Dual high-stake emerging technologies: a review of the climate engineering research literature

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The literature on climate engineering, or geoengineering, covers a wide range of potential methods for solar radiation management or carbon dioxide removal that vary in technical aspects, temporal and spatial scales, potential environmental impacts, and legal, ethical, and governance challenges. This paper presents a comprehensive review of social and natural science papers on this topic since 2006 and listed in SCOPUS and Web of Science. It adds to previous literature reviews by combining analyses of bibliometric patterns and of trends in how the technologies are framed in terms of content, motivations, stakes, and recommendations. Most peer-reviewed climate engineering literature does not weigh the risks and new, additional benefits of the various technologies, but emphasizes either the potential dangers of climate engineering or the climate change consequences of refraining from considering the research, development, demonstration, and/or deployment of climate engineering technologies. To analyse this polarity, not prevalent in the literature on earlier emerging technologies, we explore the concept of dual high-stake technologies. As appeals to fear have proven ineffective in spurring public engagement in climate change, we may not expect significant public support for climate engineering technologies whose rationale is not to achieve benefits in addition to avoiding the high stakes of climate change. Furthermore, in designing public engagement exercises, researchers must be careful not to steer discussions by emphasizing one type of stake framing over another. A dual high-stake, rather than risk–benefit, framing should also be considered in analysing some emerging technologies with similar characteristics, for example, nanotechnology for pollution control. © 2015 The Authors. WIREs Climate Change published by John Wiley & Sons, Ltd.

INTRODUCTION

Climate engineering, or geoengineering, is among the newest and most controversial items treated in international policymaking and research into climate change responses. It is an umbrella term for a large set of proposed technologies for large-scale, deliberate manipulation of the Earth’s climate either by removing greenhouse gases (GHGs) from the air or by reflecting solar energy. Climate engineering includes a wide range of potential methods, such as ocean fertilization, air capture, space mirrors, stratospheric sulfur aerosol injection, and cloud reflectivity enhancement. These methods vary greatly in technical aspects, temporal and spatial scales,
potential environmental impacts, and legal, ethical, and governance challenges. Recent social science research describes climate engineering as comprising emerging technologies characterized by great uncertainty, motivated by high stakes of climate change, and under research and development. The inclusion of climate engineering technologies in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) signals their increased prominence in climate change research.

To complement the subdivided IPCC assessment, this paper comprehensively reviews the natural and social science literature on climate engineering. Previous reviews have been of three main types: (1) reviews of climate engineering technologies as such, with respect to their possible adverse effects and potentials; (2) reviews of the ethical, science policy, legal, and other governance aspects of climate engineering and public engagement; and (3) bibliometric analyses of publication patterns in climate engineering research. Although these publications make important contributions by reviewing the emergence of the climate engineering literature, no review has yet analysed both bibliometric patterns and how climate engineering technologies are framed in peer-reviewed journal papers in terms of core arguments and conclusions.

AIM

This paper offers a meta-analysis of the rapidly expanding publications of climate engineering by reviewing papers on this topic listed in the SCOPUS and Thomson Reuters Web of Science (WoS) databases from 2006 to 2013. In categorizing the major strands of peer-reviewed climate engineering research, we ask four questions:

- What are the major trends in the scientific literature on climate engineering?
- What are the motivations for studies of climate engineering?
- Are possible side effects of the technologies acknowledged and, if so, how are they framed?
- What recommendations regarding climate engineering are highlighted in the scientific literature?

REVIEW MATERIALS AND METHODS

We conducted a broad article search in the SCOPUS database using the keywords ‘climate engineering’ and ‘geoengineering’, excluding papers that did not treat geoengineering in the context of solar radiation and/or carbon dioxide removal (e.g. papers on engineering in connection to geology). SCOPUS was chosen since it is the largest abstract and citation database of peer-reviewed literature and includes much of the social science literature in addition to the natural science literature. To ensure that no major strands of literature were excluded due to the limitations of the SCOPUS database, we compared our sample (291 papers) with the results of a WoS search, using the same keywords and time period. This search identified slightly fewer articles (234), though most identified papers appeared in both databases.

The keywords were sought in the titles, abstracts, and keywords of publications appearing from 2006 to 2013. We selected 2006 as our starting year as the Kyoto Protocol had entered into force in February the previous year, completing a decade-long round of negotiations initiated by the 1995 Berlin Mandate, which called for an agreement establishing quantified emission limits for developed countries. In 2006, the authors of geo-engineering papers could therefore relate their potential positions on climate engineering technologies to a concrete political outcome. For example, Nobel laureate Paul Crutzen published an iconic paper in 2006, advocating serious research into stratospheric aerosol injection in the face of failed political efforts to mitigate GHG emissions. Belter and Seidel and Oldham et al. show a rapid increase in the number of published papers on geoengineering from 2007/2008. Oldham et al. conclude that after Crutzen’s 2006 article, climate engineering publications more than tripled.

To survey the literature, we retrieved indexed keywords for the original set of publications from the GEOBASE indexed thesaurus, accessed via SCOPUS. Network maps of the co-occurring indexed keywords were prepared using BibExcel to create co-occurrence tables and were analysed by means of visualization using Gephi 0.8.2 with the ForceAtlas 2 network layout algorithm. Maps were created for the first years of the study, 2006–2008, versus the recent years, 2012–2013, and keywords had to occur in at least two publications during a period to be included in the network maps.

Publications from the original set indexed in WoS were used for author analysis and citation analysis. The citation data were provided by CWTS, Leiden University, using Thomson Scientific/ISI as the data source. Author names were extracted from WoS data. Author initials were then manually standardized and arranged by publication using BibExcel. The citation analysis was based on WoS articles and reviews from 2006 to 2012. The indicators field-normalized citation
rate, journal field-normalized citation rate, and the top 10% were derived using a 1- to 5-year open citation window and excluding self-citations.

As we set out to analyse the core focus emphasized by the authors, we concentrated on the abstracts and the conclusions of the papers. Our coding template was designed to capture what arguments the authors chose to highlight, thus we did not code the full papers. To ensure that the study had reasonable comparability, it was necessary to limit the study to the scientific literature with similar format for abstracts and conclusions. Thus, we did not include grey literature and books in our coding, although we have referenced such literature elsewhere in the paper.

We excluded peer-reviewed articles with abstracts conveying little or no information on the content, leaving 291 abstracts from the SCOPUS search. We used the SCOPUS function to divide them into natural or social science abstracts. As SCOPUS does not differ between social science and humanities disciplines, the social science category also includes papers from humanities disciplines such as philosophy or law. After an initial scanning, we re-categorized the abstracts in which the SCOPUS categorization had obviously misrepresented the discipline, categorizing 95 as social science and 196 as natural science abstracts. We found that the distinction served to nuance our analysis of the literature, although we recognize that some papers could well be categorized in either category and some are clearly interdisciplinary.

The abstracts were coded in categories according to the technologies addressed, motivations, side effects, concerns, and recommendations. To increase the reliability of the coding, the template was designed by four readers reading a sample of papers to identify key features of the abstracts. These readers jointly read ten social science and ten natural science papers to scrutinize each other’s coding in order to increase the rigor of the method and of the interpretations of the papers in relation to the analytical categories. These categories were subsequently adjusted and clarified before the next coding, which included all abstracts and was undertaken by the authors of this paper. As our review demonstrated that the abstract often excluded the article’s recommendations, we complemented the abstract analysis of 291 papers by reading the conclusions of all full-text papers electronically available through our university’s library. We were not able to access 61 papers. So, in total 230 full-text conclusion sections were analysed and coded with respect to their recommendations, if any, about climate engineering.

An analysis of a large set of abstracts provided an overview of the context in which authors chose to position their publications, helping us identify overarching positioning trends. To analyse the central organizing ideas structuring the climate engineering literature, we use the concept of ‘framing’.26 As pointed out by Huttunen and Hildén,16 ‘in the context of geoengineering and research, frames depict the ways in which geoengineering is discussed’ (Ref 16, p. 6). Unlike some earlier studies of climate engineering,9,16,28,29 our intent is not to conduct a formal frame analysis, but rather to identify what elements of climate engineering are given salience in the research literature.28 Our analysis of how a policy or research issue is framed considers what potential consequences of the technologies are emphasized and how these consequences are valued and described.

THE DEVELOPMENT OF CLIMATE ENGINEERING RESEARCH

The climate engineering literature has expanded rapidly since 2006, as indicated by growth from six abstracts in WoS in 2006 to 55 in 2013, for a total of 234 abstracts (Figure 1).

Although over twice as many natural science as social science papers, in total, were identified in the SCOPUS search, the number of social science papers has grown rapidly in the last 2 years (Figure 2). The publication pattern of social science research into climate engineering differs from that of social science research into other emerging technologies. In the case of climate engineering research, natural and social science publications expanded in parallel until 2013, when social science papers outnumbered the natural science papers published in any previous year. This trend particularly differs from early research into food production biotechnologies, where most studies of the ethical, legal, and social implications and of public understanding were initiated after the demonstration and deployment of the technologies.7,9,30,31

When analysing the keywords indexed in WoS, we can see some notable changes over the analysed period. In the 64 publications from 2006 to 2009, the
dominant keywords, in order of decreasing frequency, were: ‘climate change’, ‘global warming’, ‘aerosol’, ‘stratosphere’, ‘anthropogenic effects’, ‘greenhouse gas’, and ‘climate modeling’. In the 2012–2013 period, all of these were still frequently used as keywords, but ‘solar radiation’, ‘carbon dioxide’, ‘radiative forcing’, and ‘precipitation’ were added to the list of the most frequent keywords. The most notable differences were the near doubling of the share of publications using ‘climate change’ (from 17% to 38% of the papers) and ‘stratosphere’ (from 12% to 20%) as keywords, while the use of ‘anthropogenic effect’ halved. Although ‘solar radiation’ increased by a factor of six to appear as a keyword in more than a third of the publications, ‘aerosol’ increased only slightly, from appearing in 14% to 17% of the papers. The 2012–2013 keywords also referred to a wider range of technologies, indicated by new keywords appearing in at least 5% of the papers: ‘albedo’, ‘carbon sequestration’, ‘sea salt’, and ‘stratocumulus’. The keyword analysis also illustrates the divergence of the literature over time, from 24 keywords occurring at least in two papers in the first period, compared with 104 in the second.

The heightened interest in climate engineering research is also revealed by the relatively high number of citations. For 164 citation-analysed publications in WoS, the field-normalized citation rate was 1.6, which is significantly higher than the normalized average of one. Twenty-one percent of the articles were among the top ten most cited in their academic fields. Analysis of publication patterns demonstrates that for both social and natural science climate engineering papers, the share of papers in highly cited journals is significantly above average. The field-normalized journal citation rate for all WoS publications with climate engineering or geoengineering in the abstracts, titles or keywords is 1.3. This literature also attracts a wide range of authors. In the WoS-identified publications, 506 authors contributed: 394 of these contributed to only one listed article, 53 to more than three, and 21 to more than five.

We conclude that climate engineering attracts considerable interest from many involved researchers. Although the public discussion may be dominated by a few outspoken researchers, their share of authorship in peer-reviewed papers is proportionately less. The scope of examined technologies has widened, but our analysis demonstrates that climate engineering research is still unapplied and largely only conceptual in focus. Among the natural science papers, modeling studies dominated, followed by assessments and literature reviews. About a quarter of the abstracts gave no information about methodology or were explicitly theoretical. Only a few of the abstracts cited any actual field studies.

A wide range of methodological approaches was reported in the social science abstracts, such as literature review, assessments, focus group interviews, game theory analysis, ethical analysis, argumentation analysis, and discourse analysis. Many of the abstracts did not specify their methodological approach.

THE TECHNOLOGIES IN FOCUS

Solar radiation management (SRM) encompasses potential technologies for reflecting some of the sun’s light and heat back into space to counter the warming effects of increased GHG emissions. SRM includes increasing the Earth’s albedo effect (i.e. surface reflectivity) by brightening built environments (e.g. by painting rooftops white,32 breeding and planting high-reflectivity crops,33 placing reflective material in deserts,34 and enhancing the brightness of marine clouds35). The effects of volcanic eruptions may be mimicked by injecting particles of aerosols such as sulfates into the lower stratosphere.36 Farther into space, deflectors have been suggested to prevent some solar energy from reaching the Earth.37

Carbon dioxide removal (CDR) includes proposals for both land- and ocean-based technologies that seek to capture CO₂ from the atmosphere: for example, safeguarding or amplifying carbon sinks,38 using biomass for carbon sequestration to achieve negative emissions,39 accelerating weathering processes that remove CO₂ from the atmosphere,40 and engineering to directly capture CO₂ from the air.41 Ocean-based CDR methods include proposals for boosting CO₂ uptake by increasing the amounts of nutrients in the ocean.42
The analysis of the natural science literature demonstrated that the main focus was on specific climate engineering technologies, rather than on climate engineering as a general concept. Among the 196 natural science abstracts, 79% addressed specific technologies, while only 11% examined climate engineering as a general concept without specifying the type of technology. The 95 social science abstracts display a different pattern. Fifty-nine percent of the publications addressed climate engineering as a general phenomenon, while 28% examined one or several specific technologies. The rest of the abstracts broadly distinguished between SRM and CDR.

Among the abstracts differentiating between technologies, the main focus was on SRM technologies (60% of natural science and 17% of social science abstracts). In contrast, fewer of the abstracts that differentiated between technologies discussed CDR technologies (26% of natural science and 6% of social science). In addition, 10% abstracts compared CDR and SRM technologies (Figure 3).

After a peak in 2010 and 2011 in the share of abstracts specifically treating stratospheric aerosol injection (36%), the share declined to 23% in the following two years. We also see a decreasing relative share of abstracts treating ocean fertilization, that is 3% in 2013, compared with 9% in 2010. In contrast, the share of abstracts discussing other specific technologies remained constant (Figure 4).

Our results differ from those of Belter and Seidel, who identified 750 papers published between 1988 and 2011; they concluded ‘that the vast majority of climate engineering publications focus on CO₂ removal’ (Ref 20, p. 423) including many publications treating ocean fertilization. The difference between their results and ours may be explained by the wide-ranging keyword search Belter and Seidel used, for example, including the broad topic search for ‘ocean* NEAR/3 fertiliz*’ (Ref 20, p. 418), whereas our search was designed to identify papers explicitly addressing geo- or climate engineering.

Our findings also differ from those of Bellamy et al., who in a review of geoengineering appraisals identified closure emphasizing specific technologies, primarily stratospheric aerosol injection. Bellamy et al. argued that ‘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’ (Ref 9, pp. 610–611). Our analysis of peer-reviewed journal papers identified no such closure. The number of abstracts concentrating on stratospheric aerosol injection leveled out, whereas those treating other technologies increased.

The contrast between our findings and those of Bellamy et al. may be because their study covered 25 geoengineering appraisals, all but one published before 2012. Another possible reason for the difference is that our categorization is based on what the authors highlight in the abstract, keywords, and conclusions of peer-reviewed papers. Stratospheric aerosol injection may well be iconic, if grey literature, books and news articles are included, but based on our analysis of peer-reviewed literature, we argue...
that it would be premature to conclude that there is a closure in scientific literature on climate engineering in the sense that stratospheric aerosol injection would be synonymous with climate engineering. Three sets of technologies in addition to stratospheric aerosol injection predominantly exemplify climate engineering: other albedo-enhancing technologies (e.g., increasing crop albedo or marine cloud brightening), space reflectors, and ocean fertilization.

**MOTIVES FOR CLIMATE ENGINEERING RESEARCH**

As climate engineering comprises emerging and, for many, controversial technologies, we hypothesized that researchers would tend to go beyond basic science motivations in justifying the research focus in the abstract. Seventy-one percent abstracts justified the research by citing one or more of the following arguments as starting points for the climate engineering analysis presented: (1) the adverse effects of human-induced climate change, (2) failed climate change politics justifies research into policies and measures alternative or additional to mitigation and adaptation, (3) the controversies around or increased attention to climate engineering, and (4) the potential adverse effects of climate engineering (Figure 5).

Adverse human-induced climate change was the most common starting point over the analysed period, with an average of 47% of the abstracts setting their analysis of climate engineering in this context. However, this proportion decreased from an average of 58% of abstracts in 2006–2008 to 44% in 2011–2013. The number of abstracts referring to failed climate change politics remained fairly constant, decreasing only slightly to 10% toward the end of the 2006–2013 period. Those referring to controversy about or increased attention to as well as adverse effects of climate engineering increased somewhat in prevalence as starting points.

Although only 11% of abstracts referred to failed climate politics, 66% of the abstracts referred to the potential roles of climate engineering in climate action, though this theme was slightly less common in natural than social science abstracts (Figure 6).

In both the natural and social science abstracts, we identified a similar tendency to address the role of climate engineering as an option for climate action. The share of abstracts addressing this role decreased markedly from 2006–2008 (84%) to 2011–2013 (57%), while the share of abstracts not explicitly referring to climate action almost tripled. Perhaps for the latter period it is assumed that climate engineering papers fall within a climate change policy framing, so there is deemed to be less need for the policy justification of climate engineering research.

**SIDE EFFECTS AND STAKES**

Even in the abstracts, most of the papers framed climate engineering as risky and uncertain, identifying potential side effects and the stakes involved. We define a stake as a goal valuation of a desired state that,
if lost, will have high-magnitude consequences. An example is the desire not to jeopardize a functioning ecosystem balance, as this would impede food security or biodiversity. We use the concept of ‘stake’ instead of ‘risk’, which the literature commonly conceptualizes as ‘the probability of events and the magnitude of specific consequences. Risk is often defined as the multiplication of the two terms’ (Ref 45, p. 177). We take ‘high stakes’ to denote significant consequences that radically or irreversibly change the preconditions for human or environmental well-being.

Sixty-two percent of the natural science abstracts addressed the side effects of climate engineering technologies. Of the social science abstracts, the share explicitly addressing the side effects of climate engineering was smaller at 54%. The side effects can be regarded as positive, negative, or neutral depending on actors’ specific goals or preferences on different occasions.46 Most side effects mentioned in the abstracts were framed as negative, in the sense of having undesirable outcomes, or else as neutral/uncertain. Only 2% of the abstracts mentioned positive side effects in the sense of attaining new goals, rather than the potential benefits of maintaining a current state. These papers primarily stressed positive impacts on food security, for example, through improved soil moisture and productivity in European cropland regions due to increased precipitation.47,48

For the abstracts that identified the adverse side effects of climate engineering, we analysed whether these side effects were described in negative or catastrophic terms. Forty-eight percent of all the abstracts featured negative or catastrophic aspects of climate engineering, slightly more so for natural science (50%) than social science (45%) abstracts. Of these 48% of abstracts, one eighth of them referred to some kind of catastrophic effects. Most of them referred to natural disasters, but a few identified other potential perils, for example, ‘that a consideration of climate engineering in the context of climate change can provide a dangerous illusion of controllability’.49

What, then, is said to be at stake in abstracts? We distinguished whether abstracts referred to: (a) general concern over the consequences of climate engineering, (b) high stakes, and (c) general debates or other scholars addressing stakes.

Fifty-six percent of all the abstracts addressed some type of stakes related to climate engineering. Twenty-one percent of all abstracts expressed general concerns, for example, saying that the adverse effects were ‘particularly problematic’,51 noting poor understanding of the nature and magnitude of aerosol–cloud interactions,52 uncertainty regarding climate damage, valuation inconsistency, and institutional barriers.53 Thirty percent of natural science and 23% of social science abstracts emphasized high stakes, for example, arguing that climate engineering ‘can cause major dynamical feedbacks’.50 An additional few abstracts (7%) referred to others talking about stakes due to either climate engineering or the lack of research, development, demonstration, and/or deployment. Many abstracts emphasized uncertainties, implicitly alluding to the high stakes of the technologies rather than explicitly citing them.

In total, 70% of the analysed abstracts voiced arguments concerning either climate change or climate engineering stakes, or both combined. For example, many papers start with the threat posed by climate change but conclude that the high stakes of climate engineering imply that its potentially great negative impacts must be considered and further explored, even, as in the following quotation from Hartzell-Nichols,54 leading to the rejection of climate engineering:

It is argued that any form of solar radiation management that poses threats of catastrophe cannot constitute an appropriate precautionary measure against another threat of catastrophe, namely climate change. (Ref 54, p. 158)

Different patterns emerged for the various climate engineering technologies (Figures 7 and 8). Many of the articles employed a single-stake frame, emphasizing either the high stakes of climate change or the potential high stakes of climate engineering.

Thirty-one percent of the natural science and 40% of the social science abstracts identified dual high stakes, both framing climate engineering as a response to the challenges posed by climate change and noting the stakes related to climate engineering itself.

In natural science abstracts it was most common to discuss dual climate engineering and climate change stakes in relation to unspecified SRM (41%) and ocean fertilization (40%). High stakes related to climate change were most frequently referred to in natural science abstracts on CDR technologies other than ocean fertilization (27%) and specific SRM technologies other than stratospheric aerosol injection (40%). The high stakes of pursuing climate engineering recurred in natural science abstracts on stratospheric aerosol injection (26%) and climate engineering in general (25%).

Abstracts discussing both climate engineering and climate change stakes were common among the social science papers. In particular, 55% of the social science abstracts on CDR presented both these types of stakes. Forty-two percent of social science abstracts on stratospheric aerosol injection highlighted climate
RECOMMENDATIONS IN THE LITERATURE

In combination with the abstract analysis, we read the ‘conclusions’ sections of all full-text papers available through our university library’s databases. The vast majority (87%) of these 230 articles ended in one or several recommendations. However, very few of these explicitly articulated a clear ‘yes’ or ‘no’ regarding various climate engineering technologies: 6% advocated rejecting climate engineering altogether while not even 2% unreservedly advocated its deployment. The most frequent recommendation was that more research and/or experiments were needed (42%). Twenty-eight percent of the papers making recommendations stated that, given the challenges arising from climate change, climate engineering technologies should be considered. Some of these were presented as long-term solutions whereas some, such as stratospheric aerosol injection, were proposed as potential emergency options for mitigating runaway greenhouse effects or abrupt climate change.55,56 Caution in climate engineering research and/or deployment was explicitly called for in 24% of the papers with recommendations. It is also noteworthy that no fewer than 27% of these papers concluded by
making combined recommendations, recommending both more research and experiments and the exercise of caution.

The publications discussing climate engineering in general make policy recommendations more frequently than do those specifically treating SRM and CDR. Nonetheless, we found a wide range of recommendations when we compared the various climate engineering technologies. Sixty-one percent of the publications treating CDR called for more research—slightly higher than the proportion calling for more SRM research (56%). Forty-three percent of the papers dealing with CDR indicated that these technologies might have to be considered. It was the same percentage for papers on SRM technologies. Compared with CDR technologies, more of the papers treating SRM urged caution in its use or rejected the technology (39% for SRM and 31% for CDR). However, if we home in on stratospheric aerosol injection, the most common recommendation was to call for more research (38%), followed by advocating caution regarding the future use of the technology (26%) and considering it as a potential future response measure (19%). Papers advocating caution regarding the use of stratospheric aerosol injection were more likely to call for more research than were those arguing that it may have to be considered.

The general lack of clear conclusions explicitly stating that climate engineering should be either rejected or deployed may reflect that these technologies are not operational. Still, the recommendations are slightly more critical of stratospheric aerosol injection than of SRM technologies as a group and even more critical than of CDR.

DISCUSSION: DUAL HIGH-STAKE TECHNOLOGIES?

Climate engineering technologies have repeatedly been described as emerging technologies.7,9,29,57 Our study confirms that they share similarities with other emerging technology areas in their upstream and potentially transformative characteristics. However, we argue that in its strategic framing, climate engineering differs fundamentally from how other emerging technologies have been framed.

Studies of other technologies, such as biotechnology, nanotechnology, IT, and genomics, have identified at least three common characteristics of emerging technologies.58 First, emerging technologies are in the developmental58 or ‘upstream’ stage. As Corner and Pidgeon7 put it, ‘significant research and development has not yet begun, public controversy about the topic is not currently present, and entrenched attitudes or social representations have not yet been established’ (p. 32). Both Bellamy et al.9 and Corner and Pidgeon7 argue that this also applies to climate engineering research. Our study supports that climate engineering can be defined as a set of emerging technologies in this respect. Most abstracts and conclusions sections emphasize that research into climate engineering has just commenced. Very few publications signal entrenched positions regarding the deployment or rejection of climate engineering; most discuss arguments for and against proposed technologies, emphasizing the uncertainties of our knowledge of climate engineering effects.

Second, emerging technologies are ‘revolutionary or transformative’58 in that they can profoundly change society. As noted by Allenby,59 ‘technological change at this scale … represents movement toward new, locally stable, earth systems states that integrate natural, environmental, cultural, theological, institutional, financial, managerial, technological, built, and human dimensions in new and unpredictable ways’ (Ref 59, p. 121). This observation is confirmed by our study as well. Many abstracts emphasize the potentially profound effects of most climate engineering technologies on all of society. For example, several abstracts emphasize that climate engineering, in general, should be a last resort or ‘plan B’ simply because it could relatively quickly—provided the technologies can be deployed—revolutionize societies’ global warming countermeasures. Even among the abstracts that did not go as far in considering climate engineering as a last resort, many still kept the door ajar by advocating more research because the possibility that the technologies may have to be considered could not be ruled out. Others warned of the hazards of embarking on stratospheric aerosol injection, as it would represent a profound and irreversible force in the Earth system.

Third, according to Einsiedel,58 emerging technologies can be labeled ‘strategic technologies’. Such technologies involve forward thinking and planning, are tied to national investments and aspirations,58 and evoke hopes as well as fears.60 For example, the case of genetically modified organisms (GMOs) has, on the one hand, been framed as a risky technology being developed beyond public control that may lead to loss of biodiversity and, especially in developing countries, greater farmer dependence on large multinational companies. On the other hand, the development of GMOs has also been framed as a way to achieve new goals, such as increasing crop yields to feed a growing world population or facilitating sustainable development through diminished...
dependence on chemicals in agriculture. Another example is the development of nanotechnology, which has likewise been framed as entailing both promise and peril. Nanotechnology advocates have emphasized the potential economic and social advantages in areas as diverse as computer efficiency, pharmaceuticals, and pollution control, while opponents have singled out safety and ethical concerns and voiced their fear that nanoparticles may be toxic and that nanotechnology development may ultimately be steered by vested interests.

Our literature review demonstrates that, regarding the first and second characteristics mentioned above, the framing of climate engineering is similar to the framing of other emerging technologies. However, when it comes to the third characteristic, there seem to be very few hopes and aspirations to achieve meliorations in terms of new goals, such as increased food production (in the case of GMO crops) or new pharmaceuticals (in the case of nanotechnology), tied to climate engineering.

While some scholars have described climate engineering as a potentially complementary category of options for addressing global warming, in addition to strategies for mitigating GHG emissions and adapting to climate change, considerable attention has been paid to the environmental consequences as well as to the ethical, legal, political, and social challenges that may result from climate engineering technologies. In their review of a limited sample of climate engineering papers, Huttunen and Hildén identified a risk–benefit framing as structuring academic discourse on climate engineering, noting that ‘geoengineering is seen as both an opportunity and a threat’ (p. 4). This is similar to framings identified in media discourse on climate engineering, for example, where innovation and risk frames coexist or where the weighing of risks and benefits is prominent.

However, our more comprehensive sample suggests a somewhat different pattern in the scientific literature. Few see stratospheric aerosol injection, ocean fertilization, or space reflectors as a complete solution to climate change, but rather as a possible last resort, a ‘plan B’ that may avert catastrophe. Our analysis finds a strong emphasis on a cautious approach to climate engineering in the peer-reviewed research literature. Only a few studies (7 out of 291) note any positive side effects of climate engineering, mostly in the case of crop albedo technologies, whereas several publications specifically note this lack of positive side effects. In the case of SRM technologies, numerous authors emphasize that the technologies fail to mitigate other negative effects of heightened CO₂ emissions, notably ocean acidification.

We conclude that the bulk of the papers do not weigh the various technologies’ risks and melioration benefits, that is, to achieving a condition superior to earlier conditions. Instead, it emphasizes either the potential dangers of pursuing climate engineering or the climate change consequences of refraining from considering the research, development, demonstration, and/or deployment of climate engineering technologies. To analyse this discussion, which is not prevalent in the literature on earlier emerging technologies, we explore the concept of dual high-stake technologies. With this concept we refer to technologies for which the major argument in their favour is that not considering them as options may have disastrous consequences, while the major argument against them is that considering them as options may also have disastrous consequences. In both cases, profoundly negative, even catastrophic, effects are anticipated for our planet. In a dual high-stake frame, the essence of the debate boils down to choosing ‘the lesser of two evils’.

However, climate engineering is not a homogenous research field. Different patterns emerged for the different climate engineering technologies. Our review emphasizes that in discussing the governance of research, development, demonstration, and/or deployment, it is crucial to distinguish between the individual technologies, instead of treating climate engineering as a single, coherent technological field to be governed through a single entity.

Two sets of technologies differed somewhat from the dual high-stake framing: carbon sequestration, both terrestrial and in connection with bioenergy production (BECS), and enhancing albedo through vegetation. These were instead framed as beneficial technologies reducing the negative consequences of climate change while promoting, as Singarayer et al. put it, the ‘positive impacts of increasing crop canopy albedo on soil moisture’ and increased primary crop productivity (Ref 47, p. 45110) or, according to Moore et al., ‘ecosystem richness, water management, and social amenities’ from afforestation for BECS (Ref 39, p. 15701).

CONCLUSION

The climate engineering literature is rapidly expanding, with many authors attracting considerable peer interest, as attested to by many well-cited publications. A wide range of technologies is in focus. Contrary to a previous review, we found no tendency in the peer-reviewed literature to treat stratospheric aerosol injection as synonymous with climate engineering. This technology dominated the published literature in
2007 and 2008, attaining near iconic status. Although stratospheric aerosol injection is still the technology most frequently treated in articles on particular technologies, other albedo techniques, space reflectors, and ocean fertilization are also commonly examined. Still, over all our analysis finds a strong emphasis on a cautious approach to climate engineering in the peer-reviewed research literature.

There is no dominant recommendation as to the deployment of climate engineering. In none of the areas we analysed did we see any tendency toward a consensus view: some scholars call for more research, some warn against prematurely embarking on a path that will lead to deployment, others warn against prematurely refraining from considering climate engineering, while still others discuss both of these high-stake arguments.

Climate engineering technologies share the characteristics of other emerging technologies, such as genetic modification or nanotechnology, in being ‘upstream’, that is in a development stage, and in being potentially revolutionary and transformative. In their strategic features, however, climate engineering technologies differ significantly from other emerging technologies. The dual high-stake framing in the climate engineering research literature describes technologies for which the discourse is dominated by two contrasting potential disaster arguments: one that refraining from research, development, demonstration, and/or deployment may be harmful; the other that pursuing this technology may be equally bad, if not worse. Thus, warnings about profoundly negative, even catastrophic, anticipated effects on the planet are used in arguing both for and against climate engineering technologies.

This finding of our review is important for at least three reasons. First, the proposed climate engineering technologies, unlike other emerging technologies, are rarely seen to have any co-benefits, but are justified primarily by a desire to avoid jeopardizing stakes. As such, climate engineering is a logical outgrowth of a climate discourse focused on risk-aversion policies. Climate engineering therefore contrasts with climate management strategies that have ancillary benefits, such as increased energy security through renewable energy. In public climate change communication, fear appeals have proven ineffective in spurring public engagement in climate change. If this holds, we should not expect significant public support for climate engineering technologies whose rationale is only to avert worst-case scenarios rather than the attainment of additional benefits. Second, in line with the recommendations of Bellamy et al., researchers need to be especially careful when designing public engagement exercises, so as not to steer the discussions by emphasizing one type of stake over another. Instead, they should allow participants to respond to the different types of stake arguments discussed in the literature. Third, our findings suggest that a dual high-stake, rather than risk–benefit, framing should also be considered in analysing certain emerging technologies with similar characteristics, such as nanotechnology for pollution control.

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