et al.*, 2012). What is curious here is that both of the frames emerged independently of each strand in the DMG and without having been introduced by the research team, suggesting a saliency of these imagined futures around which geoengineering proposals are being driven and constructed. Indeed, it demonstrates the co-production (Jasanoff, 2004) of their social and technical orderings.

In contrast with the insufficient mitigation frame, however, the climate emergency frame is unorthodox and is greatly contested outside of its small community of proponents (e.g. Blackstock *et al.*, 2009). It is argued that solar geoengineering proposals, particularly stratospheric aerosol injection, should be researched in anticipation of and could be deployed pre-emptively or in response to an ostensible climate emergency. Emergencies of this nature are frequently portrayed as arising from the perturbation of large-scale climate ‘tipping elements’ beyond their corresponding ‘tipping points’ (Lenton *et al.*, 2008). However, such an imagined future rests upon a number of critical substantive and normative assumptions. Pre-emptive deployment would require the reliable ‘early warning’ of such an emergency, for which the possibility for prediction is viewed as limited due to noise (e.g. Ditlevsen & Johnsen, 2010; *cf.* Lenton, 2011). Respectively, responsive deployment would require the reliable identification of such an emergency once an Earth system had ‘tipped’. Perhaps the most critical assumption in both of these cases is that the normative notion of an emergency can be collectively defined and agreed, and that solar geoengineering action in advance of or in response to such a definition can be agreed. Indeed, arguments from necessity do not meet the demands of its legal definition in international law (Markusson *et al.*, 2013). Nevertheless, it has been suggested that ‘the emergency frame feeds off uncertainty about the future’ and that therefore it is ‘unlikely that [it] will go away’ (*ibid*: 288).

Seeking to impact upon global temperature directly, reduce global temperature or undertake the maintenance of global temperature invokes a related but more overtly hubristic sociotechnical imaginary: developing a **global thermostat**. The idea of a global thermostat that humans could control at will is one that is prevalent in debates around geoengineering; and in particular around solar geoengineering and stratospheric aerosol injection. Yet, Hulme (2014: 54) argues that ‘the idea that global temperature is a suitable object of governance and one through which the well-being of humanity can be secured is a delusion’. He suggests that such an endeavour conflates regional and local peoples and climates and would be both ungovernable and unreliable. Indeed, he describes stratospheric aerosol injection as ‘a flawed idea… that seeks an illusory solution to the wrong problem’ (*ibid*: 130). But **sustained reliability** is another sociotechnical imaginary for geoengineering. Seeking a sustained duration of effect and minimal uncertainty over efficacy reveals an envisaged future where geoengineering is a controllable long-term undertaking; a vision that is in stark contrast with those of critics of the global thermostat.

These sociotechnical imaginaries begin to reveal the imagined futures around which the purposes of geoengineering are being constructed. They invite us to gain foresight of these purposes: to reflect on the uncertainties, ambiguities, and indeterminacies of their assumptions and, ultimately, to reflect on what is trying to be achieved. If, for example, the aim is to 'achieve... stabilisation of greenhouse gas concentrations in the atmosphere' as outlined in Article 2 of the UNFCCC (1992); then there is a possible supplementary role for carbon geoengineering proposals to aid conventional mitigation efforts. Solar geoengineering proposals, however, unlike their carbon counterparts do not remove greenhouse gases from the atmosphere and cannot directly contribute to that end. By contrast, if the aim was to counteract a climate emergency there is a possible role for solar geoengineering, but not for carbon geoengineering, mitigation or adaptation. As we have seen, however, there is a need to interrogate such imaginaries in terms of both their plausibility and their desirability. Ultimately, these and other possible visions for geoengineering the climate invite reflection on where, or whether, resources can be best targeted in resolving such issues.

3.2 Governance needs context

Definitions of 'geoengineering' are ambiguous, revealing disagreements as to what constitutes geoengineering, which terminology best delivers a linguistic framing, and how its subset-classes should be demarcated (Bellamy *et al.*, 2012). Indeed, such ambiguities have been argued to provide 'interpretative flexibility for articulating diverse interests within and across contested framings' (Cairns, 2013: 3). Nonetheless, attempts have been made to prescribe greater precision, including by Boucher *et al.* (2013) who offer categories of responses to climate change that overlap between geoengineering, mitigation and adaptation. In a different typology, Heyward (2013) argues that geoengineering be disaggregated and kept distinct from mitigation and adaptation: 'research and debate [should] cease to be about "geoengineering" and instead focus on the specific features of the proposed technologies, and the appropriate mix of [options]' (*ibid*: 26). Indeed, she appeals for an abandonment of the term altogether.

In disaggregating geoengineering in practice, the findings of the DMG show that the disparate proposals have distinct issues and performance ranges spanning all appraisal criteria groups. This further reinforces the need to discriminate between different geoengineering proposals and consider them on a case-by-case basis. Yet, the approach adopted here cautions against the appraisal and governance of geoengineering in contextual isolation as has been done in other assessments. The project, and those typologies discussed above, each follow earlier calls for appraising and governing geoengineering in the context of 'the wider portfolio of climate change strategy options, spanning mitigation and adaptation' (Bellamy *et al.*, 2012: 610). By heeding the comparative imperative the decision context is invariably opened up, which in turn assists in guarding against premature entrenchment (Collingridge, 1980), path-dependency (David, 2001), and lock-in to particular options and future pathways (Arthur, 1989).

3.3 Performance should be robust

The idea of 'robustness' in decision making has its origins in the field of operational research, where it was first proposed as a response to an apparent 'optimality paradox' (Rosenhead *et al.*, 1972). Of course, optimal solutions should, by definition, be the best course of action available to decision makers; yet uncertain or ambiguous outcomes can often render them unacceptable. Indeed, as we have already seen, the application of narrow and non-reflexive methods in geoengineering assessment can lead to ostensibly 'optimal' solutions (Bellamy *et al.*, 2012). Yet, when these framings are exposed it becomes clear that such solutions are only optimal under the specific conditions upon which they are built. Robustness was advanced as a remedy to this paradox: 'a measure of the flexibility which an initial decision of a plan maintains for achieving near-optimal states in conditions of uncertainty' (*ibid*: 413). The concept has since been developed for identifying options under deep uncertainty that perform 'relatively well, compared to alternatives, across a wide range of plausible futures' (Lempert *et al.*, 2006: 514), and has been encouraged in climate change adaptation policy (Dessai *et al.*, 2011). This article further develops the concept of robustness to mean **the identification of options that perform relatively well, compared to alternatives, under a diversity of framings**.

The diverse specialists and citizens participating in the DMG independently developed 80 unique criteria with which to appraise geoengineering proposals and other options for tackling climate change. These criteria constitute 39 criteria subgroups and 9 criteria groups (see Table 1). Together, these groups interrogate the possible **utility** value of geoengineering proposals to society (efficacy, feasibility, economic, and co-benefits criteria groups); their possible wider **impacts** on the world (environment, economic, safety, and social criteria groups), and possible means for their **control** (political, social, and ethical criteria groups). These criteria offer a reflective and reflexive (Stirling, 2006) framework for the appraisal of geoengineering and other options for tackling climate change both within and across each of the criteria groups and each of the perspectives participating in the assessment.

Table 1
Criteria for appraising geoengineering and alternative options for tackling climate change (after Bellamy *et al.*, 2013; Bellamy *et al.*, submitted)

Criteria group	Criteria subgroups	Unique criteria
Efficacy	Climate change impacts reduction†;	Climate change impacts reduction†; climatic response time†; CO_2

	climatic response time[†]; duration of effect; efficacy of intended effects; global temperature reduction[†]; greenhouse gas reduction[†]	concentration stabilisation[†]; duration of effect; efficacy and completeness[†]; efficacy of intended impacts; efficacy uncertainty[†]; emissions reduction[†]; global temperature maintenance; global warming reduction; greenhouse gas reduction; impact on global warming[†]; scale of effectiveness
Environment	Carbon footprint; environmental impacts[†]; environmental side effects[†]; impact reversibility; transboundary impacts[†]	Carbon footprint; environmental impacts; environmental risk; foreseeable environmental impacts; impact reversibility; risk of adverse effects; environmental safety[†]; transboundary effects[†]; unforeseen impacts; unintended consequences; unintended environmental impacts[†]; unintended environmental risks; unintended or unanticipated risks
Feasibility	Development time; resource availability; state of knowledge; technical feasibility[†]	Demonstration; ease of operation; ensemble uncertainty; feasibility; lead-time; practicality; scalability; technical feasibility[†]; technical know-how; workability
Economic	Commercial viability; cost[†]; cost-benefit ratio; cost effectiveness; economic sustainability; investment return; public investment	Affordability; cost-benefit ratio; cost[†]; cost effectiveness; economic cost[†]; economic efficiency; economic feasibility; investment return; public investment; set-up cost; subsidisation; sustainability
Political	(Inter)governmental cooperation; governance[‡]; political acceptability[†]; political viability	Democratic compatibility[†]; (inter)governmental cooperation; governance[‡]; legislation; political acceptability[†]; political feasibility; political, social and legal feasibility; political and technical feasibility; political will

Safety	Impacts on humans‡; side effects on humans	Dangerousness; human impacts‡; side effects on humans
Social	Cultural acceptability; social acceptability†; socioeconomic impacts	Cultural acceptability; impact on lifestyles; public acceptability†; public convincement; public perception; social acceptability; social support; socioeconomic impacts†
Ethical	Availability; distributive justice†; ethical questions; intergenerational equity‡; misuse; morality; ownership and control†	Availability; centralised or distributed control†; ethical questions raised; fairness in practice; intergenerational equity‡; monitoring; moral obligation; moral pursuit; openness to abuse; social impact progressivity†; social inequality reduction
Co-benefits	Co-benefits†	Co-benefits†

All listed are criteria except where † indicates that the corresponding criterion was also used as a principle to rule options out, and ‡ indicates a principle.

For a geoengineering proposal or other option for tackling climate change to be considered robust, it should not only perform relatively well against, say, one unique environment criterion, but also against other unique environment criteria within different environment criteria subgroups; and against unique efficacy, feasibility, economic, political, safety, social, ethical, and co-benefits criteria within their different subgroups. Furthermore, options should not only perform relatively well against these criteria under particular academic perspectives, but also against other academic perspectives; and against those from across civil society, industry, and government. In other words, options for responding to climate change should satisfy diversity, and those that perform relatively well under these conditions, compared to alternatives, can be considered more robust.

3.4 Mitigation and adaptation are the priority

Unlike methods of participatory appraisal that seek to build a consensus between different perspectives on an issue, Deliberative Mapping is designed to map the divergence of those perspectives. It is especially remarkable then that the findings of the DMG have revealed a high degree of consistency between diverse perspectives on geoengineering and other options for tackling climate change. With the exception of the participating industry specialists, geoengineering proposals were consistently outperformed by mitigation option alternatives under diverse academic, civil society, government, and public perspectives. Three tiers of performance emerged, with voluntary low carbon living, offshore wind energy, and afforestation constituting the 'highest' performing options. In contrast, geoengineering proposals constituted three of the four 'lowest' performing options: stratospheric aerosol injection, iron fertilisation, and space reflectors. The anticipated likelihood of the fourth lowest option, business as usual, being deliberately, tacitly, or inadvertently pursued, compels adaptation as a priority response to its myriad harmful impacts documented across the criteria groups. The eight remaining 'middle' options (a new carbon market mechanism; biochar; air capture and storage; nuclear fusion energy; nuclear fission energy; coal energy with carbon capture and storage; a carbon tax; and cloud albedo enhancement) displayed a more ambiguous performance.

The highest performing options can also be considered more robust, having performed relatively well against the diversity of criteria groups and perspectives. Adaptation, too, can be considered more robust, through its broad capacity for responses to the impacts posed by business as usual across the criteria ensemble. Of course, however, these options are by no means optimal. For example, whilst voluntary low carbon living performs relatively highly against most criteria groups, against efficacy and co-benefits criteria it performs relatively poorly. Thus it is clear that no single option for responding to climate change is a panacea, reaffirming other commentators' assertions of there being no elegant 'silver bullet' for climate change (Prins & Rayner, 2007), still less from geoengineering (Shepherd, 2012). Yet, it is nevertheless clear that some options perform better, and are most robust, than others. These findings suggest that resources that could otherwise be invested in mitigation options and adaptation that perform in a more robust manner across the ensemble of appraisal criteria are being invested in geoengineering proposals that do not. However, this is not to suggest that research into geoengineering be abandoned or that any specific proposals can be ruled out; though of course there are perspectives that would, and have, ruled out certain options (most often stratospheric aerosol injection and business as usual) on principle (Bellamy *et al.*, 2013). Instead, resources should be allocated proportionally according to different options' robustness. Mitigation options and adaptation are therefore the relative priority, which would concurrently go some way towards alleviating concerns over a 'moral hazard' whereby those efforts might otherwise be diminished (Royal Society, 2009).

3.5 'Open up' before 'closing down'

The DMG accomplished its objective of 'opening up' geoengineering appraisal to a greater diversity of framings than those of current appraisals. It has opened up to broader problem definitions, alternative options, diverse perspectives and criteria; and in doing so revealed a radically different view of option performance, posing important implications for future research and policy. However, as with all research, it is not without its limitations. There is one principal limitation of the research that stems from its modest resources and budget: scale. The research scale was limited to twelve international specialists and thirteen citizens from Norfolk, UK who were recruited to participate in two sets of interviews and two citizens panels, respectively, together with a joint citizen-specialist workshop. This was not intended to be statistically representative of specialists or citizens, but rather to be a rich, exploratory mapping of the issues under consideration. A larger and more internationally diverse sample size would have inevitably introduced an even greater diversity of perspectives. Future research should therefore continue to open up geoengineering appraisal in diverse and reflexive ways.

However, making decisions based on the findings of any research inevitably involves elements of closing down. The questions thus arise: when and how should governance close down? The concept of 'clumsy solutions' recognises that there will always be endemic conflict between at least three (hierarchical, individualist, or egalitarian) actively contending framings (Verweij *et al.*, 2006). Any decision that is modelled on a singular framing would therefore be 'at best, partial and, at worst, ineffective or even counterproductive' (*ibid*: 19). For these reasons, closure in decision making should not take place until these contending framings have been sufficiently heard and mapped. This point in time will become clearer as mapping exercises become more saturated by diversity and fewer novel framings emerge. In then closing down, a clumsy policy response would be a plural one forged through a flexible combination of framings in which none of those contending is excluded.

4. Beyond Climate Control

Growing scientific and political interest in geoengineering as a possible third way for responding to climate change and recent controversies relating to its experimentation has prompted efforts to govern the proposals before they are deployed (Rayner *et al.*, 2013) and to manage their responsible emergence (or non-emergence) in society (Stilgoe *et al.*, 2013). Yet, many of the assessments that support geoengineering governance considerations are demonstrably framed in narrow terms and show little reflexivity (Bellamy *et al.*, 2012). Narrow problem framings have led to geoengineering being considered in contextual isolation of legitimate alternatives for tackling climate change. Mischaracterisation of the post-normal scientific context in which climate change and geoengineering resides has led to narrowly framed, exclusive, analytic and reductive assessments that exclude broader framings, wider participation, deliberation and complexities, and treat the issue as a simple one of 'risk'. Low levels of reflexivity have ultimately led to such assessments prematurely closing down on particular geoengineering proposals that appear preferable under the narrow framings upon which they are built.

This article has explored the governance implications of the first effort to overcome these significant and pervasive limitations and open up geoengineering appraisal (Bellamy *et al.*, 2013; Bellamy *et al.*, submitted). A radically different view of option performance has given rise to five propositions, not only for geoengineering governance, but for climate response governance at large. These propositions argue that (1) the sociotechnical imaginaries driving purposes and innovation need to **gain foresight**; (2) **governance needs context** from alternative options for tackling climate change; (3) **performance should be robust** within and across diverse framings; (4) **mitigation and adaptation are the priority** for presently making robust decisions; and (5) governance should **'open up' before 'closing down'** through clumsiness. Ultimately, these propositions amount to a call to go beyond deliberate, tacit, or inadvertent instrumental commitments to climate control: to go beyond ostensibly uncontested purposes and gain foresight; to go beyond narrow problem definitions and gain alternatives; to go beyond false notions of optimality and gain robustness; and to go beyond elegant but premature closure and gain clumsiness.

These propositions should be pursued as part of wider ambitions to realise frameworks for responsible innovation (Owen *et al.*, 2013). In synergy, they encourage the anticipation of possible intended or unintended impacts of climate responses, institutional reflexivity in climate response governance, inclusion of diverse perspectives and framings, and responsiveness to changing perspectives and circumstances. In seeking foresight of the sociotechnical imaginaries driving climate response purposes a host of anticipatory methods exist that interrogate the assumptions and values underlying innovation, including scenario planning (Ogilvie, 2002) and vision assessment (Grin & Grunwald, 2000) amongst others (see Stilgoe *et al.*, 2013). In mapping diverse criteria for appraisal this article offers a reflective and reflexive (Stirling, 2006) framework for appraising and governing geoengineering in the context of alternative options for tackling climate change. Future research and policy should employ and build upon this framework; continuing to open up to diversity and reflexivity before facilitating clumsy governance in closing down. Only then will we be in a position to govern in such a way that enables us to go beyond appeals to climate control.

Acknowledgements

The author would like to thank Jason Chilvers, Irene Lorenzoni, Steve Rayner, Andy Stirling, and Naomi Vaughan for their insightful comments on an earlier draft of this article. The author would also like to thank the anonymous specialists and citizens for their enthusiastic participation in this issue of great complexity and uncertainty. This research was generously funded by the Norfolk Charitable Trust. The author gratefully acknowledges funding from the Climate Geoengineering Governance (CGG) project in preparing this article (ESRC/AHRC Grant ES/J007730/1).

References

Arthur, W. (1989): Competing technologies, increasing returns, and lock-in by historical events. *Economic Journal*, **99**, 116 – 131.

Barben, D., Fisher, E., Selin, C. and Guston D. (2008): Anticipatory governance of nanotechnology: foresight, engagement and integration. In: Hackett, E., Lynch, M., Wajcman, J. (Eds.). The handbook of science and technology studies, third edition, 979 - 1000. *MIT Press: Cambridge, MA*.

Barrett, S. (2008): The incredible economics of geoengineering. *Environmental and Resource Economics*, **39**, 45 – 54.

Bellamy, R. (2013): Framing geoengineering assessment. Opinion article, Geoengineering our Climate Working Paper and Opinion Article Series. Available at wp.me/p2zsRk-9H, last accessed 29-05-14.

Bellamy, R., Chilvers, J., Vaughan, N. and Lenton, T. (2012): A review of climate geoengineering appraisals. *WIREs Climate Change*, **3**, 597 – 615.

Bellamy, R., Chilvers, J., Vaughan, N. and Lenton, T. (2013): 'Opening up' geoengineering appraisal: Multi-Criteria Mapping of options for tackling climate change. *Global Environmental Change*, **23**, 926 – 937.

Bellamy, R., Chilvers, J. and Vaughan, N. (submitted): Deliberative Mapping of options for tackling climate change: citizens and specialists 'open up' appraisal of geoengineering.

Benedick, R. (2011): Considerations on governance for climate remediation technologies: lessons from the 'ozone hole'. *Stanford Journal of Law, Science and Policy*, **4**, 6 – 9.

Bickerstaff, K., Lorenzoni, I., Pidgeon, N., Poortinga, W. and Simmons, P. (2008): Reframing nuclear power in the UK energy debate: nuclear power, climate change mitigation and radioactive waste. *Public Understanding of Science*, **17**, 145 - 169.

Blackstock, J., Battisti, D., Caldeira, K., Eardley, D., Katz, J., Keith, D., Patrinos, A., Schrag, D., Socolow, R. and Koonin, S. (2009): Climate engineering responses to climate emergencies. *Novim*. Available at arxiv.org/ftp/arxiv/papers/0907/0907.5140.pdf, last accessed 29-05-14.

Bodansky, D. (1996): May we engineer the climate? *Climatic Change*, **33**, 309 – 321.

Boucher, O., Forster, P., Gruber, N., Ha-Duong, M., Lawrence, M., Lenton, T., Maas, A. and Vaughan, N. (2013): Rethinking climate engineering categorisation in the context of climate change mitigation and adaptation. *WIREs Climate Change*, **5**, 23 – 35.

Boyd, P. (2008): Ranking geo-engineering schemes. *Nature Geoscience*, **1**, 722 – 724.

Burgess, J., Chilvers, J., Clark, J., Day, R., Hunt, J., King, S., Simmons, P. and Stirling, A. (2004): Citizens and specialists deliberate options for managing the UK's intermediate and high level radioactive waste: a report of the Deliberative Mapping trial, June – July 2004.

Burgess, J., Limb, M. and Harrison, C. (1988): Exploring environmental values through the medium of small groups 1. theory and practice. *Environment and Planning A*, **20**, 457 – 476.

Burgess J., Stirling A., Clark J., Davies G., Eames M., Staley K. and Williamson S. (2007): Deliberative mapping: a novel analytic–deliberative methodology to support contested science–policy decisions. *Public Understanding of Science*, **16**, 299 – 322.

Cairns, R. (2013): Examining framings of geoengineering using Q methodology. *Climate Geoengineering Governance Working Paper 2*. Available at geoengineering-governance-research.org, last accessed 29-05-14.

Collingridge, D. (1980): The social control of technology. *Francis Pinter: New York*.

Cooper, R. (1990): Stage-gate systems: a new tool for managing new products. *Business Horizons*, **33**, 44 - 54.

Corner, A. and Pidgeon, N. (2010): Geoengineering the climate: the social and ethical implications. *Environment*, **52**, 24 – 37.

Corner, A., Parkhill, K., Pidgeon, N. and Vaughan, N. (2013): Messing with nature? Exploring public perceptions of geoengineering in the UK. *Global Environmental Change*, **23**, 938 – 947.

Cressey, D. (2012): Geoengineering experiment cancelled amid patent row. *Nature News*. Available at nature.com/news/geoengineering-experiment-cancelled-amid-patent-row-1.10645, last accessed 29-05-14.

Crutzen, P. (2006): Albedo enhancement by stratospheric sulfur injections: a contribution to re-solve a policy dilemma? *Climatic Change*, **77**, 211 – 219.

David, P. (2001): Path dependence, its critics and the quest for 'historical economics'. In: Gar- rouste, P. and Ioannides, S. (Eds.). Evolution and path dependence in economic ideas: past and present. *Edward Elgar: Cheltenham*.

Davies, G., Burgess, J., Eames, M., Mayer, S., Staley, S., Stirling, A. and Williamson, S. (2003): Deliberative Mapping: appraising options for closing 'the kidney gap'. Final Report to the Wellcome Trust.

Dessai, S., Hulme, M., Lempert, R. and Pielke Jr., R. (2011): Do we need better predictions to adapt to a changing climate? *Eos, Transactions American Geophysical Union*, **13**, 111 – 112.

Ditlevsen, P. and Johnsen, S. (2010): Tipping points: early warning and wishful thinking. *Geophysical Research Letters*, **37**, L19703.

Fleming, J. (2010): Fixing the sky: the checkered history of weather and climate control. *Columbia University Press: New York*.

Funtowicz, S. and Ravetz, J. (1993): Science for the post-normal age. *Futures*, **25**, 739 – 755.

Goes, M., Tuana, N., and Keller, K. (2011): The economics (or lack thereof) of aerosol engineering. *Climatic Change*, **109**, 719 – 744.

Grin, J. and Grunwald, A. (2000): Vision assessment: shaping technology in 21st century society: towards a repertoire for technology assessment. *Springer: Berlin*.

Heyward, C. (2013): Situating and abandoning geoengineering: a typology of five responses to dangerous climate change. *PS: Political Science and Politics*, **46**, 23 – 27.

Heyward, C. and Rayner, S. (2013): A curious asymmetry: social science expertise and geoengineering. *Climate Geoengineering Governance Working Paper 7*. Available at geoengineering-governance-research.org, last accessed 29-05-14.

Honegger, M., Michaelowa, A. and Butzengeiger-Geyer, S. (2012): Climate engineering: avoiding Pandora's Box through research and governance. *Fridtjof Nansens Institutt Climate Policy Perspectives*. Available at fni.no/doc&pdf/FNI-Climate-Policy-Perspectives-5.pdf, last accessed 29-05-14.

Horton, J. (2011): Geoengineering and the myth of unilateralism: pressures and prospects for international cooperation. *Stanford Journal of Law, Science and Policy*, **4**, 56 – 69.

House of Commons Science and Technology Committee (2010): The regulation of geoengineering. *The Stationary Office: London*.

Hulme, M. (2014): Can science fix climate change? A case against climate engineering. *Polity: Cambridge*.

Humphreys, D. (2011): Smoke and mirrors: some reflections on the science and politics of geoengineering. *Journal of Environment and Development*, **20**, 99 – 120.

Irvine, P. and Ridgwell, A. (2009): 'Geoengineering' – taking control of our planet's climate. *Science Progress*, **92**, 139 – 162.

Irvine, P., Ridgwell, A. and Lunt, D. (2011): Climatic effects of surface albedo geoengineering. *Journal of Geophysical Research*, **116**, 1 – 20.

Institute of Mechanical Engineers (2009): Geo-engineering: giving us the time to act? Available at imeche.org/knowledge/themes/environment/climate-change/geo-engineering, last accessed 29-05-14.

International Maritime Organisation (2007): Convention on the prevention of marine pollution by dumping wastes and other matter, 1972 and its 1996 protocol: statement of concern regarding iron fertilization of the oceans to sequester CO_2. Available at whoi.edu/cms/files/London_Convention_statement_24743_29324.pdf, last accessed 29-05-14.

International Maritime Organisation (2013): Convention on the prevention of marine pollution by dumping wastes and other matter, 1972 and its 1996 protocol: report of the thirty-fifth consultative meeting and the eight meeting of contracting parties. Available at imo.org/MediaCentre/SecretaryGeneral/Secretary-GeneralsSpeechesToMeetings/Pages/LC35LP8.aspx last accessed 29-05-14.

Jasanoff, S. (2004): States of knowledge: the co-production of science and social order. *Routledge: New York*.

Jasanoff, S. and Kim, S-H. (2009): Containing the atom: sociotechnical imaginaries and nuclear power in the United States and South Korea. *Minerva*, **47**, 119 – 146.

Keith, D. (2000): Geoengineering the climate: history and prospect. *Annual Review of Environment and Resources*, **25**, 245 – 284.

Keith, D., Ha-Duong, M. and Stolaroff, J. (2005): Climate strategy with CO_2 capture from the air. *Climatic Change*, **74**, 17 – 45.

Lampitt, R., Achterberg, E., Anderson, T., Hughes, J., Iglesias-Rodriguez, M., Kelly-Gerreyn, B., Lucas, M., Popova1, E., Sanders, R., Shepherd, J., Smythe-Wright, D. and Yool, A. (2008): Ocean fertilisation: a potential means of geoengineering? *Philosophical Transactions of the Royal Society A*, **366**, 3919 – 3945.

Lempert, R., Groves, D., Popper, S. and Bankes, S. (2006): A general, analytic method for generating robust strategies and narrative scenarios. *Management Science*, **52**, 514 – 528.

Lenton, T. (2011): Early warning of climate tipping points. *Nature Climate Change*, **1**, 201 - 209.

Lenton, T., Held, H., Kriegler, E., Hall, J., Lucht, W., Rahmstorf, S. and Schellnhuber, H. (2008): Tipping elements in the Earth's climate system. *Proceedings of the National Academy of Sciences of the United States of America*, **105**, 1786 – 1793.

Lin, A. (2009): Geoengineering governance. *Issues in Legal Scholarship*, **8**, 1 – 24.

Macnaghten, P. and Owen, R. (2011): Good governance for geoengineering. *Nature*, **479**, 293.

Macnaghten, P. and Chilvers, J. (2013): The future of science governance: publics, policies, practices. *Environment and Planning C: Government and Policy*, **31**, doi:10.1068/c1245j

Macnaghten, P. and Szerszynski, B. (2013): Living the global social experiment: an analysis of public discourse on solar radiation management and its implications for governance. *Global Environmental Change*, **23**, 465 - 474.

Markusson, N., Ginn, F., Ghaleigh, N. and Vivian, S. (2013): 'In case of emergency press here': framing geoengineering as a response to dangerous climate change. *WIREs Climate Change*, **5**, 281 – 290.

McLaren, D. (2012): Negatonnes - an initial assessment of the potential for negative emission techniques to contribute safely and fairly to meeting carbon budgets in the 21st Century. *Friends of the Earth*. Available at foe.co.uk/resource/reports/negatonnes.pdf, last accessed 29-05-14.

Mercer, A., Keith, D. and Sharp, J. (2011): Public understanding of solar radiation management. *Environmental Research Letters*, **6**, 1 – 9.

Morrow, D., Kopp, R. and Oppenheimer, M. (2009): Toward ethical norms and institutions for climate engineering research. *Environmental Research Letters*, **4**, 045106.

Natural Environment Research Council (2010): Experiment Earth? Report on a public dialogue on geoengineering. Available at nerc.ac.uk/about/consult/geoengineering.asp, last accessed 29-05-14.

Ogilvie, J. (2002): Creating better futures: scenario planning as a tool for a better tomorrow. *Oxford University Press: New York*.

Owen, R., Stilgoe, J., Macnaghten, P., Gorman, M., Fisher, E., Guston, D. (2013): A framework for responsible innovation. In: Owen, R., Bessant, J. and Heintz, M. (Eds.). Responsible innovation: managing the responsible emergence of science and innovation in society, 27 – 50. *John Wiley & Sons: Chichester*.

Parson, E. and Keith, D. (2013): End the deadlock on governance of geoengineering research. *Science*, **339**, 1278 – 1279.

Pidgeon, N., Parkhill, K., Corner, A. and Vaughan, N. (2013): Deliberating stratospheric aerosols for climate geoengineering and the SPICE project. *Nature Climate Change*, **3**, 451 – 457.

Prins, G. and Rayner, S. (2007): The wrong trousers: radically rethinking climate policy. A Joint Discussion Paper of the James Martin Institute for Science and Civilization, University of Oxford and the MacKinder Centre for the Study of Long-Wave Events, London School of Economics. Available at http://eureka.bodleian.ox.ac.uk/66/, last accessed 29-05-14.

Ravetz, J. (1997): The science of 'what-if'? *Futures*, **29**, 533 – 539.

Rayner, S., Heyward, C., Kruger, T., Pidgeon, N., Redgwell, C. and Savulescu, J. (2013): The Oxford Principles. *Climatic Change*, **121**, 499 – 512.

Reynolds, J. (2011): The regulation of climate engineering. *Law, Innovation and Technology*, **3**, 113 – 136.

Ricke, K., Moreno-Cruz, J. and Caldeira, K. (2013): Strategic incentives for climate geoengineering coalitions to exclude broad participation. *Environmental Research Letters*, **8**, 014021.

Robock, A. (2008): 20 reasons why geoengineering may be a bad idea. *Bulletin of the Atomic Scientists*, **64**, 14 – 18.

Rosenhead, M., Elton, M., Gupta, S. (1972): Robustness and optimality as criteria for strategic decisions. *Operational Research Quarterly*, **23**, 413 – 430.

Royal Society, The (2009): Geoengineering the climate: science, governance and uncertainty. *The Royal Society: London*.

Russell, L., Rasch, P., Mace, G., Jackson, R., Shepherd, J., Liss, P., Leinen, M., Schimel, D., Vaughan, N., Janetos, A., Boyd, P., Norby, R., Caldeira, K., Merikanto, J., Artaxo, P., Melillo, J., and Granger Morgan, M. (2012): Ecosystem impacts of geoengineering: a review for developing a science plan. *Ambio*, **41**, 350 – 369.

Shepherd, J. (2012): Geoengineering the climate: an overview and update. *Philosophical Transactions of the Royal Society A*, **370**, 4166 – 4175.

Solar Radiation Management Governance Initiative (2011): Solar radiation management: the governance of research. Available at srmgi.org/files/2012/01/DES2391_SRMGI-report_web_11112.pdf, last accessed 29-05-14.

Stilgoe, J., Owen, R. and Macnaghten, P. (2013): Developing a framework for responsible innovation. *Research Policy*, **42**, 1568 – 1580.

Stirling, A. (1997): Multicriteria mapping: mitigating the problems of environmental valuation? In: Foster, J. (Ed.). Valuing Nature: economics, ethics and environment. *Routledge: London*.

Stirling, A. (2006): Precaution, foresight and sustainability: reflection and reflexivity in the governance of science and technology. In: Voß, J., Bauknecht, D. and Kemp, R. (Eds.). Reflexive governance for sustainable development, 225 – 272. *Edward Elgar: Cheltenham*.

Stirling, A. (2008): 'Opening up' and 'closing down': power, participation, and pluralism in the social appraisal of technology. *Science, Technology and Human Values*, **33**, 262 – 294.

Stirling, A., Leach, M., Mehta, L., Scoones, I., Smith, A., Stagl, S. and Thompson, J. (2007): Empowering designs: towards more progressive appraisal of sustainability. STEPS working paper 3. *STEPS Centre: Brighton*.

Strong, A., Chisholm, S., Miller, C. and Cullen, J. (2009): Ocean fertilisation: time to move on. *Nature*, **461**, 347 – 348.

Szerszynski, B., Kearnes, M., Macnaghten, P., Owen, R. and Stilgoe, J. (2013): Why solar radiation management geoengineering and democracy won't mix. *Environment and Planning A*, **45**, 2809 – 2816.

Tollefson, J. (2012): Ocean fertilisation project off Canada sparks furore. *Nature*, **490**, 458 – 459.

UK Government (2010): Government response to the House of Commons Science and Technology Committee 5th report of session 2009–10: the regulation of geoengineering. *The Stationary Office: London*.

van Vuuren, D., Edmonds, J., Kainuma, M., Riahi, K., Thompson, A., Hibbard, K., Hurtt, G., Kram, T., Krey, V., Lamarque, J-F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S. and Rose, S.

(2011): The representative concentration pathways: an overview. *Climatic Change*, **109**, 5 – 31.

Vaughan, N. and Lenton, T. (2011): A review of climate geoengineering proposals. *Climatic Change*, **109**, 791 – 825.

Verweij, M., Douglas, M., Ellis, R., Engel, C., Hendriks, F., Lohmann, S., Ney, S., Rayner, S. and Thompson, M. (2006): The case for clumsiness. In: Verweij, M. and Thompson, M. (Eds.). Clumsy solutions for a complex world, 1 – 27. *Palgrave Macmillan: New York*.

Victor, D. (2008): On the regulation of geoengineering. *Oxford Review of Economic Policy*, **24**, 322 – 336.

Virgoe, J. (2009): International governance of a possible geoengineering intervention to combat climate change. *Climatic Change*, **95**, 103 – 119.

Wright, M., Damon, A., Teagle, H. and Feetham, P. (2014): A quantitative evaluation of the public response to climate engineering. *Nature Climate Change*, **4**, 106 – 110.

Wynne, B. (1992a): Uncertainty and environmental learning: reconceiving science and policy in the preventive paradigm. *Global Environmental Change*, **2**, 111 – 127.

Wynne, B. (1993): Public uptake of science: a case for institutional reflexivity. *Public Understanding of Science*, **2**, 321 – 337.

Zürn, M. and Schäfer, S. (2013): The paradox of climate engineering. *Global Policy*, **4**, 266 – 277.