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Appraising Geoengineering

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Deliberate large-scale interventions in the Earth's climate system – known collectively as 'geoengineering' – have been proposed in order to moderate anthropogenic climate change. Amidst a backdrop of many ways of framing the supposed normative rationales for or against their use, geoengineering proposals are undergoing serious consideration. To support decision makers in the multitude of governance considerations a growing number of appraisals are being conducted to evaluate their pros and cons. Appraisals of geoengineering are critically reviewed here for the first time using a systematic literature search and screen strategy. Substantial variability between different appraisals' outputs originates from usually hidden framing effects relating to contextual and methodological choices. Geoengineering has largely been appraised in contextual isolation, ignoring the wider portfolio of options for tackling climate change – spanning mitigation and adaptation – and creating an artificial choice between geoengineering proposals. Most existing methods of appraisal do not adequately respond to the post-normal scientific context in which geoengineering resides and show a strong emphasis on closed and exclusive 'expert-analytic' techniques. These and other framing effects invariably focus – or close down – upon particular sets of problem definition, values, assumptions and courses of action. This produces a limited range of decision options which seem preferable given those framing effects that are privileged, and could ultimately contribute to the closing down of governance commitments. Emergent closure around particular geoengineering proposals is identified and argued to be premature given the need for more anticipatory, responsible and reflexive forms of governing what is an 'upstream' domain of scientific and technological development.

Deliberate large-scale interventions in the Earth's climate system – known collectively as 'geoengineering' – have been proposed in order to moderate anthropogenic climate change. Scientific, political, private and public interests in geoengineering proposals are rising against a backdrop of many ways of framing the supposed normative rationales for or against their use. These include desires to avoid 'dangerous' climate change using geoengineering that would otherwise seem unattainable amidst insufficient mitigation efforts; or concerns that the lure of geoengineering 'techno-fixes' might induce a 'moral hazard' whereby mitigation efforts are further neglected (Royal Society, 2009; Corner & Pidgeon, 2010; see Betz & Cacean, 2011, for an overview of the arguments in favour of or opposing geoengineering).

The term geoengineering encompasses a wide range of distinct technology proposals which can broadly be classified into 'carbon' and solar' variants, yet its definition remains ambiguous. In the absence of a thorough treatment of the term and its different linguistic framings we begin to map out its complex etymology in the next section of this paper. Whatever framings are constructed and used – be they normative, linguistic or otherwise – geoengineering proposals are fast becoming a feature of visions on how to tackle climate change. Indeed, the new Representative Concentration Pathway (RCP) scenarios to be used in the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) already assume at least two of the carbon geoengineering proposals – large-scale afforestation (RCP4.5) and Bio-Energy with Carbon Sequestration (BECS) (RCP2.6) – will be used, in addition to 'other technologies that may remove CO_2 from the atmosphere' in Extended Concentration Pathway (ECP) 3PD (van Vuuren, D. *et al.*, 2011, p25).

Geoengineering proposals are undergoing serious consideration by prominent institutions and governments around the world (e.g. HoC IUSSC, 2010; GAO, 2011; UBA, 2011). To support decision makers in the multitude of necessary governance considerations a growing number of appraisals are being conducted to evaluate the pros and cons of the different proposals and possible future pathways of technological development. A host of approaches are on offer for appraising geoengineering, ranging from established and exclusive 'expert-analytic' methods, such as benefit-cost analysis and risk assessment, to newer and inclusive 'participatory-deliberative' methods, such as citizens' panels and consensus conferences. Much as with the different courses of action they seek to evaluate, however, appraisals themselves are highly sensitive to different framing pre-commitments and effects (Jasanoff, 1990).

Through contextual and methodological choices expert-analytic and participatory-deliberative methods of appraisal alike can frame inputs that range from 'narrow' to 'broad' and outputs that range from 'closed' to 'open' (Stirling *et al.*, 2007). These choices amount to often overlooked 'instrumental framing conditions', which can exert considerable inadvertent or deliberate power on the results of appraisal. Appraisal inputs relate to the diversity of legitimate conditioning knowledges included, such as disciplines, perspectives, purposes, procedures, criteria, and the options or course(s) of action themselves. Appraisal outputs relate to the 'reflexivity' where these diverse frames and pre-commitments shaping knowledge-commitments are conveyed, transparently acknowledged and openly reflected upon (Wynne, 1992). Closed outputs correspondingly produce 'unitary and prescriptive' decision support, closing down on particular course(s) of action; whilst open outputs produce or 'plural and conditional' decision support, instead opening up the diversity of available pathways and their different sensitivities (Stirling, 2008).

Whilst some closure on which course(s) of action to commit to is ultimately necessary, it can marginalise the diversity of conditioning knowledges and result in premature 'lock in' (David, 1985; Arthur, 1989) and conflict between divergent values and interests (Stirling, 2008). Such was the case with the appraisal of a previously emergent suite of technologies: genetically modified (GM) organisms and crops. There, narrowly framed and closed expert appraisals of risk with no consideration of alternative options ignored deeper public concerns over 'upstream questions' about the purposes, visions, vested interests, equity and social implications of scientific and technological development (Wilsdon & Willis, 2004; Wynne, 2005). These concerns were recognised only when it became too late to influence developmental trajectories, resulting in an EU-wide moratorium on GM crops.

Much like the early stages in the development of GM crops before it, the science and proposals of geoengineering can be considered 'upstream'. That is to say that significant research and development on them has not yet taken place; many of their possible impacts have not yet been explored; and as yet there are few salient media or public discourses. This makes geoengineering proposals very sensitive to appraisal as knowledge of both their technical and social science is immature. Here we undertake a timely and critically reflexive review of geoengineering appraisals for the first time, examining the role of instrumental framing conditions in shaping appraisal inputs and outputs, and ultimately epistemic commitments for particular kinds of response to climate change. We do so with particular attention to four key dimensions by which appraisals are framed: i) the definition of the problem or issue in question and the purposes of science and technology in addressing it (context); ii) the appraisal methods and criteria used; iii) the particular options or courses of action being appraised; and iv) reflexivity with which results are conveyed. The extent to which these framing conditions narrow or broaden, and close down or open up the results of appraisal will be discussed, together with recommendations for further research and ultimately, the implications for governance.

DEFINING GEOENGINEERING

The idea of control over the Earth's weather and climate predates the modern concept of 'geoengineering' by millennia (Fleming, 2010). It has a rich history in ancient mythologies and religions, including those of Ancient Greece and the Roman Empire. Once powers bestowed by gods, control over weather and climate is now sought through technology. Indeed, this hubristic shift in humanity's relationship with nature was presaged by renowned physicist of Ancient Greece, Archimedes, who is believed to have said: 'Give me a lever long enough and a place to stand, and I will move the world.'

Following the discovery of the greenhouse effect in 1824 by Joseph Fourier and its later experimental demonstration by John Tyndall; in 1908 Svante Arrhenius proposed deliberately enhancing the greenhouse effect by burning more fossil fuels to enhance agricultural productivity (Arrhenius, 1908). Political as well as academic interests in potential weather and climate control ensued during the early to mid Twentieth Century, eventually reaching its height in the Cold War. Concerted proposals to 'optimise' weather and climate during this period (e.g. Rusin & Flit, 1960; Willoughby *et al.*, 1985), were, however, followed by proposals to weaponise it during the Vietnam War.

The controversy that followed and was sustained by the emergent environmental movement led to the signing of the United Nations (UN) international treaty, the Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques (ENMOD) (UN, 1976). The Convention, however, specifically reserved the entitlement to use weather and climate modification 'for peaceful purposes' (Article 3.1), helping to maintain modest academic and political interest following the discovery of anthropogenic greenhouse gas-induced climate change in 1960 by Charles Keeling (Keeling, 1960). Indeed, climate modification techniques were initially the only responses to climate change under consideration (President's Science Advisory Committee, 1965); with no mention of what has now become the dominant – even totalising – policy discourse: reducing fossil fuel consumption (mitigation) (Keith, 2000).

The term 'geoengineering' was coined in the early 1970's by Italian physicist Cesare Marchetti and later formally published in the inaugural issue of the journal *Climatic Change* in 1977 to describe a method for 'disposal' of atmospheric CO_2 through injection into sinking thermohaline oceanic currents (Marchetti, 1977). The term is a compound noun derived from the prefix 'geo' from the Greek *gê* meaning 'Earth'; and the noun 'engineering' meaning the 'application of science to design' (Oxford English Dictionary). Until recently geoengineering has been absent from common dictionaries due to its origins and confinement within the epistemic discourses of Earth system science and related academic disciplines.

Following its deployment by various actors and emergence in public discourses on climate change, in June 2010 the term was considered to warrant a common definition in the Oxford English Dictionary. However, defining geoengineering is of course somewhat more complex than the Oxford English Dictionary's modest offering (see Table 1). Here we begin to map out the complex etymology of geoengineering, revealing ambiguities as to what: i) constitutes geoengineering; ii) best delivers a linguistic framing; and iii) segregates its subset-classes.

Table 1 – Selected definitions of geoengineering

Source	Definition of 'geoengineering'
NAS (1992) p 433	'[Geoengineering proposals] involve large-scale engineering of our environment in order to combat or counteract the effects of changes in atmospheric chemistry.'
Keith (2000) p 245, 247	'Geoengineering is the intentional large-scale manipulation of the environment... For an action to be geoengineering, the environmental change must be the primary goal rather than a side effect and the intent and effect of the manipulation must be large in scale, e.g. continental to global... Three core attributes will serve as markers of geoengineering: scale, intent, and the degree to which the action is a countervailing measure.'
Barrett (2008) p 45	'[Geoengineering] is to counteract climate change by reducing the amount of solar radiation that strikes the Earth... [not] by changing the atmospheric concentration of greenhouse gases...'
AMS (2009) p 1	'Geoengineering – deliberately manipulating physical, chemical, or biological aspects of the Earth system [to reduce the risks of climate change].'
Royal Society (2009) p ix	'...the deliberate large-scale intervention in the Earth's climate system, in order to moderate global warming...'
Oxford English Dictionary (2010)	'The deliberate large-scale manipulation of an environmental process that affects the Earth's climate, in an attempt to counteract the effects of global warming.'

Whilst most are in agreement that for an action to constitute geoengineering it must be large in scale (cf. MacCracken, 2009), ambiguities exist relating to the issue of intentionality. For Keith

(2000), an action constitutes geoengineering when it is large in scale (e.g. continental to global manipulation) and intentional and countervailing in nature. On the other hand, others argue that neither intentionality nor a countervailing nature is a useful criterion for constituting an action as geoengineering. Fleming (2010) points out that those criteria should not be used to constrain actions already defined by their scale, and which could lead to undesirable as well as desired countervailing ends. Indeed anthropogenic climate change itself has been considered to be inadvertent geoengineering (NAS, 1992).

Ambiguities as to what best delivers a linguistic framing for geoengineering and its subset-classes often relates to preferences or semantics. The term geoengineering has been – and still is to some extent – competing with a host of alternative terms, including 'climate modification' (e.g. McCormick & Ludwig, 1967), 'climate engineering' (e.g. Bodansky, 1996), 'Earth systems engineering' (e.g. Schneider, 2001), 'planetary engineering' (e.g. Hoffert *et al.*, 2002), and most recently 'climate remediation' (BPC, 2011). Climate remediation is a particularly interesting case as it represents an attempt to 'rebrand' geoengineering. It was chosen by some to sit more comfortably alongside the more conventionally termed 'mitigation' and 'adaptation' strategies (BPC, 2011), but it did not go unopposed in its adoption (see Sarewitz, 2011). Similarly, within its subset-classes the term SRM has been rebranded 'Sunlight Reflection Methods' due to concerns over its emotively provocative predecessor 'Solar Radiation Management' (see SRMGI, 2011). Others have simply used 'geoengineering' itself to refer solely and explicitly to solar geoengineering proposals – and in particular stratospheric aerosols – ignoring carbon proposals in the definition altogether (see Barrett, 2008).

Ambiguities as to what segregates subset-classes of geoengineering often relate to proposals' technical and political implications. The UK's Royal Society (2009) has provided perhaps the most widely accepted definition of geoengineering, having been reaffirmed by the UK Government (HoC IUSSC, 2009) and the Intergovernmental Panel on Climate Change (IPCC, 2010) among others. This authoritative report divides geoengineering proposals along technical lines into two classes: Carbon Dioxide Removal (CDR) techniques and Solar Radiation Management (SRM) techniques. The same report recognises to a lesser extent a further taxonomic division between geoengineering proposals: those pertaining to Earth systems enhancement or traditional 'black-box' engineering (Rayner, 2011). Others have divided proposals along similar lines but included a third class of 'other' proposals (AMS, 2009); whilst others still have further divided those subset-classes into sub-subset-classes based on the broad Earth systems they seek to manipulate, including the top of the atmosphere, atmospheric or surface albedo, land or ocean (Lenton & Vaughan, 2009) and surface albedo modification (SAM) (Irvine *et al.*, 2011). Some divide proposals differently altogether, according to their 'commons' or 'territorial' governance implications (Humphreys, 2011).

Here we have begun to map out the complex etymology of geoengineering and revealed some of its ambiguities. Indeed this is reflected in the varied public understandings of the term, where just 8% of Americans, British and Canadians are able to 'correctly' define geoengineering (Mercer *et al.*, 2011). Whilst recognising the ambiguities of geoengineering, for clarity this review will use the term to refer to deliberate large-scale intervention in the Earth's climate system in order to moderate climate change; and 'carbon geoengineering' and 'solar geoengineering' to refer to classes of proposals which seek to remove and sequester CO_2 from the atmosphere and to increase the reflection of sunlight back into space, respectively.

THE GEOENGINEERING ISSUES

The ambiguities present in defining geoengineering are joined by a deeper diversity of complex technical and social issues, which pose unique challenges for appraisal. Technical issues of concern relate primarily to the potential effectiveness and impacts of different geoengineering proposals, all of which are subject to significant scientific uncertainties. The speed at which geoengineering proposals can reduce the Earth's temperature is one such consideration about their potential effectiveness. For instance, carbon geoengineering proposals act at a much slower rate than solar proposals, posing reservations about their suitability for moderating abrupt climate changes (Lenton & Vaughan, 2009). Whether or not geoengineering proposals address the 'second CO_2 problem' – ocean acidification – is a further another significant consideration about their potential effectiveness. In this case, solar geoengineering proposals do not address the issue whereas carbon proposals do (Royal Society, 2009).

The potential side effects of geoengineering proposals are a particular area of consideration. Stratospheric aerosols, often heralded as the most promising solar geoengineering proposal in terms of their effectiveness are also deemed high risk due to their risk of depleting of stratospheric ozone (e.g. Crutzen, 2006). Conversely, large-scale afforestation is thought to be one of the least effective carbon geoengineering proposals but also one of those posing the lowest risk (e.g. Keith, 2000). The side effects of geoengineering proposals do not only vary greatly between solar geoengineering proposals and their carbon counterparts, but also between the individual proposals within those subset-classes. Whilst solar geoengineering proposals are broadly considered to pose more undesirable risks than carbon proposals, this is not always true (Royal Society, 2009). Surface albedo changes in urban settlements, for example, would pose far fewer risks to ecosystems than iron fertilisation of the oceans.

Social issues of concern to appraisal relate primarily to the legality, economics, ethics, and ultimately public perception of different geoengineering proposals, all of which are subject to greatly divergent perspectives and values. The legality of geoengineering, and in particular stratospheric aerosols, is sometimes called into question with reference to treaties such as the Long-Range Transboundary Air Pollution Convention and the 1990 amendment to the Clean Air Act (Merrill, 1997). Whilst there are often calls for geoengineering to be regulated as much as possible under existing mechanisms, these older treaties did not account for geoengineering during their conception and could be renegotiated (Virgoe, 2009). Others argue that the 1977 UN ENMOD treaty would make any geoengineering illegal (MacCracken, 2006); but overlook the treaty's specific preservation of the right to use such techniques for peaceful purposes (Article 3.1) (Virgoe, 2009).

The economics of geoengineering proposals has been described as 'incredible' (see Barrett, 2008). In the face of conventional mitigation strategies, some have concluded that many geoengineering proposals would be relatively cheap to implement (Panel on Policy Implications of Greenhouse Warming, 1992; Teller *et al.*, 2003). Whilst the benefits are said to outweigh the costs of solar geoengineering proposals and carbon proposals alike, the benefits of solar proposals have been argued to be greater (Bickel & Lane, 2009). On the other hand, considerable uncertainties are cited in opposition to conclusions such as these (Pielke Jr., 2010). Moreover, the seemingly low costs of geoengineering have fuelled concerns about the possible unilateral deployment of certain proposals (Barrett, 2008).

The ethics of geoengineering is invariably complicated by its diverse range of proposals, meaning that not all proposals raise the same ethical issues (Gardiner, 2010). The issue of consent, for example, is likely to be limited by the jurisdictions in which they operate such as the global commons or the sovereign territories of states (Humphreys, 2011). However, other ethical issues such as the 'moral hazard' do apply to geoengineering more widely. In this case the lure of geoengineering 'techno-fixes' is feared to threaten the further neglect of mitigation efforts (Royal Society, 2009; Corner & Pidgeon, 2010), echoing earlier concerns that 'defeatist' adaptation efforts could have the same effect (Pielke Jr., 2007). On the other hand, it has been argued that even considering geoengineering could, in point of fact, galvanise mitigation efforts rather than harm them (Royal Society, 2009; NERC, 2010).

The technical and social issues relating to geoengineering appraisal ultimately contribute to the overarching issue of public understandings and concerns. Elicited perceptions of geoengineering vary widely with some researchers finding considerable support for geoengineering (Spence *et al.*, 2010; Mercer *et al.*, 2011), whilst others find an overwhelming preference for conventional mitigation efforts (Bellamy & Hulme, 2011). Carbon geoengineering proposals are seen to be broadly preferred over solar proposals, but a diversity of opinion exists as ever in relation to individual proposals within those subset-classes (NERC, 2010). Indeed, public discourses on stratospheric aerosols have been found to operate within multiple and often conflicting 'frames', with support for research but hesitation to the idea (Parkhill & Pidgeon, 2011). Despite the range of technical and socio-economic issues outlined above, it is evident that discourses of geoengineering have to date crowded out the sort of upstream public concerns that have pervaded other novel technologies. It is upon these considerations over the underlying purposes, values, directionality and equity of geoengineering science and technology – and the extent to which it reflects human needs and concerns – which public responses to geoengineering and other strategies for tackling climate change will ultimately depend.

FRAMING GEOENGINEERING APPRAISAL

Review method

We conducted a review of geoengineering appraisals to date using a systematic strategy for searching and screening articles of relevance. The Web of Knowledge electronic database was searched with the aim of identifying peer-reviewed and grey literature where geoengineering proposals were formally and explicitly appraised. The search used the following parametric terms: 'GEO*ENGINEERING' or 'CLIMATE ENGINEERING'. 272 returned articles were then screened for their relevance to the aforementioned search aims. 49 relevant articles were then further screened for their scope, where articles appraising specified geoengineering proposals were included within the review. 9 articles met the inclusion criteria along with a further 12 articles included using the same search and screening criteria in a general internet search using the Google search engine, giving a total of 21 articles. Of these articles an overwhelming majority of 18 were identified as fully expert-analytic in nature. In order to more widely reflect on emergent participatory appraisals of geoengineering the initial screen strategy was relaxed to include those participatory processes where individual proposals or geoengineering as a collective was appraised. A further 4 articles were added accordingly, bringing the total to 25 appraisals under review (see Table 2).

Table 2 – Appraisals of geoengineering included in the review. Numbering in chronological order (alphabetical by year). Acronyms: atmosphere-ocean general circulation model (AOGCM); benefit-cost analysis (BCA); cost of mitigation (COM); multi-criteria analysis (MCA); technology readiness level (TRL). Notes: * indicates appraisals not identified in the initial search and screen strategy. Contextual frames relate to the article context frame or method context frame where stated. We have been necessarily selective in the information provided in this table.

No.	Source	Appraisal design and methods	Notes on framing
1	Keith & Dowlatabadi (1992)	Expert literature review with select non-technical issues and subjective risk, relating to 8 carbon and solar geoengineering proposals	• Climate change impacts contextual frame • Subjective opinion of risks • Concludes stratospheric aerosols have the lowest COM
2	NAS (1992)	Expert literature review with marginal CO_2-equivalent mitigation costs, relating to 7 carbon and solar geoengineering proposals	• Climate change impacts contextual frame • Costs are based on considerable uncertainties • Concludes all geoengineering proposals are low cost and feasible except space reflectors, and mechanical cloud albedo and stratospheric aerosols are the most promising
3	Keith (2000)	Expert literature review with select uncertainties, non-technical issues and subjective risk, relating to 7 carbon and solar geoengineering proposals	• Climate change impacts contextual frame • Subjective opinion of risks • Concludes stratospheric aerosols have the lowest COM
4	Levi (2008)	Expert advice with plotting of costs and risks, relating to 6 carbon and solar geoengineering proposals plus mitigation	• Multiple contextual frames: climate change impacts, rapid climate change, insufficient mitigation • Subjective plotting of costs and risks • Concludes space reflectors are highest risk and cost, and mitigation is the least risky
5	Bickel & Lane (2009)	BCA relating to 4 carbon and solar geoengineering proposals	• Multiple contextual frames: 'dangerous' climate change, rapid climate change, insufficient mitigation • Uses different emission controls scenarios and market and ethical discount rates

			• Concludes mechanical cloud albedo and stratospheric aerosols have the greatest direct benefit-cost ratios, recommending funding for geoengineering research with solar geoengineering a priority owing to its earlier net benefit potential
6	Boyd (2008)	Expert MCA using 9 criteria (spanning efficacy, affordability, safety and rapidity), relating to 5 carbon and solar geoengineering proposals	• Multiple contextual frames: rapid climate change, insufficient mitigation • Technical criteria only with subjective scoring and little attention to uncertainty or sensitivities • Concludes iron fertilisation is the most effective; mechanical cloud albedo is the most affordable; air capture and storage is the safest; and mechanical cloud albedo and stratospheric aerosols are the fastest acting
7	Robock (2008)	Expert advice relating to 2 solar geoengineering proposals	• Multiple contextual frames: 'dangerous' climate change, insufficient mitigation • Concludes geoengineering may be a bad idea
8	Crabbe (2009)	Expert review of modelling simulations applied to coral reefs, relating to 18 carbon and solar geoengineering proposals	• Multiple contextual frames: climate change impacts, insufficient mitigation • Recommends further research into carbon geoengineering proposals, particularly in relation to air capture and storage, biochar and afforestation
9	Feichter & Leisner (2009)	Expert literature review relating to 3 solar geoengineering proposals	• Multiple contextual frames: climate change impacts, insufficient mitigation • Concludes none of the schemes are a sole solution to climate change
10	Irvine & Ridgwell (2009)	Expert literature review with select pros and cons and subjective risk, relating to 5 solar geoengineering proposals	• Multiple contextual frames: 'dangerous' climate change, insufficient mitigation • Subjective opinion of risks • Concludes geoengineering should not be relied upon to stop climate change but recommends further research to be prudent in case of emergency
11	Izrael *et al.* (2009)	Expert literature review with subjective assessment (spanning feasibility and efficacy), relating to 13 carbon and solar	• Multiple contextual frames: climate change impacts, insufficient mitigation • Subjective opinion of feasibility • Concludes stratospheric aerosols can be the most effective

		geoengineering proposals	
12	Lenton & Vaughan (2009)	Radiative forcing potential calculations relating to 19 carbon and solar geoengineering proposals	• Multiple contextual frames: 'dangerous' climate change, insufficient mitigation • Assumes strong mitigation scenario baseline • Concludes only stratospheric aerosols, mechanical cloud albedo and space reflectors can return the climate to its pre-industrial state
13	Royal Society (2009)	Expert literature review with MCA using 4 criteria (efficacy, affordability, safety and timeliness), plotted and relating to 20 carbon and solar geoengineering proposals; plus telephone interview survey and focus groups exploring public perceptions, relating to 3 carbon and solar geoengineering proposals	• Multiple contextual frames: 'dangerous' climate change, insufficient mitigation and 2°C policy target framed the report; geoengineering definitions framed the telephone survey and focus groups • MCA features technical criteria only with subjective scoring • MCA concludes that stratospheric aerosols, space reflectors, air capture and storage and enhanced weathering are most effective, afforestation is the most affordable, stratospheric aerosols, desert albedo and CCS are the most rapid, and air capture and storage, urban albedo and CCS are the safest • Survey and focus groups conclude that perceptions of geoengineering were generally negative
14	Moore *et al.* (2010)	Linear response model simulations compare limiting sea-level rise, relating to 5 carbon and solar geoengineering proposals	• Multiple contextual frames: climate change impacts, climate emergency • Assumes geoengineering does not affect exchange processes between the atmosphere, biosphere and oceans • Concludes that bio-energy with carbon sequestration is the least risky and most desirable for limiting sea level rise
15	NERC (2010)	Deliberative public dialogue exploring perceptions (spanning public groups, discussion groups, online survey and open access events), relating to 9 carbon and solar geoengineering proposals	• Multiple contextual frames: insufficient mitigation framed the report; pros and cons and climate emergency framed the dialogue • Climate emergency framing may have influenced stated public acceptability of geoengineering • Concludes that carbon geoengineering proposals are preferred to solar proposals, and afforestation and biochar were specifically preferred
16	Spence *et al.*	Face-to-face interview	• Multiple contextual frames: 'dangerous'

	(2010)*	survey exploring perceptions, relating to geoengineering proposals as a collective	climate change and Climate Change Act framed the report; geoengineering definitions framed the interviews • Uses simple quantitative measures • Concludes that most people do not know what geoengineering is but would support it
17	Bellamy & Hulme (2011)*	Online survey and focus groups exploring perceptions, relating to geoengineering proposals as a collective	• Rapid climate change contextual frame used in the article and online survey and focus groups • Presents geoengineering as one option of a range of possible responses to climate change • Concludes geoengineering is unfavourably perceived
18	Fox & Chapman (2011)	Expert literature review and ranking applied to engineering feasibilities, relating to 10 carbon and solar geoengineering proposals	• Multiple contextual frames: climate change impacts, rapid climate change, insufficient mitigation • Arbitrary ranking of feasibilities • Concludes afforestation is the most feasible proposal
19	GAO (2011)	Expert technology assessment (spanning maturity, effectiveness, cost factors and consequences), relating to 14 carbon and solar geoengineering proposals; plus online survey and focus groups exploring public perceptions, relating to 4 carbon and solar geoengineering proposals	• Multiple contextual frames: climate change impacts, rapid climate change and insufficient mitigation framed the report; geoengineering definitions framed the online survey and focus groups • Includes foresight exercise using scenarios to elicit views of the future of geoengineering research • Technology assessment concludes that all geoengineering proposals are at TRL 2, except stratospheric aerosols which are the least mature (TRL 1) and air capture and storage which is the most mature (TRL 3) • Survey and focus groups concludes that most are unfamiliar with geoengineering but would be open to research, whilst demonstrating concern about safety and governance
20	Irvine *et al.* (2011)	AOGCM simulations compare global and regional effects, relating to 3 solar geoengineering proposals	• Multiple contextual frames: climate change impacts, insufficient mitigation, 2°C policy target • Limitations to regional modelling of effects • Concludes none of the schemes reverse climate changes under a doubling of CO_2
21	Jones *et al.* (2011)	AOGCM simulations compare climatic	• Multiple contextual frames: climate change

		impacts, relating to 2 solar geoengineering proposals	impacts, alternative to mitigation • Limitations to cloud modelling • Concludes geoengineering is unlikely to avoid significant regional climate changes
22	Mercer *et al.* (2011)*	Online survey exploring perceptions, relating to solar geoengineering proposals as a collective	• Multiple contextual frames: societal responses to climate change, inexpensive, and risks framed the article; pros and cons and climate emergency framed the online survey • Risk of constructed preferences • Concludes the public supports research into solar geoengineering
23	Parkhill & Pidgeon (2011)*	Deliberative workshops exploring perceptions, relating to 1 solar geoengineering proposals: stratospheric aerosols	• Societal responses to climate change contextual frame used in the workshops • Presents geoengineering as a risk issue • Concludes that participants show a reluctant acceptance of a delivery-mechanism test-bed for stratospheric aerosols
24	Vaughan & Lenton (2011)	Expert literature review with select efficacies and feasibilities, relating to 19 carbon and solar geoengineering proposals	• Multiple contextual frames: rapid climate change, insufficient mitigation • Assumes strong mitigation scenario baseline • Concludes that geoengineering is not an alternative to mitigation, but could complement it
25	Russell *et al.* (2012)	Expert literature review with select ecological impacts, relating to 5 carbon and solar geoengineering proposals	• Climate change impacts contextual frame • Concludes that research on ecological impacts of geoengineering is needed before large-scale field trials or deployment

Context: appraisal problem framing and purpose

The foremost framing condition shaping the appraisal of geoengineering proposals relates to contextual choice in terms of the object of appraisal – i.e. the problem or issue being addressed. These instrumental framing conditions can be highly subjective and set the context and tone of each appraisal. Here we identify six groups of geoengineering appraisal context or problem 'frames' identified across the appraisals under review (see Table 3). All of the appraisals framed the issue broadly around climate change in scientifically-defined terms and the need to alleviate its potential risks (cf. Wynne, 2005). Within this domain risk framing articles varied in their choice of illustrative risks. Issue frames ranged from unspecified or specified climate change impacts to special climate 'emergency' conditions, including the onset of rapid or 'dangerous' climate change or climate 'tipping points'. The majority of appraisals were also framed around assumptions of 'insufficient mitigation' efforts; whilst a minority were also framed around the climate policy targets such as the UK Climate Change Act or the 2°C warming above pre-industrial limit. Few appraisals were framed around broader societal responses to climate change or geoengineering as an alternative to mitigation.

Table 3 – Frequency of different context frames in geoengineering appraisals. Note: frames are elicited from article introductions and methods. Most appraisals used multiple frames, which are counted here separately.

Context frame	Frequency of frames
Climate emergency	15
Insufficient mitigation	15
Climate change impacts	13
Climate policy	3
Societal responses to climate change	2
Alternative to mitigation	1

Each of these context frames represents particular definitions of the problem, sets of values and assumptions, and visions of the future – whilst ignoring others – when it comes to the future circumstances under which geoengineering the climate might be considered. Obvious exclusions include the alternative purposes of geoengineering technologies associated with profit, social control, military applications, and so on; anticipation of the (often unintended) social and ethical implications; and recognition of the complex and indeterminate social, cultural-institutional and geopolitical futures embedded within such visions. These 'imaginaries' are particularly potent in participatory processes, where different context frames can exert significant power upon participants' appraisals through the phrasing of questions. For instance, during the Experiment Earth? public dialogue (NERC, 2010) facilitators and experts described the future using a climate 'emergency' frame, which is likely to have influenced the perceived acceptability of geoengineering proposals through the implicit implication of necessity (Corner *et al.*, 2011).

Similarly, it is a climate 'emergency' frame that underpins apparent public support for solar geoengineering reported in the online survey by Mercer *et al.* (2011). Concordantly, with the majority of geoengineering appraisals adopting the 'insufficient mitigation' frame, necessity of at least researching geoengineering is implicitly implied.

Appraisal methods and criteria

Beyond the construction of broad contextual problem frames lie specific methodological choices and selection of criteria to judge different courses of action in tackling climate change. These powerful instrumental framing conditions set the lens through which each appraisal is conducted. Of the original 21 geoengineering appraisals identified for review an overwhelming majority (18) were identified as expert-analytic in nature (see Table 4). That is to say they were conducted by experts without the inclusion of publics, and utilised methods of appraisal that can be construed as relatively constrained, opaque and often quantified in their treatment of the issue. These methods ranged from computer modelling to economic assessments to expert reviews and opinions to multi-criteria analysis (MCA). A further two of the geoengineering appraisals reviewed were expert-analytic in principal focus, but were supported by minor participatory elements. These expert-participatory methods included an expert review of the geoengineering literature and simple MCA conducted by the UK Royal Society and a technology assessment conducted by the US Government Accountability Office each featured surveys and focus groups to elicit perceptions of geoengineering (Royal Society, 2009; GAO, 2011). The one dedicated participatory-deliberative appraisal identified in the initial search was the Experiment Earth? public dialogue (NERC, 2010). A further 4 participatory articles were added following a relaxation of the screening strategy.

Table 4 – Frequency of different geoengineering appraisal methods.

Appraisal method	Frequency of appraisals
Expert-analytic	18
Participatory	5
Expert-participatory	2

The expert-analytic appraisals of geoengineering can be classified amongst those involving calculations or computer modelling, expert reviews and opinions, economic assessments, and MCA. Those appraisals using calculations or computer models are naturally constrained to the disciplinary study of technical criteria involving the efficacies of geoengineering proposals. Methodological choices made within these appraisals inevitably involve making contestable assumptions about the futures in which geoengineering would operate. The use of the Bern carbon model in producing CO_2 scenarios, for instance, assumes that geoengineering would have no impact on the carbon exchange processes between atmosphere, biosphere, and oceans (e.g. Moore *et al.*, 2010). Similarly the use of strong mitigation or balanced use of energy sources as scenario baselines assumes certain social and technical developments whilst ignoring other possible futures and sensitivities (e.g. Lenton & Vaughan, 2009; Jones *et al.*, 2011).

Sources of uncertainty in climate models relating to the representation of baseline conditions, forcings and sensitivities are well documented (e.g. Randall *et al.*, 2007), but pose some specific issues for modelling the efficacies and impacts of geoengineering. Atmosphere-ocean general circulation models (AOGCMs) are widely used and considered to provide credible projections of future temperature change at large spatial scales. However, projections made at smaller spatial scales such as regional precipitation patterns are poor, confounding conclusions made in relation to regional geoengineering impacts such as those by surface albedo changes (e.g. Irvine *et al.*, 2011). Moreover, considerable uncertainties remain such as the modelling of cloud formation and opacity, confounding conclusions made in relation to specific geoengineering proposals such as cloud albedo enhancement (e.g. Jones *et al.*, 2011).

Expert reviews and opinions dominate the expert-analytic category of geoengineering appraisals, seeking to synthesise disparate existing information (e.g. Vaughan & Lenton, 2011) or apply it to a novel context (e.g. Crabbe, 2009) or use it to inform expert opinion (e.g. Izrael *et al.*, 2009). Whilst each of these objectives is capable of closing down the range and quality of outputs through the inherently selective choice of information for inclusion or exclusion, expert opinions hide a range of subjectivities. A frequent opinion aired in appraisals of geoengineering relates to the risk of side effects. For instance the purported risks of a particular solar geoengineering proposal – space reflectors – vary wildly, from very low (e.g. Keith & Dowlatabadi, 1992) to low (e.g. Keith, 2000) to moderate (e.g. Royal Society, 2009) to high (e.g. Levi, 2008; Irvine & Ridgwell, 2009). The subjective reasoning that underpins these discreet and seemingly 'matter of fact' statements is often under-explained and unaccounted for. Similarly the reasoning and methods behind arbitrary rankings for different geoengineering proposal feasibilities lacks transparency (e.g. Fox & Chapman, 2011).

The GAO (2011) technology assessment review undertook a notably different approach in exploring the envisaged future of research on geoengineering. Whilst still constrained to expert opinions only, the assessment recognised the roles that subjectivities and imaginaries play in technology advancements and developed a foresight exercise in which four scenarios were constructed and engaged with. Despite the limited range of scenarios and participants this exercise represents an important step forward in opening up visions of the range of possible futures in which geoengineering could reside.

A limited number of economic assessments have been made to appraise geoengineering, seeking to identify the benefits and / or costs of different proposals. Here those methods involve calculating the marginal CO_2-equivalent cost of mitigation (COM) (NAS, 1992) or benefit-cost analysis (BCA) (Bickel & Lane, 2009). Critiques of appraisals based solely on economic efficiency criteria are well established, often citing their ignorance of wider issues as well as an inadequate or even inappropriate representation of 'non-market goods' (e.g. Anderson, 1993). Moreover, economic assessments of novel proposals such as those within geoengineering can more generally suffer from 'appraisal optimism' due to systematic biases in underestimating costs (Flyvjberg *et al.*, 2003).

Economic assessments are particularly open to instrumental framing effects relating to their treatment of sensitivities and the discounting of time. Whilst the BCA conducted by Bickel & Lane (2009) does include a number of different emission controls scenarios as well as market and ethical discount rates, these assumptions rely upon huge uncertainties in the literature. Furthermore in a demonstration of these methodological framings influencing outputs, another BCA using the same Dynamic Integrated model of Climate and the Economy (DICE) but different assumptions led to conflicting conclusions. Where stratospheric aerosol injection achieved an admirable benefit-cost ratio of 25 to 1 in Bickel & Lane (2009), Goes *et al.* (2011) concluded that the solar geoengineering proposal failed benefit-cost analysis under no less plausible assumptions (see Pielke Jr., 2010).

Multi-criteria analyses can account for a much wider range of appraisal criteria than BCA or other expert-analytic methods, but are no less susceptible to instrumental framing effects. Here, the chosen diversity of criteria and weightings given to them is critical, constraining the appraisal scope and privileging certain criteria above others. Both Boyd (2008) and the Royal Society

(2009) have performed MCA appraisals relating to the same, loosely defined technical criteria: efficacy, affordability, safety and timeliness. Whilst these appraisals fail to take advantage of the wider range of possible criteria for inclusion within MCA, including a plethora of possible social, political and ethical considerations, a much broader critique befalls the use of MCA itself. Quantitative methods of appraisal, such as MCA, require criteria of the same dimensionality in order to use a mathematical approach. That is to say, if the multiple units of appraisal are not compatible, the unit-less outcome amounts to adding apples and oranges (Dobes & Bennett, 2010).

The participatory-deliberative appraisals of geoengineering can be classified amongst those involving surveys, focus groups, and deliberative workshops, each seeking to elicit public and/or stakeholder views and perceptions of geoengineering. Appraisals employing surveys were the most frequent of those attempting to open up inputs, doing so via online instruments, telephone interviews, or face-to-face interviews. Whilst not strictly deliberative these often quantitative methods are also constrained by a limited appreciation of the participant reasoning that underpins claims. For instance the seemingly discreet finding that 72% of people somewhat or strongly supporting solar geoengineering proposals, together with limited information on possible variables tells us little about supportive or confounding influences on that claim (e.g. Mercer *et al.*, 2011). Moreover, survey research cannot ensure the derivation of opinion on emergent issues such as geoengineering, instead often deriving 'constructed preferences' via information provision (Slovic, 1995).

Focus groups can offer much deeper explanations of what underpins public understandings and concerns about geoengineering, but are still focussed in terms of a stated agenda for discussion. For instance Bellamy & Hulme (2011) introduce geoengineering as an option for counteracting climate tipping points, seeking to elicit policy preferences. The Royal Society (2009) sought to elicit the perceived benefits, risks and uncertainties about geoengineering. The GAO (2011) focus groups sought to elicit reactions to geoengineering proposals, support or opposition, and how to best make decisions about geoengineering in government, industry and as individuals. Whilst broadening the range of appraisal criteria they are still bound by their choice of focus for the discussion. Concurrently the recruitment of participants also constitutes an important framing effect. For instance the use of university participants in convenience sampling, an accessible and popular strategy in psychological research, can produce unrepresentative Western, Educated, Industrialised, Rich and Democratic ('WEIRD') representations of humanity (see Jones, 2010) (e.g. Bellamy & Hulme, 2011).

The deliberative workshops on geoengineering offer the least constrained methods of eliciting public perceptions of and concerns about geoengineering. Whilst still employing focus to direct the deliberations, these methods allow participants to frame the discussions to some extent and thereby facilitate deeper exploration of perspectives. Such methods are just as susceptible to other framing effects as other methods, however, including the provision of information. As with all participatory methods the provision of information with respect to emergent issues about which little is known is a critical framing effect, risking the formation of constructed preferences rather than derived opinions (Slovic, 1995). For instance the provision of selected pros and cons of different geoengineering proposals is technically focussed, marginalising other issues such as ethics (Corner *et al.*, 2011) (e.g. NERC, 2010). Parkhill & Pidgeon (2011) refer to this as 'treading a fine line' between providing sufficient information for discussion without influencing participants' views.

Appraisal options

The scope of options – or courses of action – included within appraisals of geoengineering is a critical instrumental framing effect, narrowing or broadening the possible future pathways for addressing climate change. Geoengineering options were selected for inclusion or exclusion from the appraisals under review on the basis of a number of normative rationales. For instance, they have been selected on the basis of their being 'promising suggestions' (e.g. Feichter & Leisner, 2009); their 'promise for affecting global climate' (e.g. Bickel & Lane, 2009); their prominence in 'popular and scientific media' (e.g. Boyd, 2008); and their 'plausibility' (e.g. Parkhill & Pidgeon, 2011); or on no apparent basis at all (e.g. GAO, 2011). Appraisals of geoengineering assessed a mean average of 8.5 different options per article, composed of an even 4 solar and carbon options per article. However, from an analysis of the frequency of different individual geoengineering proposals featured in appraisals we identify an emergent focus – or closing down – on particular proposals (see Figure 1).

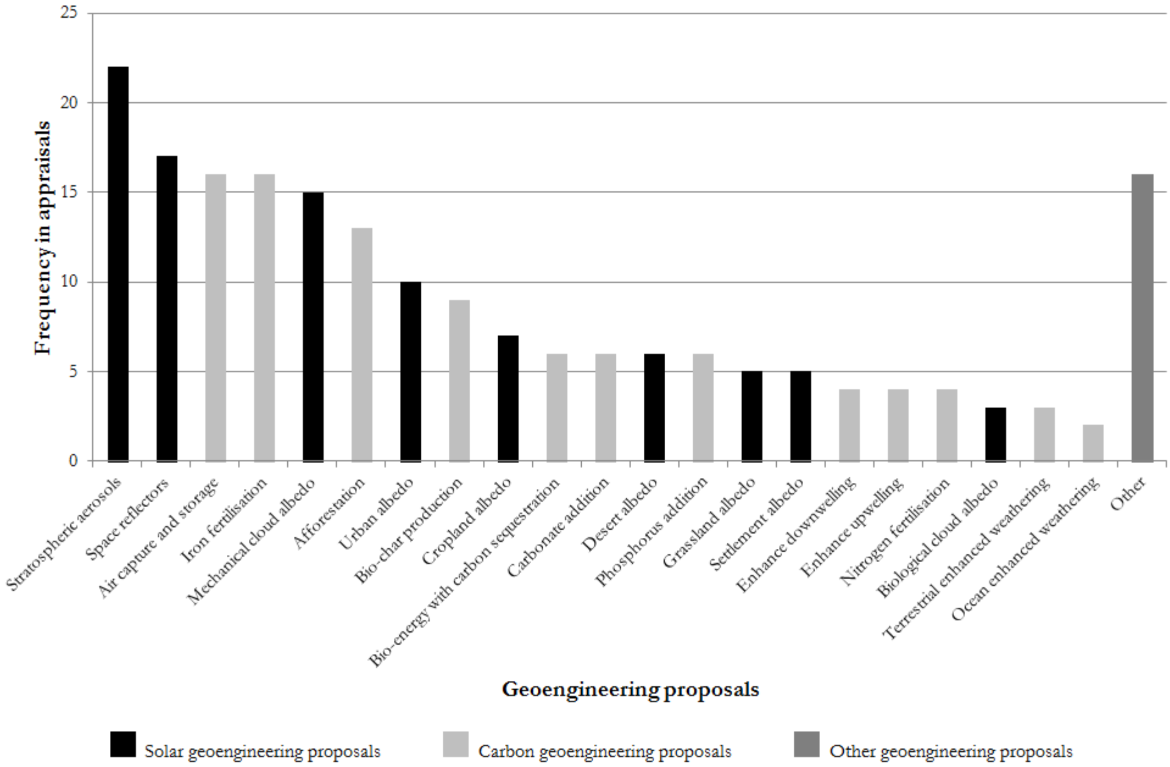

Figure 1 – Frequency of different geoengineering proposals featured in the appraisals reviewed. Note: 'other' geoengineering proposals are those featured only once. Supplementary appraisals (i.e. the participatory appraisals undertaken by the Royal Society (2009) and GAO (2011) in addition to their primary expert-analytic appraisals) are counted here as separate appraisals.

The frequency of different geoengineering proposals featured in appraisals shows an emergent tiered distribution, with certain proposals clearly receiving more attention than others. Three of arguably the most controversial geoengineering proposals occupy positions in the top four most frequently appraised proposals: stratospheric aerosols, space reflectors and iron fertilisation. Stratospheric aerosols are by far the most frequently appraised proposal, appearing in 22 of the appraisals and on average 5 times more frequently than other proposals.

The appraisals appear to close down upon certain geoengineering proposals and not others, while many fail to open up the decision context to include legitimate alternative options. Alternative courses of action are commonly and narrowly represented by other geoengineering proposals, ignoring the necessary and wider portfolio of climate change strategy options – mitigation and adaptation – and facilitating contextual isolation. This creates an artificial 'yes / no' choice between geoengineering proposals. The few exceptions to this open up the decision context by appraising geoengineering alongside single (e.g. carbon capture and storage [Royal Society, 2009]) or multiple (Bellamy & Hulme, 2011) courses of mitigation action.

Reflexivity

The extent to which appraisals of geoengineering acknowledge the myriad of instrumental framing conditions bearing upon their outputs is a decisive framing condition in itself. The 'reflexivity' – or degree of transparent acknowledgement – with which those conditioning knowledges are conveyed directly impacts on the legitimacy of any conclusions or recommendations drawn from them. Levels of reflexivity – in terms of opening up the inputs and outputs of appraisals – were identified as low for the majority of those geoengineering appraisals under review (see Figure 2). Substantial variability between different appraisals' outputs, but relating to the same geoengineering issues, was found and can be attributed to the hidden uncertainties and subjectivities bound within the instrumental framing conditions. For instance, where iron fertilisation is viewed as relatively effective by Boyd (2008), it is viewed as relatively ineffective by the Royal Society (2009). Moreover, where the Royal Society (2009) reports the mean performance scores with small error bars given by a number of experts, the full range and diversity of scores as well as their reasoning underpinning those means is hidden and unaccounted for.

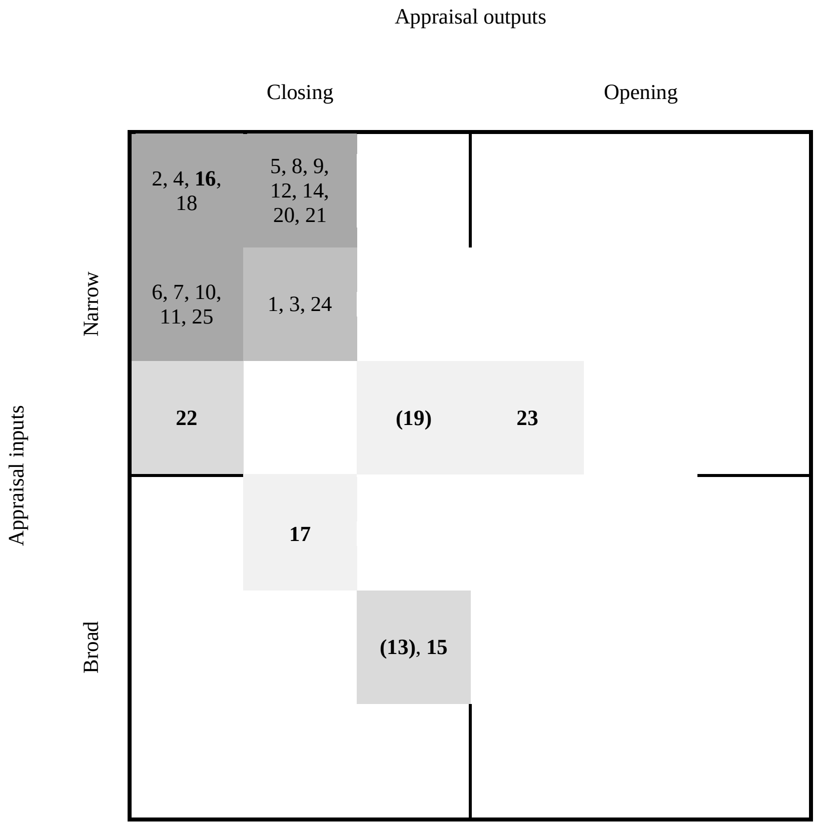

Figure 2 – Breadth of inputs and openness of outputs in geoengineering appraisals (after Stirling *et al.* 2007). Note: numbers are in ascending chronological order and relate to appraisals in Table 2. Appraisal positions in the grid are necessarily interpretative, and not definitive but indicative. Appraisal breadth was assessed as either low or high in a 2 × 2 matrix in relation to the scope with which appraisals accounted for the character of the decision context and the diversity of legitimate knowledges; then positioned relative to one another within a 3 × 3 sub-matrix. Appraisal openness was assessed as either low or high in a 2 × 2 matrix in relation to the reflexivity with which instrumental framing conditions are conveyed and outputs made; then positioned relative to one another within a 3 × 3 sub-matrix.

Ultimately, these low levels of reflexivity amount to many appraisals making unitary and prescriptive decision recommendations, closing down on particular course(s) of action. Each of the geoengineering appraisals under review recommends further research. However, some go further and produce definitive recommendations as to which geoengineering proposals are best in different respects or deserve particular attention or funding. Of those appraisals, recommendations were advanced on the basis of the technical factors of efficacy, feasibility, economics, safety or the social factor of preference. Stratospheric aerosols, space reflectors, mechanical cloud albedo (Lenton & Vaughan, 2009) or iron fertilisation (Boyd, 2008) are heralded as the most effective. Bio-energy with carbon sequestration is heralded as the least risky and most desirable for limiting sea-level rise (Moore *et al.*, 2010). Stratospheric aerosols, afforestation (Fox & Chapman, 2011) or air capture (GAO, 2011) or all geoengineering options except space reflectors (NAS, 1992) are heralded as the most feasible. Mechanical cloud albedo and stratospheric aerosols are heralded as the most cost effective (Boyd, 2008; Bickel & Lane, 2009). Air capture and storage is heralded as the safest (Boyd, 2008). Afforestation and bio-char production are heralded as preferred by the public (NERC, 2010). Each of these recommended decision options seem preferable given the respective instrumental framing conditions upon which they are built.

DISCUSSION AND RECOMMENDATIONS

Contextual isolation

Different contextual frames were identified in the appraisals under review, hinting at the diversity of supposed normative rationales for considering the use of geoengineering. Such framings can have a profound impact on appraisal inputs and outputs, as demonstrated by the likely influence of the climate 'emergency' frame on participants used during the NERC (2010) Experiment

Earth? public dialogue (Corner *et al.*, 2011). A narrow emphasis on this climate 'emergency' frame as well as the 'insufficient mitigation' frame was found amongst the appraisals under review. These frames suggest implicitly that conventional measures for mediating climate change are not enough and that geoengineering is required. This may therefore artificially enhance the perceived acceptability of geoengineering proposals. Correspondingly, issues of reflexivity arise with respect to these framings: why use these context frames and not others? What are the normative rationales underpinning the use of those frames and what might their framing effects be? Recognising the many different ways in which geoengineering can be contextually framed and the effects these can have will strengthen the transparency and legitimacy of appraisal conduct and output.

Whilst the appraisals emphasise certain context frames above others, isolating them from the diversity of the supposed normative rationales for or against the use of geoengineering, so too do they isolate geoengineering from the wider decision context in which it resides: moderating climate change. By narrowly appraising geoengineering proposals only against one another, legitimate alternatives are ignored and contextual isolation is facilitated. To avoid this false 'yes / no' choice between geoengineering proposals the necessary and wider portfolio of climate change strategy options – spanning mitigation, geoengineering, and adaptation options – should be addressed. Opening up and appraising the full range of courses of action available to decision makers broadens the inputs to appraisal and better acknowledges the complexity of the issue.

Handling uncertainty

The propriety of different methods in appraisal can be ascertained by examining the decision context characterising a given issue. The upstream nature of geoengineering proposals, together with the large Earth system uncertainties and high stakes of climate change itself – and of its intentional manipulation on top of that – places geoengineering firmly within the realms of 'post-normal' science (Funtowicz & Ravetz, 1992; 1993). It is important in decision contexts such as these to include within appraisals axiological factors (value judgements) from an 'extended peer community' or all those with a stake in the issue and not simply experts. While there is no doubt that participatory forms of appraisal are equally susceptible as technical-analytic ones to instrumental framing effects and the closing down of wider policy discourses (Chilvers, 2008; Stirling, 2008), participation by definition brings other voices, perspectives, knowledge and visions of the future into the process which challenges existing assumptions and interests, whether that be related to normative or substantive reasons (Fiorino, 1990).

However, the overwhelming majority of the appraisals under review were identified as expert-analytic in nature. This is not to say that such expert-analytic methods are not welcome or needed; on the contrary such methods are an essential and necessary contribution to the appraisal of technical issues. Rather this observation recognises the need for a balancing of appraisal methods, to include more participatory-deliberative appraisals of geoengineering. Only by including such methods can we begin to fully account for the great systems uncertainties and high stakes that characterise the post-normal state in which the upstream science of geoengineering resides (Funtowicz & Ravetz, 1992; 1993).

Appraisals of geoengineering more widely reflect methodological responses to the incertitude of decision making. Stirling *et al.* (2007) outline four characteristics of incertitude relating to knowledge about probabilities and outcomes. Unproblematic knowledge of both probabilities and outcomes characterises a 'risk' issue and expert-analytic methods such as risk assessment and BCA are considered appropriate methods of decision support. With respect to geoengineering, however, knowledge about either probabilities or outcomes or both is often problematic and highly uncertain. This characterises geoengineering as an 'uncertainty' issue, an 'ambiguity' issue, or an 'ignorance' issue respectively, each where expert-analytic methods are deeply insufficient when used in isolation (Hayek, 1978). Accordingly, a host of different methods of appraisal for decision support are considered more appropriate. Under uncertainty decision heuristics or sensitivity analyses might be considered. Under ambiguity foresight scenario workshops or multi-criteria mapping might be considered. Under ignorance broader aims such as institutional learning and adaptive management might be considered (Stirling *et al.* 2007).

Lock-in and diversity

As the above analysis has shown, low levels of reflexivity as identified in the appraisals of geoengineering under review contribute to the production of unitary and prescriptive decision recommendations. This closure around particular sets of hidden values or assumptions – be it around climate models, scenario baselines, selective information consideration, subjectivities of risk, valuations, criteria for inclusion or exclusion, presentation of findings, information provision, choice of focus, recruitment of participants, choice and characterisation of options, or a host of other framing effects not necessarily covered in this review – produces variably limited ranges of decision options which seem preferable given those framing effects that are privileged (Stirling, 2008). Accounting for and acknowledging these framing effects through reflexive declaration will enhance transparency and ultimately the rigor of accountability in relation to any decisions made from recommendations therein (Stirling *et al.*, 2007).

The scope of options addressed in appraisals of geoengineering already demonstrates closure around specific proposals, and in particular stratospheric aerosol injection. Whatever the supposed rationales for consistently including stratospheric aerosols in appraisals more often than any other geoengineering proposal – be it because of its normative reasons of plausibility or promise, or seemingly substantive reasons of efficacy or economics, or any other reason – we have demonstrated that these assertions are at this stage simply too uncertain and sensitive to instrumental framing effects to justify closure around a quintessentially upstream idea. Furthermore this premature closure could contribute to stratospheric aerosols becoming a salient or even synonymous icon of geoengineering, whereby support or opposition to geoengineering in general is judged by one proposal. Indeed some already use the term geoengineering synonymously with stratospheric aerosols (e.g. Barrett, 2008).

The outputs of many geoengineering appraisals can be considered examples of different types of 'decision justification', whereby appraisals can exert inadvertent, tacit or deliberate influences of power on decision making through their various framings and prescriptive policy advice (Collingridge, 1982; Habermas, 1984; Stirling, 2008). This could contribute to a premature closing down of governance commitments on geoengineering, or even more widely on responses to climate change. In contrast, to open up choices to decision makers is to widen the scope of appraisal inputs and outputs and ultimately inform governance with enhanced rigor, transparency and accountability. Plural and conditional policy advice instead accounts for alternative decision options and the different frames under which each might appear favourable or unfavourable.

Geoengineering proposals currently exist as a diverse range of ideas open to different actors in science, policy and society as a plurality of possible imagined futures. As an upstream suite of technology proposals, however, they are particularly sensitive to these instrumental framing effects and could easily be quickly and prematurely closed down, locking us in to certain technological trajectories but not others (David, 1985; Arthur, 1989). Ultimately, potentially unsung divergent values and interests in such a lock-in could cause controversy (Stirling, 2008). Appraisals should therefore broaden the inputs into and open up the outputs from appraisals of geoengineering, placing them in the lower right hand quadrant of Figure 4. A number of appraisal methodologies already exist which actively seek to address instrumental framing conditions in such a way, including expert-analytic methods such as Multi-Criteria Mapping (Stirling & Mayer, 2001); participatory-deliberative methods such as scenario workshops (Ogilvie, 2002), Q-method (McKeown & Thomas, 1988) and Stakeholder Decision Analysis (Burgess, 2000); and the analytic-deliberative hybrid Deliberative Mapping (Burgess *et al.*, 2007).

Geoengineering governance

Ultimately, the issues addressed in appraisals of geoengineering pose unique challenges for the governance of geoengineering research and development. Indeed the diversity of issues is considered to rule out any single mode of governing geoengineering (Humphreys, 2011). As an 'upstream' suite of technology proposals geoengineering more broadly exemplifies the 'technology control dilemma', in that predictive governance arrangements made prior to any actual developments will unavoidably fail to account for unanticipated evolutions (Collingridge, 1980; Royal Society, 2009). Indeed, this dilemma has beset previously emergent technologies such as nuclear energy and genetically modified (GM) crops. In these cases narrowly framed expert considerations of performance and risk ignored deeper public concerns about the values, visions and vested interests driving scientific and technological development (Wilsdon & Willis, 2004). Recent research comparing public dialogues on geoengineering and many other areas of emerging science and technology shows these concerns over the purposes of science, trust, inclusion, speed and direction of innovation, and equity to be highly durable and in need of reflection (Macnaghten & Chilvers, 2012).

Accounting for these public concerns and the values, visions and vested interests that drive science, however, can contribute to an enhanced societal capacity for foresight, and ultimately anticipatory rather than predictive governance (Guston & Sarewitz, 2002). The test-case for this anticipatory governance has been the emerging science and technologies of nanotechnology (Macnaghten *et al.* 2005), the 'control of matter at dimensions of roughly 1 to 100 nanometres, where unique phenomena enable novel applications' (NNI, 2007). In recognising the co-production of socio-technical knowledges (Jasanoff, 2004), as well as the normative, substantive and instrumental arguments in favour of public participation in appraisal, experiments with the anticipatory governance of nanotechnology using forward-looking and inclusive participatory methods of expert and public engagement alike have yielded promising results (Guston, 2008).

The sentiments of anticipatory governance were captured to some extent in proposed governing principles for geoengineering: the Oxford Principles (Rayner *et al.*, 2009). The principles call for

i) geoengineering to be regulated as a public good, ii) public participation in geoengineering decision making, iii) disclosure of geoengineering research and open publication of results, iv) independent assessment of impacts, and v) governance before deployment. Welcomed with caveats by the UK Government's House of Commons Science and Technology Committee (HoC, 2010), ambiguities with respect to the nature of the public participation and the flexibility of governance regimes have since been redressed by the Asilomar Conference Recommendations on Principles for Research into Climate Engineering Techniques 2010 (ASOC, 2010).

CONCLUSIONS

In this review we have critically examined appraisals of geoengineering with a view to understanding framing effects and promoting greater reflexivity in appraisal conduct. Appraisals of geoengineering can be seen to be closing down around particular sets of values and assumptions with respect to the instrumental framing effects of contexts, methods and criteria and options. Each of these framing effects can exercise differing and considerable powers on the outputs of appraisal, artificially promoting seemingly preferable decision option given those framing effects that are privileged. We recommend a greater awareness and acknowledgement of the power these framing effects can bear upon appraisals of geoengineering. Such reflexive accountability and responsibility will invariably enhance the transparency and rigor of appraisal outputs and ultimately contribute to more robust decision making.

Ultimately this review raises issues for the governance of geoengineering. The post-normal scientific context that characterises decision making on geoengineering demands the inclusion of axiological factors and therefore public participation. This is in addition to the other powerful normative, substantive and instrumental reasons for public participation (Fiorino, 1990). The narrowly framed considerations of performance and risk offered by traditional technocratic expert-analytic methods of appraisal (and some participatory ones as well) and the predictive governance that they support cannot therefore account for unanticipated evolutions in geoengineering (Collingridge, 1980; Royal Society, 2009). This technology control dilemma can be mitigated through the use of reflexive anticipatory governance in accounting for values, visions and vested interests driving the issue, before it is too late to influence developmental trajectories.

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