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How geoengineering scenarios frame assumptions and create expectations

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Abstract: Geoengineering could remake environments and societies, and early governance can help to steer the development of technologies towards sustainable outcomes. In the absence of observational data, geoengineering research and discussions are increasingly informed by scenarios, which provide heuristic tools for 'envisioning' potential futures. Although designed for specific research goals, scenarios can have broader implications by influencing expectations about the societal role that emerging geoengineering technologies can play. Yet the design of geoengineering scenarios has gone largely unscrutinized. This study is a meta-analysis in which we evaluate geoengineering scenarios from the literature to identify emerging expectations and assess these in the context of sustainability science. We find that geoengineering scenarios can be classified into three types based on purpose and use: for scientific knowledge-building; as 'structured conversation' starters; or as exploratory research tools. The first category dominates the literature; these scenarios stem from physical science disciplines where scientific tradition dictates simplification and standardization, both of which may provide misleading images of the future and therefore hinder robust decision-making. In contrast, scenarios used as exploratory tools depict not one single image of why and how geoengineering might evolve, but many. Analysis of these exploratory scenarios reveal expectations that a geoengineered future may hinge on at least four key elements—the potential for a universal geoengineering agreement, public perceptions of geoengineering, technical controllability, and the severity of climate impacts. These elements were not studied in the scientific knowledge-building scenarios, suggesting the need for an additional category of scenarios. Aligning with concepts of sustainability science, new geoengineering scenario exercises would merge participatory practices of exploratory scenarios with deterministic practices of technical scientific scenarios.

Keywords: geoengineering; scenarios; sustainability science; expectations; anticipatory governance

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1 Introduction

In response to insufficient greenhouse gas emissions reduction, geoengineering techniques are being proposed to decelerate warming. The Royal Society defines geoengineering—also known as climate engineering—as the "deliberate large-scale intervention in the Earth's climate system, in order to moderate global warming" (Royal Society 2009, p.ix). Geoengineering technologies are uncertain and complex and, depending on their governance, could present opportunities or threats to sustainability.

Despite a lack of legal safeguards explicitly associated with geoengineering (Reynolds 2016), research progresses. Given the uncertainties and long timeframes, geoengineering research increasingly relies on scenarios as heuristic tools for 'envisioning' possible outcomes. The term 'scenario'—as applied here—was defined by Herman Kahn (Schnaars 1987) as a "hypothetical sequence of events constructed for the purpose of focusing attention on causal processes and decision points" (Kahn and Wiener 1967, p.6). While designed for specific research goals, scenarios can have broad implications influencing the development of governance frameworks (Borup et al. 2006).

This paper reviews geoengineering scenarios to identify emerging expectations through common features and characteristics, prevailing practices, and key assumptions or omissions. It considers these in the context of sustainability science: an evolving academic discipline that seeks to understand and sustain the interdependent needs of human and environmental systems (Turner et al. 2003).

The paper is structured as follows. Section 2 provides background and context. Section 3 outlines the review method. Section 4 characterizes the scenarios in terms of three categories. Section 5 draws out emerging expectations by identifying trends in the choice of variables, assumptions, omissions and driving forces underlying the scenarios. Section 6 reflects on these from a sustainability science perspective. Section 7 concludes.

2 Background

2.1 Geoengineering

Generally, two geoengineering technology types are distinguished: technologies designed to reflect solar energy away from Earth—known as solar radiation management (SRM); and techniques designed to reduce atmospheric carbon dioxide (CO_2) levels—known as carbon dioxide removal (CDR). The most prominent SRM methods involve atmospheric processes (Belter and Seidel 2013), particularly stratospheric aerosol injection (SAI)—spraying aerosols into the upper atmosphere to intercept solar radiation (Crutzen 2006)—and marine cloud brightening (MCB)—spraying salt-water droplets into low-lying clouds to brighten them (Bala et al. 2011). Although still in early conceptual stages, SRM techniques are sometimes characterized as "cheap, fast and imperfect" (Keith et al. 2010, p.426), as they are likely to have uneven effects and may cause irreversible harms. Proposed CDR methods are biological or chemical in nature, involve capturing organic or inorganic carbon, and include storage aboveground (i.e. large-scale afforestation), underground, or in the ocean (Lenton 2014). These are generally distributed, costly, and slow-acting, but relatively predictable climatically.

The stakes of geoengineering are high. Disputed societal and technical dimensions of geoengineering governance demand a post-normal sustainability agenda (Funtowicz and

Ravetz 2003). The normative goals of sustainability are ecosystem diversity, integrity and health; human and social wellbeing; and justice and equity across space and time (Kajikawa 2008; Wiek et al. 2012). In support of these normative goals, sustainability science focuses on real-world problems at the interface of nature and society, where the two are interconnected so that environmental sustainability, economic development, and human wellbeing are interdependent (Clark 2007). There is an appreciation of concepts of vulnerability and resilience recognizing that real-world problems are part of tightly coupled dynamic complex systems with non-linear reactive and adaptive behaviors (Fiksel 2006). Temporal and spatial scales, and how these alter the need for specific knowledge and its translation into action, are considered (Stokes 1997; Martens 2007). Knowledge is co-produced iteratively and reflectively through inter- and trans-disciplinary research that includes stakeholder engagement (Pahl-Wostl 2002; Lang et al. 2012; Scholz and Steiner 2015).

In aiming to diminish climate change, both SRM and CDR align with principles of sustainability when broadly defined as meeting essential needs of humans and humanity within the planet's environmental limits (Kates et al. 2001; Clark and Dickson 2003). However, many individual geoengineering technologies pose risks of local and/or transboundary harm to the environment and humans (Fragnière and Gardiner 2016). Whether geoengineering is an opportunity or a threat to sustainability depends not on the technologies themselves (Jørgensen et al. 2009) but how they are developed and deployed. Currently, there are no binding instruments of international law explicitly regulating geoengineering (Reynolds 2016).

Research can help to reduce uncertainties and define appropriate legislation, but geoengineering research is contentious. Certain geoengineering methods—particularly those involving the oceans or atmosphere—call for field-testing on scales and durations that are detectable against other variables (Robock et al. 2010), but scientists have warned that polluting or modifying the natural environment for scientific purposes could be unethical (Robock 2012). However, non-polluting small-scale field-testing can also be problematic. In 2012, citing a lack of governance safeguards as a justification (Cressey 2012), three universities cancelled an environmentally benign small-scale outdoor SRM experiment after the project triggered public debate. Even desktop research can have far-reaching impacts on society, on policies and on politics. For instance, focusing on untested and unproven geoengineering techniques could constitute a 'moral hazard' (Royal Society 2009), potentially diminishing the senses of urgency (and of the irreversibility of climate change impacts) that drive current emissions mitigation efforts (Baatz 2016).

2.2 Scenarios and expectations

Trajectories of socio-technical systems are determined by combinations of economic, social, cultural, political and scientific factors that shape expectations of the technology and its capacity to deliver on future problems or promises (Grin and Grunwald 2000; Borup et al. 2006). Expectations make some technological pathways appear problematic and others propitious, thus guiding actors and defining roles for actor groups. Shared visions of technologies can "drive technical and scientific activity, warranting the production of measurements, calculations, material tests, pilot projects and models" (Borup et al. 2006, p. 285-6). The results of scientific activity (driven by shared expectations) then shape and reshape those expectations and visions.

Identifying factors that affect the "performative role of expectations in innovation" (Selin 2008, p. 1878) is not straightforward. One can examine formations of actor groups, relationships and networks—including scientists, politicians, industry players, and civil society. One can also look to shared language or consistent approaches to knowledge production, which can unite or alienate certain groups, revealing underlying motives (Brown and Michael 2003; Selin 2007).

To date, the geoengineering debate and agenda has been driven by research communities (Author et al, forthcoming). In the absence of observational data upon which to base their studies, geoengineering researchers increasingly rely on foresight methods, and particularly scenarios. Scenarios can be useful where there is complexity and uncertainty (Schoemaker 2004). Uncertainties can be represented by alternate futures, making those uncertainties tangible and more manageable (Wilkinson 2009), and illuminating driving forces, system weaknesses and causal relationships. Alternate futures can take a variety of forms—from narrative storylines to highly quantified trajectories of specific variables—and can be applied with varying degrees of formality—from hand-drawn cartoons to computer-aided simulations (Godet 2015). Scenarios can also "play an important role in the development and propagation of shared visions of the future, creating powerful expectations of the economic, social and environmental potential of emerging technologies; and mobilising the intellectual, financial, political and institutional resources necessary for their realisation" (McDowall and Eames 2006, p. 1236).

Geoengineering research questions involve developments or impacts over long timeframes, deep uncertainty, and high complexity. As a result, scenarios are widely used. A growing literature explores the discourses and framing of geoengineering in academic research (Huttunen and Hildén 2014; Oldham et al. 2014; Linnér and Wibeck 2015) and in media reporting (Luokkanen et al. 2013; Scholte et al. 2013; Anshelm and Hansson 2014). Emerging now is a body of literature investigating geoengineering scenarios on the basis that these "anchor[s] expectations and motivate[s] actors" (Low 2017, p. 69). Wiertz (2015), exploring SRM models and simulations, argues that "while climate models are used to improve scientific understandings of climate system behavior and to anticipate possible environmental impacts of SRM, they also become inventive tools, allowing scientists to envision novel ways of climate control" (p. 1). Rabitz (2016) develops a framework to scrutinize unilateral geoengineering deployment scenarios and finds that many such scenarios are implausible. Sugiyama et al. (2017), commenting on geoengineering scenarios, call for inclusion of participatory methods so that ranges of societal views and interests can be incorporated.

Our paper contributes to this emerging literature through a meta-analysis of geoengineering scenarios. The questions addressed in this paper are:

1. How are scenarios used in geoengineering research?
2. What are the key characteristics of geoengineering scenarios?
3. What assumptions and expectations do different types of geoengineering scenarios suggest?
4. What are the implications from a sustainability science perspective?

3 Method

Between 11 and 21 March 2016, academic databases Web of Science, Scopus, Science Direct, and Proquest, were searched for 'geoengineering' or 'climate engineering' and 'scenario'. Grey literature was searched through a Google Web search. Papers unrelated to climate change, or using the terms in passing reference, were excluded. Searches were restricted to 'geoengineering' and 'climate engineering' because specific terminology is one way to create and shape technological expectations (Selin 2007). Individuals choosing to adopt common terminology place their activities within the context of shared expectations. However, as language changes to reflect the dynamic nature of expectations, future research might take a broader approach.

Guided by literature on scenarios (Mitchell et al. 1979; van Notten et al. 2003; Bishop et al. 2007; Alcamo 2008) and scenario reviews (Hulme and Dessai 2008; Haasnoot and Middelkoop 2012; Trutnevyte et al. 2016), characteristics of geoengineering scenarios were identified on content, purpose, presentation, and construction process. These included ranges and types of geoengineering technologies; geographical and temporal scales; number and granularity of factors; number of scenarios; whether scenarios were qualitative or quantitative; whether they included disruptive events; whether they were storylines or snapshots in the future; whether scenarios were standard (adopted from previous studies), or tailor-made through a formal methodology; and whether that method was transparent and included input from a range of stakeholders.

The search returned 102 publications comprising 87 peer-reviewed journal articles from 41 journals and 15 'grey' reports from 14 institutions. The most represented disciplines were meteorology and atmospheric sciences, environmental sciences, economics, ethics and engineering. The most represented journals were the *Journal of Geophysical Research: Atmospheres* (13), *Atmospheric Chemistry and Physics* (6), and *Environmental Research Letters* (6).

Figure 1 provides an overview of key characteristics (more detail is available in the Supplementary Material).

INSERT FIGURE 1

Figure 1: Overview of review database (Note: white boxes relate to papers where the specific characteristic could not be determined)

4 Results

In addressing the first research question—'how are scenarios used in geoengineering research?'—three categories of scenarios were identified. A distinction became evident between how scenarios are used in physical sciences versus social sciences (or those with inter-disciplinary approaches). This created two categories. In the social sciences (or inter-disciplinary) papers, scenarios are used in two ways: to focus attention around certain potential future conditions (Lempert 2013); or to identify those potential future conditions. This distinction divided the social sciences group into two categories (Figure 2). Although theoretically the same distinction could be made in the physical science category, in practice, this group predominantly relates to quantitative projections and, as the study reveals, is relatively homogenous.

INSERT FIGURE 2

Figure 2: Three categories for evaluating geoengineering scenarios

4.1 Physical science geoengineering scenarios (category 1)

The first category comprises 71 physical science papers where scenarios are, almost exclusively, inputs into climate models. The research goal is scientific knowledge-building. The geoengineering scenarios are overlaid onto standard emissions or concentrations pathways often from existing literature, such as the Intergovernmental Panel on Climate Change (IPCC). The IPCC emissions or concentration pathways feature prominently—specifically the Special Report on Emissions Scenarios and the Representative Concentration Pathways (RCPs)—as do the Geoengineering Model Intercomparison Project (GeoMIP) scenarios. GeoMIP is a set of geoengineering experiments originally designed in 2011 as four core computer-modelling standardized SRM simulations—known as G1, G2, G3 and G4 (Kravitz et al. 2011). Subsequently, new GeoMIP scenarios have been developed focusing on specific technologies and issues (Kravitz et al. 2013, 2015), but these do not feature in the review database (due to timing of the research).

Almost all are global scenarios, although a few studies have additional regional foci. For instance, Jackson et al. (2015) simulate SRM over the Artic to study the effect on Artic sea ice. GeoMIP scenarios appear in 16 papers. Scenarios predominantly include SRM (64 papers) within two decades, and particularly SAI (31 papers) or MCB (14 papers). With the exception of one paper (Vaughan and Lenton 2012), scenarios do not explicitly combine SRM with CDR. SRM is generally overlaid onto an emissions pathway *ceteris paribus*, and mostly against rising atmospheric carbon concentrations.

Three papers use RCP2.6 (Moore et al. 2010; Couce et al. 2013; McCusker et al. 2014), the only RCP exhibiting a 50% or higher chance that temperatures stabilize at 2°C. The most prominent is RCP4.5 in which atmospheric CO_2 concentrations stabilize by 2100. This prominence of RCP4.5 is partly explained by its use in GeoMIP G3 and G4. It is a middle-of-the-range IPCC scenario. The GeoMIP authors justify its use because "[u]sing a more optimistic scenario in which rapid mitigation is implemented would result in less robust results and is […] not likely to be as illuminating" (Kravitz et al. 2011, p. 165). In 18 papers the effect of sudden SRM termination is explored, as this is a design element of the GeoMIP experiments.

The modeling focus is on average temperatures and rainfall; metrics such as maximum and minimum temperatures or diurnal ranges are rarely explored. A handful of scenarios focus on specific impacts such as on Arctic sea ice (Tilmes et al. 2014), agriculture (Xia et al. 2014), or tropical rainforests (Muri et al. 2015); one paper includes potentially triggering climate tipping points (Wu et al. 2014); and one includes a scenario where a powerful volcanic eruption occurs during SRM (Laakso et al. 2016), but generally the scenarios are not designed to study extreme events or their interaction with geoengineering. Primarily, scenarios inform on physical processes under ideal conditions. They do not account for changed behavior—political, cultural, or other—that may result from SRM.

Scenarios also assume perfect technological proficiency. Learning-by-doing is included in just four papers: one uses scenarios to question how to deploy stratospheric aerosols (Jackson et al. 2015); one to study the influence of a spray injection strategy (Niemeier et al. 2011); and two to investigate different stratospheric injection aerosol-types (Rasch et al. 2008; Jones et al. 2016).

All papers are published in peer-reviewed journals, mostly with solid reputations (impact factors above two). The authors rarely detail the scenario development, but such explanations are available in IPCC or GeoMIP source documents. It is not common practice to revisit this in subsequent uses of scenarios. However, explanations of how and why one GeoMIP or IPCC scenario is chosen over others are often neglected.

4.2 'Strategic conversation' scenarios (category 2)

The second category comprises 21 social science papers where scenarios are used (sometimes incidentally) to make broader points on geoengineering governance, ethics, economics or other. These are not scenario exercises in that the scenario is not the basis of the research but a tool for structuring it. The purpose is to stimulate or to frame key messages or to provide structure to the research and argumentation. As such, this category is labeled 'strategic conversation' scenarios. Examples from this category are Amelung and Funke (2014) presenting quasi-realistic geoengineering scenarios to laypeople to study decision-making in the face of risk; or Bodansky (2013) outlining four basic but problematic geoengineering scenarios to explore governance issues: inadequate research funding, premature rejection, unilateral individual action, and unilateral state action.

All are global scenarios. The wide breadth of scenario-types and -uses within this category make it impossible to generalize about inclusions or exclusions of certain types of content or characteristics. Scenarios are as detailed and inclusive of broader issues as needed to justify subsequent discussions. There are few clear trends in terms of included elements or future-defining forces. The majority of papers (16) focus on SRM, and in 12 papers deployment is assumed to be controllable. This assumption is explicitly questioned in one paper: a highly idealized economic study in which one of four scenarios explicitly considers continuous and discontinuous SAI (Goes et al. 2011).

The most studied scenario-type is the 'emergency' scenario (eight papers) wherein SRM is deployed quickly responding to some climate emergency, the definition of which is not always provided and thus could vary. Of 21 papers, 14 use the terms 'emergency', 'plan B', or 'buy time' to describe scenarios. There are examples of radical actions, such as the potential for unilateral solar geoengineering deployment, which is explored in seven papers. A ban or moratorium features in three papers (Olson 2011; Bodansky 2013; Parson 2014). Situations of collapse, such as where a climate tipping-point is reached, or where a geoengineering project goes awry, are presented in two papers (Olson 2011; Goes et al. 2011) and four explore the prospect of aborted SRM (Ricke et al. 2008; Goes et al. 2011; Svoboda 2012; Bickel 2013).

Except for a report on the 2030 US security implications of an abrupt climate change scenario (Schwartz and Randall 2003), the scenario time-horizon is always 2100 or beyond. No paper includes more than eight scenarios; mostly there are one to four. Eleven papers present

trajectories or storylines rather than snapshots of the future. Twelve papers are from the academic peer-reviewed literature; the other nine are available in accessible formats online. In most cases, no clear justification is given for how or why scenarios are constructed the way they are. It is assumed that no form of participatory deliberation was undertaken in creating the scenarios.

4.3 Exploratory scenarios (category 3)

The third category comprises the remaining 10 papers that are explicitly scenario exercises and include scenario development (not just analysis). The processes of scenario-construction form part of the exploratory research. The purpose of the scenarios is as a heuristic tool or to engage with a broader community. Examples include Baum et al. (2013) exploring how a 'double-catastrophe' SRM scenario—two distinct global catastrophes that become linked through SRM—could arise and its implications; or Banerjee et al. (2013) determining from a workshop process key determinants of an SRM future and combining these to shape six scenarios.

All 10 scenarios are global but some have additional regional foci, such as the RAND corporation study with its emphasis on US policy implications (Lempert and Prosnitz 2011). Except for two papers with narrow foci on specific issues—climate law in de Larragan (2012) and the 'catastrophe situation' in Baum et al. (2013)—scenarios have broad scopes and mainly explore governance questions. Again, scenarios mostly exclude non-SRM geoengineering technologies—only three include CDR (Sweeney 2014; Bellamy and Healey 2015; Böttcher et al. 2016). One paper (Banerjee et al. 2013) includes a focus on 'black swan' events, which are extreme unexpected events that humans tend to want to make explainable *ex post facto* (Taleb 2007).

Three papers include emergency SRM scenarios (Banerjee et al. 2013; Bellamy and Healey 2015; Haraguchi et al. 2015); four include unilateral deployment (de Larragan 2012; Banerjee et al. 2013; Sweeney 2014; Bellamy and Healey 2015); and in two papers SRM is deployed instead of effective emissions reduction (de Larragan 2012; Banerjee et al. 2013). Seven papers assume that the outcomes of geoengineering can be controlled perfectly, but in six papers there is also the explicit assumption that the technology is not controllable. Controllability is a defining variable of many scenarios in this category. Other defining variables are universal agreement on geoengineering, and whether this can be reached, featuring in seven papers; perceptions of geoengineering technologies, and whether these garner public support, featuring in six papers; and the severity of climate impacts, which factors as either a physical or social dimension, appearing in four papers.

Mostly, the scenario-builders opt for time-horizons of 10 to 20 years (one paper looked beyond 2070). Both storyline and 'snapshot' scenarios feature. Except for those in the RAND Corporation paper, scenarios are qualitative (although some are informed by quantitative data), and families have fewer than nine scenarios (except the RAND corporation paper with 24 scenarios).

Three papers are from the academic peer-reviewed literature (de Larragan 2012; Baum et al. 2013; Sweeney 2014); the other seven are publicly accessible reports. We found no evidence that the activities and findings from these seven papers have subsequently been published in

peer-reviewed academic journals. The methodologies used to build the scenarios vary but are mostly documented clearly in the papers, with descriptions of key assumptions and factors. Six papers describe a participatory approach; none is published in a peer-reviewed journal.

5 Emerging expectations of geoengineering

Within the categories certain themes and patterns can be identified. Of note, SRM technologies feature far more prominently than CDR technologies. This could suggest that SRM research is more applicable to scenarios for examining impacts/implications than CDR research is. Alternatively, it could suggest that researchers studying CDR technologies may be opting not to use the 'geoengineering' terminology. Our meta-analysis is thus likely to have identified only a subset of a larger literature on CDR, due to our choice of query words. At least within the scenarios literature (if not more widely) definitions for 'geoengineering' and 'climate engineering' may in practice (if not in theory) be narrowing to a focus on SRM, and perhaps an even narrower focus on SAI and MCB. It may reveal a division in the research field such that the actor groups researching and advising on SRM matters are not the same actor groups researching CDR matters. The shaping of expectations in these two separate fields could happen independently.

Also noteworthy is the absence in the review database of analyses by economists using integrated assessment models and game theory. Such studies employ the terminology of 'models', 'variables' and 'choices' rather than 'scenarios' and thus were not included in the study but may present an interesting field of further research.

5.1 Physical science scenarios simulate 'silver bullet' geoengineering

Physical sciences scenarios have clearly defined characteristics established by disciplinary tradition. The custom is to idealize and standardize model settings and to converge assumptions around limited ranges of values. This reduces uncertainty by permitting "the level of intercomparison necessary to achieve confidence in the results" (Kravitz et al. 2011, p. 163). To allow deep scrutiny of key variables, scenarios generally exclude high-impact low-probability natural or social events such as climate events, natural disasters, technological breakthroughs, or social transformations.

As noted previously, geoengineering is simulated mostly as SRM deployed on a global scale within the next two decades alongside insufficient mitigation and where there is complete control of the outcome. Perfect technological proficiency and tunability is assumed, thus the question these scenarios aim to answer is not 'how to geoengineer?', but 'what if we geoengineer?'. That geoengineering is used to maintain a *status quo* is implicitly assumed. As Heyen et al. (2015) highlight, "[e]xisting assessments […] usually assume that a previous climate state, for example the preindustrial, is the optimal climate state for all regions […], any deviation from this state is considered detrimental" (p. 559). Scenarios aim to explain and minimize such deviations, especially on a regional basis.

There is an argument that assessing these scenarios for their broad impact is inappropriate because they are designed to be relevant to climate modelling, not to reflect reality. However, as Oldham et al. (2014) argue in their geoengineering bibliometric study, academic research choices influence technologies' likely trajectories. Scenarios can become indicators

of what scientists envisage as the future of geoengineering. This justifies a wider evaluation. The image of geoengineering underlying these decisions is that of a 'silver bullet' technology available as a non-disruptive off-the-shelf product. Although the metaphor of a 'silver bullet' is not perfect because it ignores that SRM is assumed to have uneven impacts, it implies a linear approach in which geoengineering is assumed to be separable from other aspects—even though the climate is nonlinear and complex. Social, economic and environmental situations that are unchanging and unchanged during the lead-up to and after the deployment of geoengineering is assumed. This level of predictability does not incorporate, for example, the possibility of changed behavior resulting from geoengineering deployment.

5.2 'Strategic conversation' scenarios envisage a geoengineering 'insurance policy'

Three scenarios appear recurrently in the 'strategic conversation' scenario category—rapid SRM deployment as a last-resort option when emissions reduction efforts have failed; unilateral SRM deployment; and a ban or moratorium—yet the plausibility of each type has been questioned. Last-resort scenarios are useful for exploring specific ethical and governance challenges, but they presume that SRM can provide a suitable response to a climate emergency. Some authors have argued that a climate emergency cannot be avoided through altered radiative forcing, nor would any such emergency adequately justify pre-emptive SRM deployment (Sillmann et al. 2015; Horton 2015).

There are divergent views around the plausibility and consequences of unilateral deployment. Bodansky (2013) studies unilateral deployment as a plausible eventuality, while Horton (2011) finds it "unlikely to occur because the incentives faced by states do not support it" (p. 59). Similarly, although three studies discuss moratoria scenarios, none suggests that they are highly credible. Bodansky (2013) presents a moratorium as inherently unsustainable and potentially dangerous because it would hand the reins of geoengineering to less risk-averse nations. He concludes that a ban requires a sunset clause, lest it lead to a unilateral deployment scenario. Parson (2014) explores the idea of a geoengineering ban until sufficient emissions reduction has occurred and describes the scenario as requiring a "suspension of disbelief" (p. 105).

It could be argued that because these scenarios are not the focus of the research, they provide only limited insight into expectations. However, it is precisely because these scenarios are not products of serious calculation that they are likely to draw on and reflect societal concerns and agendas, or at least those of the authors (Borup and Konrad 2004). The conclusion from this category is that: first, a geoengineering ban is not seen as a sustainable option; and second, geoengineering is not seen as being gradually incorporated but as an 'insurance policy' to be used at short notice, with fast-acting SRM seen as implementable by an on/off switch. The challenges relate to climate change governance, rather than geoengineering technology, yet the scenarios in which SRM provides such solutions remain unconvincing. This category of scenarios, rather than driving creative and imaginative thinking that can 'open up' new possible futures (McDowall and Eames 2006), closes down options by narrowing the range of plausible routes.

5.3 Exploratory scenarios uncover potential variables in an SRM future

In this category, the dominant technology is again SRM-based, generally deployed within the next decades, and generally in the context of high atmospheric carbon levels. The exploratory

nature of these scenarios provides insight into the driving forces, but also the barriers, to such a future evolving. Scenarios are defined around whether and how certain challenges are met, four of which stand out. These are not exhaustive or completely representative; they merely reflect some perceptions of geoengineering.

The controllability of geoengineering technologies is seen as one key variable that could define the future of geoengineering. On the one hand, if technology is controllable it may be tuneable by region, which begs the question of who has control. On the other hand, if it is not controllable, it could result in adverse impacts for which causation may potentially not be clearly attributed, and therefore compensation not awarded, with implications for equity. As such, controllability raises political, ethical, and legal issues.

Whether collective agreement on geoengineering could be reached on a global level is another key determinant of how geoengineering might evolve. It is seen as central to questions of 'if', 'how' and 'when' geoengineering might be deployed. This is relevant because climate change politics are framed by the concepts of collective action, but the risk of unilateral and 'unencapsulated' geoengineering can reverse this.

Public acceptance or rejection of geoengineering is seen as key to influencing how and if certain technologies might be subject to a moratorium. The importance of public perception for governance (Corner and Pidgeon 2014) is highlighted by the cancelled 2012 SRM field-experiment (Cressey 2012).

A fourth key determinant of a geoengineering future is the severity of climate impacts, and whether the climate proved significantly more, or less, sensitive to rising atmospheric carbon levels than anticipated. This is factored into the scenarios as specific climate impacts and adaptation efforts. Here, the issue relates to how societies perceive their own vulnerabilities to climate impacts, which also has implications for public acceptance of geoengineering technologies.

6 In the context of sustainability science

The use of foresight activities is important in sustainability science. When effective, scenarios can drive practitioners to question established thinking patterns and guide critical thinking about risks and uncertainty (van der Heijden 2005). The goals of scenarios, here captured in three categories, cannot be conflated, and scenarios should be evaluated on their stated aims. However, visions embedded in these scenarios influence broader discussions, regardless of stated goals.

6.1 Complex human-nature relationships

The 'silver bullet' use of SRM in the physical science scenarios is problematic against the tenets of sustainability science. Studies with strong idealized inputs often produce results that are equally as extreme; for example, Robock et al. (2008) found that SRM would disrupt the Africa and Asian monsoon. These conclusions, although relevant only for radical SRM applications that would be unfathomable to rational decision-makers, influence the broader discussions and become part of the debate.

Furthermore, standardizing scenarios results in key factors being tested within only limited ranges of settings, which can misrepresent the range of possible outcomes. This can impair robust decision-making by obscuring potential outcomes to which decision-makers may become vulnerable. Sundberg (2011), studying the social dynamics of intercomparison projects, found that these projects can narrow the range of people, problems and preferred outcomes within a research topic. Absent from these scenarios are for example extreme natural events, the interplay between social and physical factors, metrics other than average temperatures, elements that study 'how' to geoengineer (not just 'what if'), partial or regional SRM deployment, or multiple different technologies deployed in parallel. However, recent papers indicate that this is starting to change: Keith and Irvine (2016) and Arino et al. (2016) explore SRM scenarios that offset only part of the warming; Cao et al. (2017) model a 'cocktail' scenario combining two geoengineering methods; and Kleinschmitt et al. (2017) explore the sensitivity of radiative forcing to the aerosol injection strategy.

The 'silver bullet' approach is techno-optimistic. It assumes that the environmental situation created by human behavior can be repaired without far-reaching changes to behavior. This can divert attention from other alternatives and understate the technological, legal and social complexities that have yet to be understood and negotiated. Given the stakes of geoengineering, social preferences, environmental settings, and economic imperatives will likely undergo substantial transformations before and when geoengineering is considered. Expectations that geoengineering technologies could be 'silver bullets' ignore the interconnectedness of nature and society and may narrow scientific investigations and governance debates.

6.2 Temporal and spatial considerations

Sustainability science captures the need for research with an applied element driven by local and practical realities of sustainability (i.e. resource availability, waste generation, life-cycle assessment) (Martens 2007). The 'last resort' framing embedded in many of the 'strategic conversation' scenarios presents SRM as a rational choice to be made at a future and desperate moment. Yet in these scenarios, the decision was made some 20 years earlier to investigate and then develop the 'necessary' technology, thus establishing it as an option and forming vested interests and path dependencies (Cairns 2014). Rather than a culture of gradual and communal learning-by-doing, which is in line with concepts of sustainability (Martens 2007), these scenarios embed the expectation that geoengineering options will be decided 'later' by 'others'.

There is also an almost exclusive focus on global matters through 'top-down' resolution, rather than on local or regional issues, which disregards the local nature of climate impacts and social responses. This has implications for the design of technologies and governance mechanisms, because it suggests that decision-making is unilateral with limited consideration of temporal and spatial scales.

6.3 Broad engagement

Interdisciplinarity is not a widespread feature of this literature, and only the exploratory scenarios include formal, inclusive and systematic participatory processes within the scenario construction method. Analysis of the exploratory scenarios found that there is not one single image of why and how geoengineering might evolve, but many. It also identified certain

variables seen as key determinants by some stakeholders, all of which were absent from the quantitative physical science studies. As a result, a section of potential scenarios remains underexplored in climate models. For example, controllability of geoengineering technologies, which was revealed as a key element in the exploratory scenarios, is assumed in the physical science scenarios, even though "public acceptance of geoengineering research and governance depends on multiple dimensions of controllability that go beyond technical considerations such as experiment scale and location" (Richler 2017, p. 624).

6.4 A fourth class of geoengineering scenarios?

The issues identified here in the context of sustainability science relate to the difficulty in reconciling the concept that scenarios act as bridges between science and policy with the scientific requirements of research, and particularly of climate modeling. While scenarios and intercomparison projects (like GeoMIP) are important for understanding or reducing uncertainty and for building credibility, science-policy institutions also play key roles in how scenarios and results are interpreted and discussed. It can be argued that both scientific research and its communication are part of a broader policy process.

A fourth class of scenarios might be needed to merge participatory practices of exploratory scenarios with deterministic practices of technical scenarios and to involve decision-makers in the design process. Here, concepts of anticipatory governance (Barben et al. 2008; Guston 2014) and responsible research and innovation (Stilgoe 2015) may be useful. These concepts describe foresight practices, such as scenario studies, as combining physical and social sciences and eliciting insight from a range of stakeholders ensuring that deliberations are inclusive and transparent (Barben et al. 2008). Assumptions and choices of variables used in quantitative or qualitative analyses would thus be informed by and "embrace pluralistic goals of SRM scenarios" (Sugiyama et al. 2017, p. 5).

7 Conclusion

This meta-analysis provides insight into the assumptions of geoengineering researchers, which influence the development and deployment of the technologies and their governance mechanisms, and therefore influence the sustainability of geoengineering. At least three types of scenarios filling different research goals exist, and within these, clear trends or broad visions begin to emerge.

A prominent image of geoengineering is of a quick-fix rather than a reflection and vehicle of societal change, but there is no engagement with issues around what a quick-fix might entail over the near-term. A geoengineered future is treated as a product of failed climate action rather than a fundamental opportunity to question what is possible and desirable through technology. A key issue is that computer models have become more than key tools of knowledge production; they are platforms for forming and conveying expectations of SRM technologies (Wiertz 2015). However, these platforms do not invite a broad range of societal interests and views (such as those expressed in the exploratory scenarios) and therefore may be delivering narrowly defined expectations.

Scenarios are fundamental to geoengineering research. To move the governance discussion forward, a novel class of scenarios is needed that supports co-evolution of governance and technology, and co-production of knowledge as part of an iterative, actionable, and

aspirational transition strategy. More broadly, an anticipatory governance approach is needed to achieve sustainable future outcomes involving ongoing applications of scenarios that explore such issues as the potential for a universal governance agreement, engagement and responses to public opinion, controllability and the severity of potential climate impacts.

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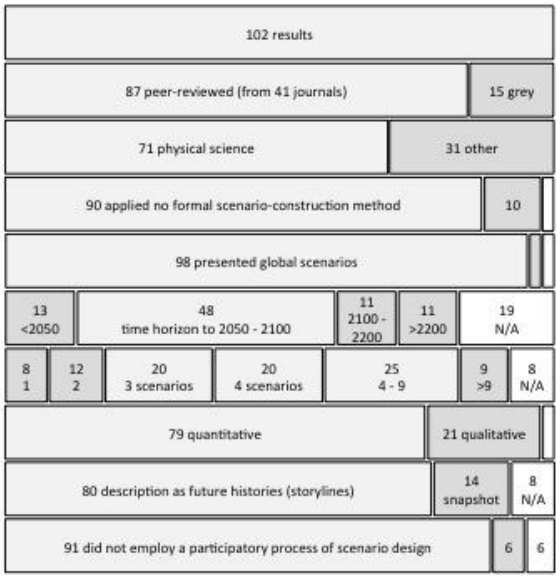
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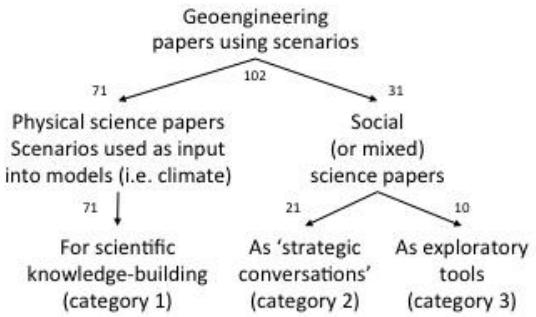
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102 results
87 peer-reviewed (from 41 journals)
15 grey
71 physical science
31 other
90 applied no formal scenario-construction method
10
98 presented global scenarios
13
<2050
48
time horizon to 2050 - 2100
11
2100 -
2200
11
>2200
19
N/A
8
1
12
2
20
3 scenarios
20
4 scenarios
25
4 - 9
9
>9
8
N/A
79 quantitative
21 qualitative
80 description as future histories (storylines)
14
snapshot
8
N/A
91 did not employ a participatory process of scenario design
6
6

827


Geoengineering
papers using scenarios
102
71
31
Physical science papers
Scenarios used as input
into models (i.e. climate)
Social
(or mixed)
science papers
71
21
10
For scientific
knowledge-building
(category 1)
As 'strategic
conversations'
(category 2)
As exploratory
tools
(category 3)

828