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Deliberating stratospheric aerosols for climate geoengineering and the SPICE project

Nick Pidgeon^{1*}, Karen Parkhill¹, Adam Corner¹ and Naomi Vaughan²

Increasing concerns about the narrowing window for averting dangerous climate change have prompted calls for research into geoengineering, alongside dialogue with the public regarding this as a possible response. We report results of the first public engagement study to explore the ethics and acceptability of stratospheric aerosol technology and a proposed field trial (the Stratospheric Particle Injection for Climate Engineering (SPICE) 'pipe and balloon' test bed) of components for an aerosol deployment mechanism. Although almost all of our participants were willing to allow the field trial to proceed, very few were comfortable with using stratospheric aerosols. This Perspective also discusses how these findings were used in a responsible innovation process for the SPICE project initiated by the UK's research councils.

The Royal Society defines geoengineering as the deliberate large-scale manipulation of the planetary environment to counteract anthropogenic climate change¹, with two distinct approaches identified: carbon dioxide removal (CDR) techniques, which extract CO₂ directly from the atmosphere, and solar radiation management (SRM) techniques, which aim to reflect a small percentage of the Sun's light and heat back into space. CDR techniques include proposals to sequester carbon dioxide from the atmosphere using large-scale chemical processing, and the industrial-scale production and burial of biochar. Suggested SRM approaches include the enhancement of marine cloud albedo and the injection of reflective aerosols into the stratosphere.

SRM is already proving controversial. There are uncertainties over its effects on ecosystems and global weather patterns¹, and it does not address the fundamental causes of climate change or secondary impacts such as ocean acidification². SRM also raises transboundary issues, as unilateral intervention could impact other countries or populations, and once started SRM would require long-term commitment by global society, as termination while atmospheric CO₂ concentrations remained increased would lead to a rapid rise in temperatures³. This suggests that an early international governance regime for SRM is needed^{1,4}, something which itself might prove challenging given recent difficulties with conventional climate negotiations. Such concerns transcend traditional questions of environmental risk assessment, and raise fundamental questions about the public value of science and the acceptability to society of the options for responding to climate change. Accordingly, the 'Oxford Principles'⁵ for the governance of geoengineering research, as well as reports by the UK Royal Society¹ and the US Government Accountability Office⁶, all recommend public engagement for exploring the acceptability of geoengineering.

Public engagement is a well-established research methodology in the social sciences^{7,8}. Fiorino⁹ describes three generic aims of this approach: normative (engagement is a valuable activity in a democratic society), instrumental (decisions are thereby rendered more transparent, trustworthy and more likely to be acceptable to people) and substantive (generating new information about risks, values and ethical concerns for informing decisions). With emerging technologies, public engagement is often described as 'upstream', and involves various public(s) deliberating a scientific or technological issue

throughout the early processes of scientific research, development and issue framing, before significant commercial realization has taken place¹⁰. Salient questions for upstream engagement include: What is a development for? What is the need? Who owns it? Who will be responsible if things go wrong? This approach has been successfully used for biotechnology¹¹, nanotechnologies^{12,13} and synthetic biology¹⁴. Stirling¹⁵ elaborates one particularly important objective of upstream public participation: to avoid premature ending of the process of problem definition by opening it up to as many different perspectives as possible. Although extended expert peer review can help with this to a certain extent, the value of public engagement here is to establish whether there are facets of the issue, or value-based concerns, deemed unimportant or trivial by scientists and other expert commentators, but which are likely to prove significant for laypeople. And although expert peer analysis might be able to specify the range of potential novel risks, ultimately only society can adjudicate on their acceptability¹⁶. Accordingly, some large multi-stage engagement processes involve quite elaborate combinations of both extended expert review and lay public deliberation¹⁷.

The very first public dialogue to be conducted for geoengineering was the Natural Environment Research Council's Experiment Earth?, a series of structured public discussion groups held in 2010¹⁸. Around 30 people in each of several locations in Britain were invited to debate the moral, ethical and societal implications of funding research into geoengineering. Through a combination of small group discussions led by professional facilitators, and presentations given by scientists, ethicists and civil society commentators, participants deliberated about nine geoengineering technologies. The controllability and reversibility of such technologies, as well as the adequacy of regulatory arrangements, were identified as key criteria on which future research should be judged.

One criticism often levelled at public engagement exercises is that the findings may have little impact in policy terms — in effect they routinely have 'nowhere to go'¹⁹. With the dialogue reported here, however, the study was commissioned to be used within a responsible innovation process specified by Research Councils UK (RCUK). Responsible innovation aims to embed an explicit evaluation of the wider worth, impacts, unanticipated risks and ethical implications into the research and development process for a new technology^{20–22}.

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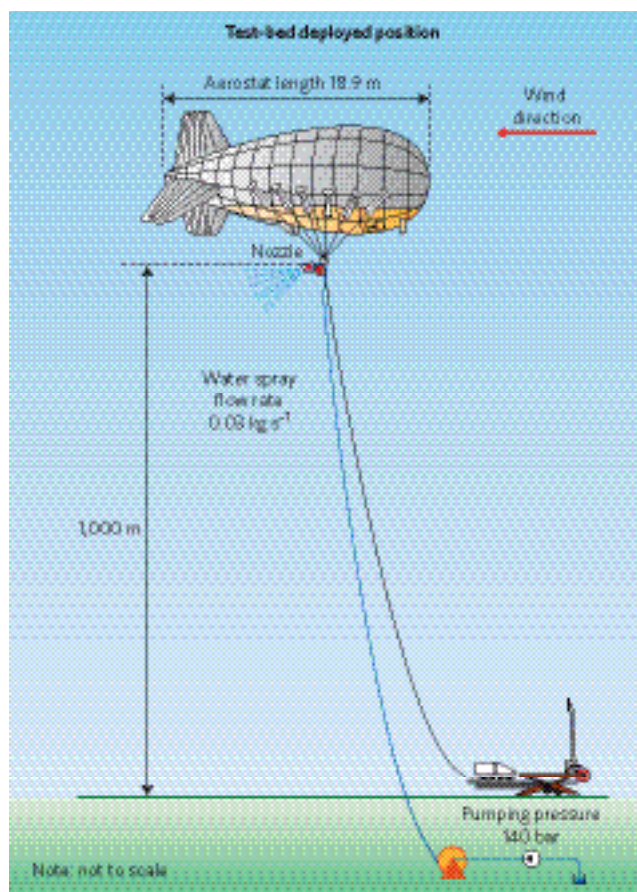


Figure 1 | Schematic of the SPICE test-bed proposal. Figure courtesy of Kirsty Kuo, Cambridge Univ. Engineering Department.

The public engagement study we report on here also forms part of the Integrated Assessment of Geoengineering Proposals (IAGP) project, which is aiming to develop an assessment framework to assist evaluation of geoengineering options. In parallel to IAGP, a second programme of research was commissioned in 2010 by RCUK — the Stratospheric Particle Injection for Climate Engineering (SPICE) project. SPICE focuses on the means, efficacy, impacts and modes of delivery of the stratospheric aerosol approach to SRM. The SPICE work package investigating modes of delivery involves the exploration of the engineering challenges of delivering aerosols continuously through a 20-km pipe held in place by a giant helium-filled balloon, primarily by means of desk-based and modelling work. However, the SPICE researchers also proposed to conduct a field trial of a scaled-down 1-km ‘pipe and balloon’ system (hereafter the ‘test bed’), involving the pumping of fresh water, primarily to observe the movements of the pipe and balloon under various wind conditions (Fig. 1).

The proposed SPICE test bed took SRM research beyond the relatively uncontroversial territory of laboratory modelling and simulation into the realm of real-world testing of SRM deployment, and quickly attracted fierce criticism from some non-governmental organizations. It is worth reflecting briefly on why proposals for such a small engineering test, effectively posing no major risk to humans or the environment, attracted such levels of opprobrium. As the Royal Society’s 1992 risk report¹⁶ makes clear, many so-called crises of technology are often less about the technology per se, or the absolute level of risk involved, which in some cases might be quite trivial. Rather, people’s responses involve a range of legitimate concerns and value-based questions which go beyond formal measurement of risk. Reflecting this, in an open letter to the then minister responsible for UK climate policy, a group of international civil society organizations argued that SPICE would be a dangerous distraction from the need for deep emissions cuts, sending a signal that the UK is “not negotiating in good faith to reduce emissions, but is instead preparing to proceed down an alternative, very high-risk technological path”²³. For some, then, the SPICE field trial represents a step too far down a very slippery slope towards a future where human–nature–society relationships are altered irrevocably. One might dismiss such objections simply on the grounds that people have unintentionally shaped the natural world for millennia, and that, philosophically speaking, geoengineering is no different in this regard. However, intentional manipulation of the climate is different in legal and ethical terms^{24,25}. Work on public opposition to biotechnology has also demonstrated how people’s unease about the ‘unnaturalness’ of the technology was bound up with a wider storyline about not ‘pushing nature beyond its limits’, and concerns over long-term unintended consequences and the degree to which scientists’ visions of increased technological control over nature and human society were ethically acceptable¹¹. It is not difficult to see why SRM has characteristics that evoke similar cultural narratives, something that may also help to explain its sensitivity among many climate scientists, regulators and academic commentators.

In keeping with the responsible innovation approach, RCUK held back funding for the SPICE test-bed component until additional materials and evidence could be evaluated through a ‘Stagegate’ process²⁶. Specifically, the SPICE project team were asked to satisfy five evaluation criteria, listed in Box 1. The public engagement study was commissioned to address one half of criterion 5: specifically, the response of informed laypeople to the test bed, after giving due consideration to stratospheric aerosols and geoengineering more broadly. The study was not designed to address the equally important question of stakeholder views (the second element of criterion 5 in Box 1), that is, of professional and interest groups including regulators, scientists, businesses, environmental groups and so on. Equally, and as Box 1 makes clear, public deliberation can only ever provide part of the information needed to decide whether a potentially controversial piece of scientific research should proceed or not.

Survey research has shown that levels of public familiarity with geoengineering are extremely low²⁷. As it is very difficult for people

Box 1 | The responsible innovation Stagegate evaluation criteria²⁶.

- Criterion 1: The test-bed deployment is safe, the principal risks have been identified and managed, and are deemed acceptable.
- Criterion 2: The test-bed deployment is compliant with relevant regulations.
- Criterion 3: The framing of the project (nature, purpose) for external communication is clear and advice regarding this has been obtained.
- Criterion 4: Future potential application(s) and associated impact(s) have been described and mechanisms put in place to review these as significant information emerges.
- Criterion 5: Mechanisms have been identified to understand wider public and stakeholder views regarding these envisaged applications and impacts.

Box 2 | Questions generated by participants regarding knowledge.

“You know the results from doing the test bed, how will they take that, how will that be the same as if they do it on a full scale?”

To what extent can you upscale the findings from 1 km to 20 km?

How can we relate small scale to large?

How can the results from the test bed be applicable to the longer pipe?

How can the data from the test bed be used?

How will this address the wider risks of stratospheric aerosols?

How much can we learn about the cooling effects from this type of trial?

Can the other effects (for example, wind, temperature and other effects) all be scaled up?

How will impacts be tested of the full-size project?

How will the negatives of the 20 km pipe be dealt with?

Will the test bed tell us what we need to know?

Are the other potential negative impacts and cons of using stratospheric aerosols also being investigated in the project?

How will fresh and salt water behave differently?

What would be, for full-scale deployment, the impacts of temperature (for example, frozen pipe) and will the test bed help?

to debate issues with which they are unfamiliar, we developed a 1.5-day generic methodology successfully used with nanotechnologies¹² in the form of an invited micro-deliberation²⁸. A cross-section of the general public was recruited to take part in a structured series of learning and deliberative phases (Methods). Throughout the study we were aware of the importance of the balance between providing enough information to facilitate informed debate, while also avoiding unduly influencing participants through over-framing the issues for them¹⁰. Although few participants had heard of geoengineering before, as found with other topics^{29,30}, once given basic information they were able to debate and critically interrogate many of the technical and social issues involved, as well as generate a range of questions of their own. Many of them were also surprised to learn that the views of the public were being sought in this way.

Geoengineering and SRM

Previous studies^{18,31} have suggested that people may prefer CDR over SRM. The findings from the public engagement study corroborate this and help to explain why. Fundamentally, participants felt that SRM would only provide a stop-gap response to climate change; as one put it: “because you’re not actually changing the conditions that created it. All you’re doing is controlling the temperature.” Perceived ‘naturalness’ was also a powerful stimulus for engendering concerns about the environmental consequences of geoengineering, with SRM perceived as interfering with natural processes: “they’re very unnatural, and I think that, in a way, worries me because it’s ... probably doing something that we shouldn’t”. Stratospheric aerosols in particular were also depicted by some as contributing to a disassociation of humankind from the physical world, with uncertainties and global risks deemed likelier as a result. Through discussing stratospheric aerosols and cloud brightening, participants also questioned how SRM would be managed, controlled and reversed (if necessary), and whether its efficacy could ever be judged given the complex, interrelated systems involved.

Echoing academic commentary^{24,25,32}, ethics and governance issues were seen as particularly problematic for stratospheric aerosols: for example, if the negative impacts affected countries that had not themselves deployed the technologies. Many participants felt that there was an imperative to develop some form of international governance structure capable of seeking consensus for developing and deploying the technology, as well as determining codes of conduct for their responsible use. However, the extent to which such a consensus on aerosol deployment could ever be achieved was also questioned: “It’s a concern because when they’ve had these climate change seminars [for example, Kyoto] and groups, nobody ever agrees, and what guarantee would we have that everybody would

actually agree over something like this?” Such views did not rule out conducting research on aerosols or SRM, as for some there was reassurance in scientists investigating all potential avenues, ensuring there are spaces for innovation, ingenuity and novel developments to address climate change.

The SPICE test bed

Participants’ views of the general idea of stratospheric aerosols discussed on day 1, and the specific SPICE test-bed proposals introduced on day 2, inhabited very different discursive spaces. That is to say, the set of perceptions, associations and interpretations (often negative) people held of stratospheric aerosols did not automatically inhibit support for the test bed when framed as a strictly limited research opportunity. However, these sets of discourses were not wholly separate, with links occurring when initial questions regarding the test bed evolved into queries and concerns about the implications for full-scale deployment. To illustrate this point we discuss in more detail the questions generated by participants at the beginning of day 2, under four categories: safety and unintended impacts; methodology and justification; knowledge limitations; and governance and communication.

Safety and unintended impacts. An unequivocal concern was that the test bed should be safe. Questions centred on how safety would be ensured (would the team conduct a risk assessment?), how danger would be avoided (for example, for aircraft) and what were the implications if something did go wrong? This included safety for humans — those operating the test bed, in close proximity to the test or who might otherwise be impacted — and wider environments and ecosystems. Although some of these concerns might seem straightforward to address, these data demonstrate how associations with other risk issues, personal memories and experiences are likely to form the basis of people’s initial ‘mental models’ when they encounter geoengineering for the first time³¹. For example, some participants wished to know if the balloon gas would be flammable, making reference to the Hindenburg disaster in 1937. Other participants made associations between the test bed (and full-scale deployment) and accidents such as Chernobyl. Such remarks should not be interpreted literally, but do reflect important ambivalences and cautions that many people hold regarding possible unintended consequences of scientific progress³³, albeit expressed indirectly, through metaphors and analogies highlighting past (and potential future) socio-technical failures^{34,35}.

Research methodology. Given that on day 1 our participants had already voiced significant reservations regarding stratospheric

Box 3 | Questions generated by participants regarding governance and communication.

What international links are there?
 Will other countries mind any outfall?
 What will be done with the information from the test bed?
 What will be done with the results?
 How will the results be shared with other countries?
 Do we know what research is happening elsewhere?
 How is the test bed being publicized?
 How will they inform people?
 What will you tell the local people about it?
 How will local government, councils, and so on be involved?
 Who's accountable if things do go wrong?
 Will scientists from other countries be involved with the full-scale project?
 Who would be in control of the full-scale project?

aerosols, they engaged critically with all aspects of the methods and research process underpinning the test bed on day 2. Importantly, questions were not restricted to logistical enquires into where or how the test bed would operate: participants were also deeply interested in why the researchers and funders had opted to pursue these lines of investigation. Most fundamentally, for some participants, an apparent lack of such justification threatened to undermine the worth of the test bed entirely. Although many saw value in completing the engineering test at this stage, others questioned why this was occurring at all, and before other more crucial questions had been answered. As one participant put it: "I think you could well be wasting a lot of money. I don't think that this will be cheap and you're looking at a delivery system ... you don't know whether you're actually going to use it because you don't know the effects of the actual technique. I think you've got to see whether the technique works before you can deliver it or not." A final justification sought by participants was whether there was any real need to pursue stratospheric aerosols at all, over and above efforts at carbon reduction (both CDR and conventional mitigation).

Knowledge limitations. A very subtle line of questioning addressed the limitations to knowledge generated through the 'pipe and balloon' trial, with the set of questions generated shown in Box 2. Precisely what knowledge could the test bed provide to assist with future research (and possibly full-scale deployment)? Accepting that the 1-km test bed was concerned with providing information regarding practical or engineering elements related to the mechanics of the pump, tethering system and the balloon did not preclude critical questions regarding the ability to upscale results, particularly given the differences between the conditions of the test bed and any full-scale deployment. We may never know the true impacts of SRM without deployment³⁶ and the comments of our participants reflected similar sentiments regarding up-scaling to 20 km (different heights, temperatures, location and so on) and whether the approach to radiation management itself would work as proposed. For some, until they became aware of the significant engineering challenges in pumping a fluid up a pipe connected to a balloon, there seemed to be an air of frustration that the test bed would be so far removed from the 'end point' conditions of deployment. Even with rigorous and systematic multistaged research we may never know enough and even then, in the event that something went wrong, how could we trace the cause?

Governance and communication. In common with Experiment Earth²¹⁸, and findings from other technologies^{11,12,33}, participants in all of the workshops were interested in how stratospheric

aerosols at full-scale deployment would be governed, regulated and communicated (Box 3). It was important that there should be some form of international governance structure for SRM, and through discussions about the SPICE research and test bed it became clear that governance structures should be, although not necessarily already in place, at least being worked on. This was to ensure that global debate about what would ultimately be a global initiative was in place — otherwise even pursuing research into it would be fruitless. Some participants felt that good communication structures would help to ensure the research would be seen as legitimate rather than fringe science, or scientists and the UK 'going rogue'. Communicating — being transparent and open about research such as SPICE within the international and national arena — was not just seen as necessary, but obligatory. A variety of actors were held responsible for ensuring such communication takes place, including politicians and the researchers themselves. Simply relying on traditional means of communicating science (for example, international conferences and science journals) was not seen as satisfactory by our participants, with dissemination needed to national publics (to maintain and build trust) and the local communities close to the test-bed site.

Discussion

Our findings suggest that the development of stratospheric aerosol technologies holds the potential for significant public concern and controversy. Concerns were centred on the inability to address the fundamental problem of increasing greenhouse-gas emissions, possible unintended consequences and the perceived 'unnaturalness' of the technique. Perhaps more importantly, aerosols were also seen to raise significant problems of international governance and control, underlining the importance of current efforts to develop research governance structures^{4,5}. Our respondents were nonetheless reluctant to rule out the SPICE test bed as a limited scientific and engineering test. In all of our groups we observed a marked alteration in discourse from the end of day 1, where views on aerosols were broadly negative, to a more nuanced and ambivalent set of frames when debating SPICE during day 2. However, participants were also clearly uncomfortable with what might happen next if the test bed was given the go-ahead. How could the knowledge gained be usefully employed? What societal controls might ultimately be needed on stratospheric aerosols? Who would take responsibility to oversee this process? It is these epistemological, social and institutional ambivalences, issues intertwined with the strictly technical and science questions, which are the key outcomes from our study, and which pose the greatest challenges for future stratospheric aerosol research and SRM governance efforts.

Our report from the workshops³⁷ was delivered to the RCUK Stagegate panel convened in June 2011 to consider the SPICE project. Our conclusions included:

- Almost all of our participants were willing to entertain the notion that the test bed as an engineering test — a research opportunity — should be pursued. That being said, the research could only proceed if (1) the test bed was safe for local inhabitants and the environment, and (2) the SPICE project was fully transparent and open about this. Information relating to the safety and impacts of the test bed should be made fully accessible for locally affected people, who should also be treated as active participants in that communication process.
- Equally, very few in our study were fully comfortable with the notion of stratospheric aerosols, with their discourses about this and the test bed often operating simultaneously within several frames. Accordingly, acceptance of the test bed should not be misconstrued as unconditional acceptance of, or support for, either stratospheric aerosols or geoengineering more generally but rather a highly 'conditional' or 'reluctant acceptance'³⁸ of

pursuing the test bed as part of a carefully developed research strategy. The ambivalences of our participants were indicative of their desire that strategic research decisions (for example, regarding the outcomes and follow-on from SPICE) did not lose sight of the end goal of scaling-up to potential full deployment.

- Although developing new scientific and technical knowledge was important for our participants, they felt that funding decisions for both the test bed and any future research stemming from it should be based as much on issues of governance and ethics, as on science and engineering criteria. A related issue for our participants was that RCUK should make transparent their strategy for funding geoengineering research and SPICE, and how this would fit within their strategy for supporting research on responses to climate change.
- A key concern for participants was that international governance and regulatory structures should be under development now to help shape geoengineering research such as the test bed, SPICE and future developments.

The test-bed proposal was deemed to meet the public engagement criterion of the Stagegate, although not all other criteria were fulfilled at that point in time²⁶. In particular, the SPICE team were asked by the panel to undertake engagement with involved stakeholders (the second element of criterion 5, Box 1). The value of the public engagement for the Stagegate process was not so much in its (limited) endorsement of the SPICE test bed ambitions, but as a means of highlighting critical issues of concern to our participants falling under criteria 1, 3 and 4. Although the safety aspects of the test bed (criterion 1) had already been addressed by the SPICE team through a risk assessment prepared for the Stagegate, they were requested by the panel to reflect on our findings in developing a communication plan for communities in the vicinity of the test bed (criterion 3). As our participants had also raised the wider 'what next' question, SPICE were additionally asked to keep under review, as a 'living document', the risks, ethics and social aspects of SPICE and SRM more generally (criterion 4): in effect to undertake reflexive appraisal as the project moved forward from that point on. Our findings also hold significant implications for research funders and scientists working on geoengineering in the future, highlighting some of the conditions (international governance, thorough consideration of the implications of scaling-up, an ethical as well as technical review) that lay publics might wish to place on moves towards funding larger-scale SRM and aerosol research. As a postscript to the study, the SPICE test bed was eventually cancelled in June 2012, primarily because of difficulties surrounding a patent application for the pipe technology. Although intellectual property was not an issue that emerged to any great extent in our groups, concerns about the conditions under which geoengineering might become commercialized in the future did. Here, a number of our participants spontaneously expressed suspicion of the involvement of commercial interests, arguing for a mechanism for societal oversight given that this issue held such major global and environmental consequences for us all.

The study serves as one model for successfully embedding public dialogue within a responsible innovation process. However, it represents only the starting point in understanding how global publics, in all their variety and complexity, will respond to geoengineering proposals as they become more prominent in the media and policy spheres. The study engaged a cross-section of participants from a single Western European nation and a particular cultural context. Although European social researchers have successfully experimented for well over 20 years using this invited micro-dialogue format, the approach has recently attracted considerable methodological and philosophical discussion. Commentators have argued that such methodologies of engagement, first developed extensively in the context of Danish civic culture and the 'consensus conference'

approach, may not always transfer successfully to countries with very different cultures of citizen participation³⁹. For example, Dryzek and Tucker argue that the advocacy politics present in countries such as the United States can seriously bias the outcomes of public engagement⁴⁰. However, recent evidence from citizen engagements with nanotechnologies^{12,41,42} suggests that many of the conditions that are held to bias outcomes are absent when an emerging technology is sufficiently 'upstream' (as by definition strong advocacy positions have yet to emerge) or can be overcome with careful process design. Equally, recruiting a cross-section of the public with little previous experience of the issue, to debate it in the terms set by a sponsoring institution, risks merely reproducing those institutionally defined framings⁴³ — or, in Stirling's¹⁵ terms, of prematurely 'closing down' the range of potential options and issues under consideration. Invited dialogue processes also construct 'the public' in a very particular way^{44,45}. By giving voice to the constituency who do not typically express their views on science and technology (in effect using a 'lay jury' model) this excludes more vocal proponents and opponents on the grounds that they do not represent the 'authentic' voice of society. In the case of this study, deliberation with the more vocal group was due to be conducted, after the Stagegate review, through the SPICE team themselves consulting relevant stakeholder groups. Our own view is that societies are composed of multiple publics, with differing values, levels of interest in an issue, and concerns, and as a result we will need varied means for engaging these different constituencies. The challenge now for the geoengineering research community is to find further innovative, culturally sensitive ways to engage a much wider set of publics: those with particularly strong views on climate change or geoengineering, and those in other countries and regions, especially developing ones, where climate change or geoengineering impacts are likely to be particularly extreme. Such public dialogue will be an essential component in the global debate about geoengineering research and its governance that now needs to be conducted.

Methods

After extensive piloting, a deliberative workshop format was developed which facilitated people from different social positions taking part. Workshops were completed in three British cities each with 8–12 participants (total $n = 32$). Locations were selected to reflect a socio-economically diverse national capital (Cardiff), a semi-rural area and city (Norwich), and a former industrial city (Nottingham). To elicit a diverse range of viewpoints, sampling was designed to capture a broad demographic cross-section of the population at each location. The overall sample (see Supplementary Table 1) reflected gender, age, socio-economic grouping and educational level, as well as the ethnicity mix present in each specific location. Recruitment was 'topic blind', with geoengineering not mentioned during the recruitment: participants were approached in a public place by a representative of a professional recruitment agency to take part in discussions related to 'societal responses to climate change'.

Each workshop was facilitated by the research team, and lasted 1.5 days with a 'homework' task given in between (Supplementary Appendix 1 shows the overall structure of each workshop). Day 1 began with facilitated discussion about climate change, followed by a World Café⁴⁶ style discussion about potential societal responses to climate change (mitigation, adaptation and geoengineering), and then introduction to four geoengineering approaches by a geoengineering expert (N.V.): biochar, air capture, cloud whitening and stratospheric aerosols (for materials used to illustrate these see Supplementary Appendix 2). This was followed by a further World Café including social and ethical prompts on SRM and CDR. These four examples were selected to give a snapshot of the range of most plausible geoengineering approaches and were repeatedly described as being just that, and not an exhaustive list. Following advice from the IAGP independent advisory panel, examples were given of research currently taking place, including the full-scale 20-km pipe proposal for SRM, but without mentioning the SPICE project explicitly at that point. Day 2 began with discussion of the homework task (to describe to a friend or relative what people had learned from day 1), a brief overview of the SPICE test bed, the RCUK Stagegate process, and the reason why the workshops were being held. Participants then developed together a series of questions that they wished to see answered about SPICE. We viewed this question generation as the most important activity of the whole workshop, in that it elicited, in all three workshops, a very wide range of responses to the proposed

field trial, ranging from the very practical to the philosophical. This was followed by the opportunity to question a member of the SPICE research team from the Cambridge Engineering Department about any of these, ending with final parallel small group discussions about SPICE and a wrap-up plenary. Workshops were held in public spaces and participants were given a small financial honorarium. All sessions were audio- and video-recorded, and full verbatim transcriptions made of all conversations, which were independently professionally verified and anonymized. Systematic and rigorous qualitative data analysis of the transcripts was conducted⁴⁷ with themes and interpretations discussed extensively by the research group.

Considerable effort was expended to ensure all materials were accurate, including being reviewed by experts in geoen지니어ing and climate science. In addition, social scientists and third-sector representatives with expertise in governance, regulation and ethics also reviewed the materials. Careful attention was paid to the framing of materials. Although climate change was emphasized as requiring urgent action, geoen지니어ing as an 'emergency' response or 'emergency stop button' framings were not introduced by the research team. Other framings avoided throughout the workshops (as a result of our analysis of issues arising with the earlier Experiment Earth? methodology) were 'naturalness' or 'mimicking natural processes', and 'carbon removal as dealing with the cause of climate change'. If such responses and issues emerged spontaneously from the participants, as they at times did, these were explored further, but the researchers themselves avoided introducing them. Estimates of costs of different approaches were also not presented: we stressed throughout that owing to the uncertainties surrounding costs and unintended impacts, nobody could currently answer this question with any confidence. The key orienting framing used throughout was that geoen지니어ing may be one possible response to climate change as a risk issue⁴⁸, rather than a debate about whether global warming was 'real' or not. Of course, there is no entirely neutral framing of such a controversial issue, and one cannot entirely rule out unintended framings entering the debate through either particular materials presented, or prompting from the facilitator team. However, throughout we were very sensitive to participants' own constructions, which we explored exhaustively through the extensive use of prompts such as 'What makes you say that?', 'Could you say a little of why you are interested in knowing that?' As such, our public(s) were active participants in the workshops and deliberative processes, capable of and encouraged to engage critically with all of the information and also to develop their own framings in an open and reflexive way. For a fuller discussion of methods see Parkhill and Pidgeon³⁷.

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Author contributions

The study was conceived by N.P. and A.C. The detailed design and materials were developed by all authors. Data collection was conducted by K.P., N.P. and N.V., and the analysis by K.P. and N.P. N.P. wrote the paper with contributions from all other authors.

Additional information

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