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ORIGINAL ARTICLE

Transdisciplinary co-design of scientific research agendas: 40 research questions for socially relevant climate engineering research

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Abstract Interest in climate engineering research has grown rapidly owing to the slow progress of international climate negotiations. As some scientists are proposing to expand research and conduct field tests, there is an emerging debate about whether and how it should proceed. It is widely accepted both by the supporters and critics that public engagement from the early stage of research is necessary. Nonetheless, most, if not all, of existing research projects of climate engineering were designed predominantly by experts. To produce socially relevant knowledge, and hence, pursue transdisciplinary research that integrates interdisciplinary research and public engagement, it is desirable for scientists to decide together with the public on what kind of research should be done. In this paper, we both as Japanese scientists and stakeholders collaboratively identify 40 socially relevant research questions on climate engineering with a particular emphasis on stratospheric aerosol injection, using a method

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designed to encourage science–policy collaboration. While we acknowledge some methodological problems and the difficulty in obtaining active participation from stakeholders, the list of identified questions covers broad interdisciplinary perspectives and diverse interests, and may provide an important foundation for future transdisciplinary research on climate engineering. Given the dynamic nature of climate change and policy responses, research agendas should be periodically and iteratively reviewed and updated through transdisciplinary processes.

Keywords Transdisciplinary research · Co-design of research agenda · Climate engineering · Stratospheric aerosol injection · Public engagement

Introduction

Climate engineering, also known as geoengineering, is an umbrella term used to describe deliberate intervention in the Earth's climate system to counteract anthropogenic climate change (Royal Society 2009; NRC 2015). Although climate engineering was considered as a taboo for a long time, research on this topic has recently gained traction. Frustrated with the slow progress of the international climate negotiations, Paul Crutzen, a Nobel laureate chemist, wrote his famous editorial in *Climatic Change* in 2006 (Crutzen 2006), which boosted climate engineering research, both in natural and social sciences (Linnér and Wibeck 2015). The Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) covered climate engineering in all three working groups (IPCC 2014). At the national level, scientific assessment reports on climate engineering were published in the United Kingdom (UK) (Royal Society 2009), Germany (Caviezel and Revermann 2014), and the United States (US) (NRC 2015).[1]

The types of climate engineering research include a wide range of disciplines from natural to social science, and can be disciplinary, interdisciplinary, or transdisciplinary. It is further separable into indoor (non-invasive or computational) and outdoor research; and particularly, outdoor experiment or field testing is surrounded by a deep controversy over whether and how such research should proceed. Some scholars advocate initiating field tests (Keith 2013; Parson and Keith 2013; Caldeira and Ricke 2013; Long et al. 2015), whereas others express a cautious attitude toward such research (Robock et al. 2010; Schäfer et al. 2013). Some scholars reject the whole concept of climate engineering altogether (Hulme 2014).

To facilitate public debate on climate engineering, a group of scientists proposed a set of principles for governing climate engineering research, known as the Oxford Principles (Rayner et al. 2013). As codified in one of the

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[1] While these reports all recognize mitigation and adaptation as first priorities, it is still significant that climate engineering has become an important part of the scientific discourse.

five principles, it is widely accepted both by supporters and critics that public engagement on climate engineering research is necessary and desirable (Royal Society 2009; Carr et al. 2013; NRC 2015).

This emphasis on public engagement is in line with the emergence of sustainability science (Kates et al. 2001; Komiyama and Takeuchi 2006) and calls for transdisciplinary research. Sustainability science is a field of research that aims to understand the complex dynamics of human–environment systems, and by doing so, to provide useful knowledge for solving real-world problems, such as climate change; therefore, it often takes the form of "use-inspired basic research" (Clark, 2007; Stokes, 1997).

In addition, there is a growing recognition among scholars that sustainability science should be managed in the mode of transdisciplinary research, which can be understood as the integration of interdisciplinary research and stakeholder engagement (Lang et al. 2012; Jahn et al. 2012; Pahl-Wostl et al. 2013; Scholz and Steiner 2015a), though the definition is somewhat ambiguous. As climate change is one of the core problems in sustainability science, climate engineering also fits into this field. Of course, this does not mean that transdisciplinary research is the only way to research climate engineering. Instead, all types of research, such as curiosity-driven basic research or problem-solving applied research, can contribute to advancing our understanding of various issues surrounding climate engineering. However, if climate engineering research seeks to address human needs and help achieve global sustainability, a significant part of it should be managed as transdisciplinary sustainability research, as we further discuss below.

And yet most, if not all, of existing research projects of climate engineering were designed predominantly by scientists; such projects may not fully reflect the broad public concerns, still halfway to embracing transdisciplinarity. To fully integrate wider public opinions into climate engineering research, it is desirable for scientists to decide together with the public on what kind of research should be done (including the option of doing no research).

In the present study, we—both scientists[2] and stakeholders—collaboratively identified 40 socially relevant research questions on climate engineering, using a method designed to encourage science–policy collaboration (Sutherland et al. 2011). We believe that our effort provides an important foundation for future transdisciplinary research on climate engineering.

Climate engineering and transdisciplinarity

What is climate engineering?

Technically, climate engineering can be grouped into two categories: solar radiation management (SRM) or albedo modification and carbon dioxide removal (CDR) or greenhouse gas removal (GGR).[3] CDR/GGR is intended to remove CO_2 and other long-lived greenhouse gases (GHGs) from the atmosphere and includes the methods of direct air capture, biomass energy with carbon capture and storage (BECCS), and ocean iron fertilization. SRM, on the other hand, aims to reduce incoming solar radiation by reflecting sunlight back into space and to cool the planet without reducing the atmospheric concentrations of GHGs. Examples of SRM include stratospheric aerosol injection (SAI), marine cloud brightening, and land-based albedo modification (e.g., desert and human settlement).[4] All of these technologies still remain in the stage of a mere proposal.

Debates surrounding stratospheric aerosol injection

Among the many proposed techniques, SAI features most prominently in the literature. In many cases, when people are talking about climate engineering, they, in fact, mean SAI (e.g., Keith 2013; Hulme 2014). We, therefore, pay closer attention to SAI than other proposals. This technology is intended to cool the climate by spraying reflective aerosol particles into the stratosphere (NRC 2015). SAI has two beneficial characteristics: it is deemed "quick" and "cheap" (Keith et al. 2010). First, unlike mitigation and CDR/GGR, SAI might be able to offset the global-mean temperature rise rapidly (NRC 2015). Because of this feature, some scientists expect that SAI may be the last resort for preventing climate emergencies (Victor et al.

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[2] Here we use the word "scientists" in a broad sense, which means that it includes not only natural scientists and engineers, but also social scientists and humanity scholars.

[3] Although we lump SRM and CDR/GGR together in this paper by following the previous literature, these two are more increasingly treated separately, because there are little common features between them (e.g., Boucher et al. 2014).

[4] Although not an SRM strictly speaking, there is another related technique which aims at thinning cirrus clouds to reduce warming effects of high clouds.

2009). Second, according to an engineering analysis (McClellan et al. 2012), the direct cost of SAI would be affordable, particularly when compared with deep cuts in GHG emissions.[5] Given these two features, some scientists and policymakers have begun considering SAI as a potential means to address climate change.

However, SAI presents numerous challenges on many fronts (see Robock 2008, 2014). First, SAI may come with various side effects, such as regional hydrological changes (Kravitz et al. 2013; Tilmes et al. 2013) and stratospheric ozone destruction (Pitari et al. 2014). If the deployment of SAI was suddenly stopped for any reason, an accelerated increase in global-mean temperature could occur (Jones et al. 2013); however, moderate and restrained deployment could avoid this termination problem (Kosugi 2013; Keith and MacMartin 2015). Some worry that there could be risks of unknown side effects which might result in serious consequences to populations vulnerable to climate change (Robock et al. 2009).

Second, the use of SAI for averting "climate emergencies" is scientifically and politically questioned. Sillmann et al. (2015) argued that SAI may not be effective for preventing some of the climate tipping points (e.g., the West Antarctic ice sheet melting and degradation of the Amazon rainforest) from passing thresholds. Moreover, justifying SAI on the plea of emergency necessarily involves value judgments, and may face political challenges (see also Hulme 2014; Markusson et al. 2014).

Third, SAI is mired in many moral obstacles as well. Some scholars question the fundamental moral status of SAI, thereby rejecting the whole idea of manipulating our climate (for a review on ethical issues, see Preston 2013). An often-cited ethical question on SAI is that the prospect of SAI creates moral hazard that might discourage the continued effort to reduce GHG emissions (Lin 2013).[6] On the other hand, some argue that the knowledge of SAI might actually have the opposite, reverse moral hazard effect because of its scariness (Preston 2013; Reynolds 2015). Some ethicists further argue that SAI may create deeper ethical subversion, which is called "moral corruption" (Gardiner 2010). This partly relates to the criticism that the very concept of SAI reflects human hubris (Hamilton 2013).

Numerous political challenges have also been reported. SAI raises concerns of potential unilateral implementation by a single nation, non-state actors, or even individuals (Victor et al. 2009). A closer investigation, however, showed that such a scenario might be politically unlikely (Horton 2011). Nevertheless, there is a strong need for a governance framework and regulation regardless of whether SAI will be used or not (Barrett 2014). Some scholars contend that it is desirable to coordinate and make use of existing international frameworks, such as the United Nations Framework Convention on Climate Change (UNFCCC) (Bodansky 2013). Others argue for a new agreement to meet the governance requirements specific to SAI (Lloyd and Oppenheimer 2014; Barrett 2014).

Last but not least, there is a concern that research into SAI could be the first step onto a "slippery slope" toward deployment, which could be characterized as the issue of path dependence or socio-technical lock-in (Cairns 2014).

To address the diversity of concerns and issues outlined above, proactive public engagement is essential from the early stages of SAI research (Corner et al. 2012; Carr et al. 2013). Such endeavors will pave the way for responsible innovation of climate engineering (Stilgoe et al. 2013).

The rationale for pursuing transdisciplinarity on climate engineering research

It is clear that some types of SAI research, field tests especially, would intrude into the complex human–environment systems, entailing large scientific uncertainty of and a conflict of values on such systems. This makes SAI research a prima facie case of "post-normal" science, defined as a type of science that deals with large systems uncertainty and significant societal stakes (Funtowicz and Ravetz 1993). This means that science itself may become a source of controversy, and it becomes increasingly difficult for scientists to defuse such controversy by themselves; rather, they are required to collaborate with various stakeholders and citizens from the very beginning, which is the stage of designing research agendas. For this reason, public engagement is normatively, substantively, and instrumentally required for SAI research from the early stage (Fiorino 1990; Carr et al. 2013).

The call for public engagement on climate engineering research coincided with the advent of transdisciplinary research in sustainability science. Because of the complex nature of the issues involved in sustainability, transdisciplinary mode of research is advocated by many scholars, which is driven by urgency of problems at hand rather than by disciplinary curiosity, and at the same time, seeks for stakeholder engagement to ensure that the research be socially relevant for real-world challenges (Lang et al. 2012; Jahn et al. 2012; Scholz and Steiner 2015a). Many transdisciplinary research projects have been conducted primarily in Europe (Scholz and Steiner 2015b). Most recently, the new international program on Earth System science, Future Earth, has incorporated the concept of

[5] The cost would nonlinearly increase with radiative forcing because of the particle size growth. In addition, the low cost may not be an inherent advantage and is the reason for the concern about unilateral deployment.

[6] Despite its naming, moral hazard is not limited to ethical issues and also concerned with risk management (Lin 2013).

transdisciplinarity as a key pillar of its research framework, emphasizing the co-design of research agendas and co-production of knowledge with stakeholders and striving to help achieve global sustainability (Future Earth 2013).

Co-designing research agenda with stakeholders

Public engagement is one of the key elements of transdisciplinary research. In this sense, there is already an emergence of transdisciplinary research on climate engineering, although this term is rarely used in the literature.[7] Attempts for public engagement have been conducted, most notably in the UK. For example, the Stratospheric Particle Injection for Climate Engineering (SPICE) project conducted an extensive public deliberation with citizens when it proposed the UK's first field experiment of SAI (so-called test-bed) to assess whether and under what condition the test-bed proposal would be permitted (Pidgeon et al. 2013).

Despite the importance of public engagement, such exercises are usually conducted after the research agendas are formulated. For instance, even though the SPICE project was an exemplary case with extensive public engagement, the scope of the research was determined by scientists only, particularly natural scientists; the involvement of social scientists was also limited (Stilgoe et al. 2013). As a move toward transdisciplinary climate engineering research, we think that there is an opportunity for swimming further upstream by engaging stakeholders in co-designing a research agenda, as suggested in the Future Earth framework.

Co-design is defined as a process, in which "the overarching research questions are articulated through deliberative dialogues among researchers and other stakeholder groups to enhance the utility, transparency, and saliency of the research" (Future Earth 2013). Following this definition, we held a one-day workshop, where both scientists and stakeholders were invited to co-design the research questions relevant to climate engineering research in Japan.

There are already a few research projects initiated in Japan, which deal with climate engineering as one of the sub-projects; however, these projects lack stakeholder engagement on deciding their research agendas. Societal interest in climate engineering is still low in Japan—as indicated by the very fact that there is so far no strategic research project in Japan directly focusing on climate engineering. Nevertheless, as climate engineering (especially, SAI) is by definition a global issue, it is necessary to start engaging Japanese stakeholders and citizens into climate engineering debate by anticipating that such research might take place in Japan. In short, our exercise of co-design can be considered as the first step toward public engagement on climate engineering in Japan.

[7] An exception is Schäfer et al. (2015).

Method

We employed a method using a collaborative workshop to select research priorities from a large number of questions suggested by diverse individuals (Sutherland et al. 2011). This method has been used for various issues, such as ecological conservation (Sutherland et al. 2006), agriculture (Pretty et al. 2010), science–policy interfaces (Sutherland et al. 2012), poverty reduction (Sutherland et al. 2013), and food security (Ingram et al. 2013). A similar method was also applied to identify 62 research priorities in the Future Earth Strategic Research Agenda 2014 report (Future Earth 2014).

Recently, researchers in biodiversity and global environmental research applied a different but related method to produce a list of priority research questions on climate engineering (McCormack et al. 2016). However, the participation was limited to researchers and the process was interdisciplinary, not transdisciplinary.

The basic steps of this method are as follows. In the pre-workshop stage, the conveners collect research questions from a large group of individuals. Then, a one-day or two-day workshop is held to select a set of research questions through an iterative process of voting and discussion. In the post-workshop stage, all of the workshop participants write a manuscript together and submit it to a peer-reviewed journal.

It is important to emphasize that what we mean by research here is not confined to natural sciences, but also includes social sciences and humanities to address a broad collection of social, political, ethical, and scientific concerns, from both supportive and critical perspectives.

Pre-workshop: selection of participants and collection of questions

Selection of participants

The research core team, or "conveners," (MS, SA, TK, AI, SE; the first five authors) convened the workshop, and solicited many individuals, or "participants," to participate in the workshop. The selection of participants was based on purposive sampling (Sutherland et al. 2011). To cover diverse interests in the context of climate change in Japan, the conveners invited a total of 30 participants (16 researchers and 14 stakeholders),[8] considering disciplinary and practical expertise, political orientation, gender, and

Table 1 Composition of workshop conveners and participants

Disciplines and sectors of participants	No. of participants
Research core team (conveners)	5
Researchers	16
Climate science and impacts	4
Economic analysis and engineering	4
Governance and law	4
Ethics and societal issues	4
Stakeholders	14
Government ministries	2
Civil society groups	5
Businesses and industries	4
Media organizations	3
Total	35

age (but not geographical distribution) (Table 1). Owing to the capacity of the conveners, the number of participants was limited to 30. All were invited to participate in individual capacities; therefore, their views do not necessarily represent those of their institutions.

For the definition of stakeholders, we followed eight categories of stakeholders defined in Future Earth (2013): research, science–policy interfaces, funders, governments, development organizations, business and industry, civil society, including non-governmental organizations (NGOs), and media. We merged some and ultimately identified four groups (governments, civil society, business and industry, and media) as stakeholders, in addition to the category of research.[9] Although we divided participants into researchers and stakeholders for the practical purpose of breakout group assignment, both were treated equally throughout the entire process.

In identifying experts, we loosely defined four broad, disciplinary categories, reflecting the interdisciplinary nature of the problem: (1) climate science and impacts, (2) economic analysis and engineering, (3) governance and law, and (4) ethics and societal issues. We then searched for experts that fit such categories.

Collection of questions

The conveners solicited the participants to suggest research questions and to collect them from their colleagues ("contributors"). The conveners distributed an electronic spreadsheet with the instructions and a two-page briefing note on SAI, as described in the Electronic Supplementary Material (ESM) S1 (an English translation and the original Japanese version). To facilitate the initial screening process by conveners, the participants and contributors were asked to classify each of their suggested questions into one of the four categories as mentioned above. The four categories also served as a reference for establishing four breakout groups in the workshop. To incorporate as much diversity as possible in the concerns, the submitted questions were not required to be in the form of research questions at the time of collection.

Each participant was asked to submit at least five questions; the conveners also submitted research questions. The submitted questions underwent two processes of screening by the conveners. The purpose of the first process was to clarify ambiguous statements, to convert non-question submissions into research questions, and to identify missing interests and concerns that were not included in the submitted questions. After the first screening, the conveners asked the participants to provide additional feedback on the results of the first screening. Afterward, we obtained a total of 593 questions from 88 individuals (5 conveners, 30 participants, and 53 contributors). In the second screening, the conveners removed duplicate questions and merged them with other questions and labeled groups of similar research questions. As a result, 355 questions remained in total, with 76 to 100 in each of the four categories (ESM S2).

Workshop: selection of 40 high-priority research questions

A one-day workshop was held in Tokyo on July 26, 2015. The workshop aimed at identifying 40 high-priority research questions by winnowing down from 355 collected questions. The target number of 40 research questions was decided to ensure that a certain number of questions from all four categories would be retained to some degree and to guarantee that at least one question considered as high priority by each participant would be retained in the final list. The process of winnowing questions down to 40 was essentially conducted through voting and discussion. The entire discussion during the workshop was under a modified Chatham House rule to guarantee free exchange of opinions, which required a written consent of the speaker if one wishes to quote him/her. Importantly, we clearly underlined that the workshop was not intended to seek consensus-building toward the development and deployment of SAI or opposition toward it, and that this would be clearly stated in the final outcome.

[8] Two individuals in stakeholder groups (one from government ministries, the other from media) were also invited, but cancelled their attendance on the day of the workshop for personal reasons.

[9] Some researcher participants regularly consult with governments and participate in the science–policy interface, and the invited government agencies are closely related to funding agencies. We did not reach out to development organizations, because this workshop focused mostly on Japan, a developed country.

Scope of the questions

The conveners set the scope of the research questions, such that the identified questions had importance for a project originating in Japan, a developed country in Asia. Although the main focus of questions addressed was SAI, the questions were not confined to this topic. The questions were allowed to cover broader issues relevant to SRM and climate engineering in general, including issues on climate governance (Fig. 1).

The conveners established the following criteria for research questions, based on, but slightly modified from, Sutherland et al. (2011): (1) address important and high-priority issues, (2) be realistically answerable through a medium-sized research project, (3) be stand-alone and not dependent on other questions, and (4) be not dependent on only a single value perspective.

For the fourth criterion, Sutherland et al. (2011) explicitly suggested that research questions should "have a factual answer that does not depend on value judgments". However, exemplified by the intense debate on SAI, a number of issues on SAI cannot be answered solely on a factual basis and inevitably involve value judgments, such as ethical issues. In some cases, as Tuana et al. (2012) argued, it is even desirable to couple scientific and ethical issues for an integrated and holistic analysis. Thus, to apply the fourth criterion to the controversial context of SAI research, we modified this criterion as above, so as to allow normative dimensions to be incorporated into research questions, but avoid such questions being solely based on a particular value system.

For ethical issues, this criterion means that questions are not dependent on a specific ethical position; rather, they must be framed as meta-ethical research questions, which require analyzing ethical implications of adopting a particular ethical position, such as utilitarianism or libertarianism without taking a specific ethical position.

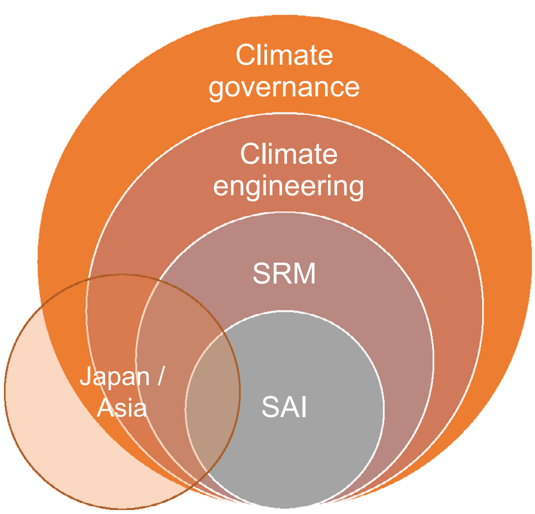

Fig. 1 Scope of the research questions

Voting and discussions

The workshop consisted of four separate sessions, each lasting 1.5 h (Fig. 2). In the first and second sessions, the participants were split into four small breakout groups of climate science/impacts, engineering/economics, governance, and ethics/society. In the third session, the four small breakout groups were merged into two medium-sized breakout groups: a natural science group, which included climate science/impacts and engineering/economics, and a social science group, which included governance and ethics/society. This session was followed by a plenary session attended by all conveners and participants.

The conveners facilitated the discussions in each session and, therefore, did not vote. Each researcher participant was assigned a breakout group that broadly corresponded to the researcher's expertise. Researchers remained in the same groups for the first and second sessions, while some of the non-researcher stakeholders took part in different groups to convey their perspectives in different groups. Four researcher participants (SW, AK, TU, and KM) helped facilitators by taking notes in each session.

Each session had a target number to which the list of questions should be shortened. In each small breakout group, we aimed at winnowing approximately 40–50 questions down to 12. In each mid-sized breakout session, the planned reduction was from 48 to 25; in the plenary session, winnowing was planned from 50 to 40. Ultimately, we winnowed the research questions down to 39 (rather than 40) by mistake during the workshop. To rectify this mistake, we conducted e-mail voting after the workshop.

In each breakout session, the participants voted at the beginning, and then held discussions on merging and rephrasing the questions. Voting was conducted twice in each small breakout session and once in each mid-sized breakout session. In the plenary session, no voting took place, and all of the participants concentrated entirely on merging questions through discussion. Each participant was given a fixed number of votes: in each small breakout session, six and three votes for the first and second voting, respectively; five votes for each mid-sized breakout session. Each participant could cast only a single vote for a single question. Any question with at least one favoring vote was retained, and only the questions with no supporting vote were removed.

The voting system that we used gives each participant the right to select at least one question to be retained in the final list and can accommodate diverse interests from pluralistic viewpoints. Our system is different from

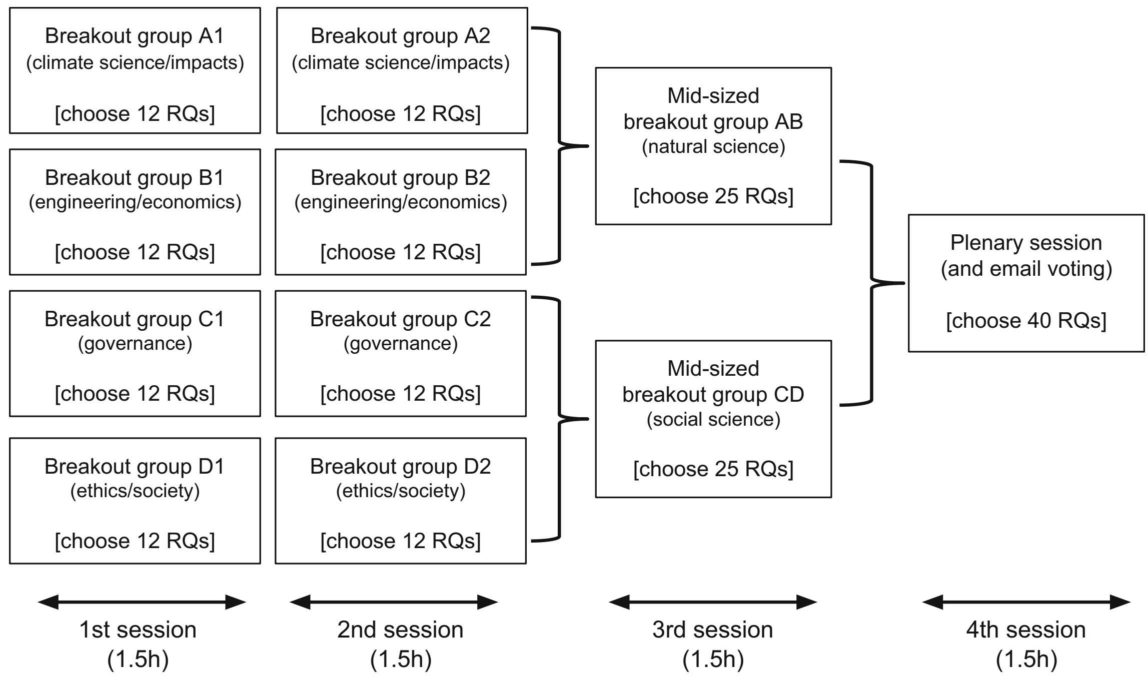

Fig. 2 Flow of the workshop

previous studies using Sutherland et al. (2011), where a score-ranking system was typically used. In this system, participants assign a score on a certain scale (e.g., 1–9) to all questions, and questions with higher mean scores are retained. The score-ranking system is useful under usual circumstances, but appears to be infelicitous for controversial topics, such as climate engineering because of the possibility of voting out minority viewpoints.

Post-workshop: e-mail voting and paper-writing

E-mail voting

As noted above, we happened to select 39 rather than 40 research questions at the end of the workshop owing to miscounting in the plenary session. This mistake was realized immediately after the close of the workshop and was quickly announced to the participants. The conveners decided to conduct a post-workshop e-mail voting to select the final question.

The conveners offered four candidate options from a list of research questions that garnered some support from the participants, but were eventually removed in the plenary session. Unlike the workshop's voting system, the e-mail voting was based on the majority rule. The question with most votes by the majority of workshop participants was chosen; the conveners did not vote. The e-mail voting employed a two-round voting system to ensure that the winner is elected by a majority. The actual voting process reached the second, runoff round.

Phrase-editing and paper-writing

The conveners rephrased the sentences of the identified 40 questions to clarify the meanings and re-categorized them into seven categories. The participants were consulted to provide feedback on the editing and re-categorization of the identified questions. After the approval of the edited questions by the participants, the conveners wrote the initial version of a manuscript, and circulated it to the participants to seek their feedback. Each and every participant agreed to become a co-author; therefore, we did not obtain approval from any institutional research ethics committee (Sutherland et al. 2012).

We conducted all of the processes in Japanese, except for the final paper-writing process. The original outcomes were in Japanese, and we translated all of the research questions into English after finalizing them in Japanese.

Results

As noted above, we re-grouped the 40 questions into 7 categories after the workshop. Each category addresses a common issue or concern rather than a disciplinary/methodological domain. The selected categories may not be mutually exclusive, and they effectively highlight interdisciplinary perspectives as well as a wide spectrum of opinions on SAI research and development, ranging from support to opposition.

We stress that all the authors do not necessarily endorse all 40 questions listed below, and that there is no priority ranking in the listing order of categories and individual research questions.

We used the term "SAI" in each question wherever possible; however, in many instances, "SAI," "SRM," and "climate engineering" can be used interchangeably. Many questions are applicable to other types of climate engineering as well as SAI.

The original Japanese version of the 40 research questions can be found in ESM S3.

I Social and economic assessment: costs, benefits, and non-economic values

1. In light of multiple evaluation dimensions, such as cost-benefit analysis (CBA) and ethical norms, how can we socially assess SAI? What is the common ground for different indicators? Is CBA applicable to an evaluation of SAI? If so, what sort of values is CBA based on? In what way can we calculate the efficacy, effectiveness, and cost of SAI?
2. What are the costs and direct/indirect benefits of the implementation of SAI? How large is their associated uncertainty? What about the costs of side effects (including the abatement cost) toward the economy, environment (ecosystem and human health), and disasters, etc., including the worst-case scenarios in both the short term and long term? In addition, how should we compare SAI with alternative options and evaluate the option value of SAI in an integrated assessment model?
3. Which method can be used to evaluate the risks of SAI from both economic and non-economic perspectives?
4. If SAI were implemented, how much benefit, cost, or loss would be imposed on various actors (e.g., nations, local communities, and industries) and different generations?
5. Who should conduct technology assessment of SAI and how? How can we ensure the impartiality and credibility of the process of such an assessment?

II. (Negative) side effects: risk, uncertainty, and policy response

6. How large are the scientific uncertainties of various side effects of SAI, such as stratospheric ozone destruction, regional precipitation changes, and acid deposition? By how much can we reduce such scientific uncertainties?
7. What are the positive and negative impacts and side effects of SAI deployment—through the change of solar radiation and climate (e.g., temperature, precipitation, and extreme weather)—on health, agriculture, ecosystems, renewable energies, economic activities, etc.?
8. Which material would have the highest cooling efficacy as well as the lowest adverse effects when injected into the stratosphere to implement SAI? How different are the side effects of each material? What kind of information and technologies do we need to scientifically demonstrate it?
9. When negative impacts and side effects are caused by research and deployment of SAI, how do we identify who should be responsible and make them compensate for such damage?

III Prediction, attribution, observation, and technological controllability

10. What kind of impact of SAI can be predicted on Japan's climate (e.g., precipitation in the rainy season, typhoons, extreme weather events, and teleconnections, such as those associated with El Niño-Southern Oscillation)? How much in detail can they be accurately represented by the current climate models? How would the impacts of SAI on the climate in other regions indirectly affect Japan through the international relations and trade, etc.?
11. What can we learn about SAI from the historical climate records and paleoclimate, especially from the past large-scale volcanic eruptions? What do we need to prepare (including the observational system) to learn from future volcanic eruptions? Conversely, what can we learn from SAI research for future volcanic eruptions?
12. To what extent can the current science of the stratosphere predict the SAI impacts in terms of atmospheric chemistry and physics before deployment? What is needed to improve the prediction to satisfy the expectations of society?
13. Can we develop a climate forensic technology to detect and verify the changes in atmospheric composition by SAI, which is necessary for regulating SAI activities? What kind of technology would it be?
14. To what degree can we detect and verify the causal link of the implementation of SAI and its effects (and the damage of its side effects)?

What kind of observational system would be required for that?

15. Can the implementation of SAI be reversible? Can we ensure the reversibility technologically?
16. To what extent can we control the global environment? What is the limit of controllability?

IV Policy approaches in broader climate risk management: mitigation, adaptation, and emergency response

17. Does the research and deployment of SAI, or even the mere recognition of SAI, create a moral hazard to discourage the efforts of mitigation and adaptation? What kind of synergy and trade-off is there between mitigation, adaptation, and the research and deployment of both SAI and other forms of climate engineering technologies? How can we prevent a moral hazard and trade-off from occurring?
18. Should SAI be considered as an "investment" in the portfolio of mitigation and adaptation policies, or as "insurance" for alleviating damage in case of an emergency, such as climate tipping points? In the latter case, to what extent can SAI alleviate such damage?
19. Can we implement SAI in combination with mitigation and adaptation, and gradually phase out SAI after successfully reducing the CO_2 concentration in the air and its climatic impacts? If so, what would be the remaining impacts of implementation of SAI?
20. In many existing studies on future climate change, carbon capture and storage (CCS) is expected to play a significant role in achieving stringent climate stabilization, such as the 2 °C target, while SAI is not. What causes this distinction between CCS and SAI?
21. Is SAI a technology that should be kept as a precautionary measure for climate emergency and/or tipping points, or as a "last resort" for preventing unacceptable climate change? If so, who can make a decision on that and how can we evaluate the credibility of such a decision? In addition, what is a crisis or catastrophe of human society that could take place as a result of continued climate change? Can SAI prevent this from happening?
22. Which is more ethically problematic: manipulating the climate through SAI or causing anthropogenic climate change by increasing energy consumption and emitting CO_2? For instance, should SAI bear a heavier moral obligation as an intentional behavior than climate change, which is an unintended consequence of human behavior? Is SAI ethically acceptable compared to other mitigation (e.g., nuclear power, CCS, and BECCS) and adaptation measures? If we were to implement SAI, what would be the desirable conditions of the future climate (considering impacts on non-human species as well)?

V Field test and technology development: technical design and socio-political framework

23. What is the appropriate framework for research and technology development of SAI, considering the issues of public engagement, public–private relationship, and the (inter-/dis)linkage to military research? How can we ensure that the public deliberation for evaluating such research framework is fair and neutral?
24. Who should make a decision on and implement a small-/large-scale field test of SAI? What is a credible, fair, and accountable process of such decision-making and implementation at both domestic and international levels? In such a process, what is the role of the expert advisory body and scholars in social sciences and humanities?
25. From a natural scientific viewpoint, how should we determine the scale, location, and method of the field test of SAI?
26. What are the criteria for making a decision to halt research and/or experimentation of SAI (e.g., when a promising alternative is found for tackling climate change or when a societal consensus is achieved on halting SAI activities)?
27. Can research, experimentation, and deployment of SAI be clearly demarcated? How can we avoid (or weaken) lock-in and/or path dependence of developing SAI? How can we solve the "Collingridge Dilemma" (a double-bind problem that if not developed, it does not reveal the effects and side effects of technology, but if developed it increases the possibility of socio-technical lock-in)?
28. Should the patent protection of cooling substances and delivery techniques for SAI be limited? Considering such technologies can also be used for other commercial purposes, how might we promote technology

development by private companies, avoiding the monopoly of private profits at the same time?

VI Governance of implementation: legal, political, and ethical challenges.

29. What is an appropriate and equitable framework for global governance of SAI? Because SAI has global impacts once implemented, how should a mechanism of decision-making and a process of democratic deliberation for experimenting, implementing, and halting SAI be set up? Do we need a new international framework for such governance? What roles should the existing frameworks, such as UNFCCC play? How can it be politically sustainable for a long time (e.g., for a millennium)? (For instance, if the stance toward SAI was overturned for political reasons, how should it be managed?)
30. What are the social, political, economic, technological, and climate-scientific conditions required for starting the implementation of SAI? How should we determine the operational details of SAI (e.g., timing/location/amount of injection, technology choice, cost sharing, and prevention of obstruction)?
31. In light of intra- and inter-generational justice, when implementing SAI, how should we consider the rights and benefits of those vulnerable to climatic impacts and of the future generation? How can we make such a decision and who should be responsible for it? For example, how can we fairly and equitably evaluate the impacts of SAI toward existing social inequalities as well as developing countries that have insufficient technological and financial capabilities?
32. How would the prospect that a certain country can potentially alter the earth's climate by SAI shift the global balance of power in international politics? How would such a shift of power balance affect the international negotiations on climate change? Conversely, if the political circumstance of international security was radically changed, how would it affect the role of SAI as a climate policy?
33. Which countries would be presumed to unilaterally implement SAI in terms of available resources and incentives? What is the scenario of such unilateral implementation and how likely is it to happen? Can we weaken the incentive of unilateral implementation? How should we manage and regulate unilateral implementation by non-governmental actors, such as private corporations and wealthy individuals?
34. Considering the uncertainty of impacts by SAI implementation, what kind of countermeasures should be considered to respond to unexpected events taking place during implementation, and how should we prepare for such events?

VII Socio-political implications and national-cultural backgrounds

35. What kind of gender perspectives would be raised in the research and deployment of SAI? Can we maintain gender equality in it? If so, how?
36. Considering that there are scientific uncertainties around the effects (both positive and negative) of SAI, how can we achieve societal agreement? For the general public, how should we conduct risk communication of SAI, especially regarding its uncertainties?
37. Despite the high scientific uncertainties, how can we share the societal understanding of SAI among citizens in different nations and regions with different social and cultural backgrounds? How will public imaginary and expectation of SAI change over time?
38. What are the positions of countries and stakeholders (e.g., climate skeptics, businesses, environmental groups, and others) regarding research and deployment of SAI? What factors are fundamental in building such positions (e.g., domestic politics; the increased geopolitical tension in Asia)?
39. What are the social and political contexts behind the advocacy of the planetary-scale governance of SAI research?
40. What is the significance of Japan's involvement in SAI research? For example, in which research fields of SAI does Japan have a comparative advantage to make an international contribution? Conversely, what are the risks of Japan's involvement in SAI research?

Discussion and conclusions

Through the process of co-design, we produced a list of socially relevant research questions, covering broad interdisciplinary perspectives that include scientific and technical topics in addition to social, political, and ethical concerns.

This was enabled by the broad participation of scientists and stakeholders from diverse disciplines and domains as well as two important modifications that we made from the standard method of Sutherland et al. (2011): (1) instead of using a score-ranking system, our voting method was designed only to eliminate the research questions that received no support, so that each participant can retain at least one of the questions they regard as important into the final list, and (2) the criterion was loosened to allow for research questions that focus on normative and ethical aspects of climate engineering. Despite the highly contentious context of climate engineering research, our approach could successfully facilitate deliberations on climate engineering research without excluding minority viewpoints.

In practice, all questions may not apply directly to actual research projects; rather, they can indicate directions for further research. These questions are neither entirely new nor raised for the first time by us; some of the questions may just repeat or rephrase those which were already referred to in the previous literature. Indeed, the real value of the list of the 40 research questions is that, seen as a whole, it lays out an epistemic map of diverse and interdisciplinary issues and concerns on climate engineering. In light of the controversial nature of climate engineering research, particularly SAI field tests, whether one supports or opposes it, these issues and concerns should be reflected when designing a research framework. It could, therefore, reasonably be said that our effort of co-designing research agendas can facilitate "opening up" public deliberation in technology choices (Stirling 2008). More importantly, it can be an opportunity for mutual learning for both scientists and stakeholders to understand what we agree and disagree. Such mutual learning is vital for transdisciplinary research to be inclusive and pluralistic (Jahn et al. 2012).

However, our results illuminated the challenges of our method itself too. In our exercise, we set 40 as the target number of the final research questions, a number slightly larger than the number of participants to allow each individual to select at least one question that most matters for him/herself. Obviously, if we were to set a different target number, it might affect participants' voting behaviors, and then eventually might change the whole results. For example, by setting a smaller number, we could refine some unclarified or overlapped questions, or contrarily by setting a larger one, we could consider some neglected issues otherwise. The methodological improvement is required to produce more rigorous results.

Numerous practical obstacles to transdisciplinary research remain, and the continued participation of stakeholders is a major challenge (Lang et al. 2012; Polk 2015; Scholz and Steiner 2015b). To ensure that stakeholder participation is substantive and effective, committed participation from different stakeholders is required. However, different stakeholders have their different interests and priorities. The involvement in research activities could be a high priority to some but could be of no value or even troublesome to others. In our case, some stakeholders declined to participate in the workshop, citing concerns of low relevance and potential conflicts with their interests.

This hurdle is probably more acute for the later phase of transdisciplinary research, that is, co-production and co-delivery of knowledge (Future Earth 2013). Various efforts for ensuring committed participation by stakeholder can be conceivable, such as shared ownership and paid reward (Klenk et al. 2015), but at the same time, it might cause concern over conflicts of interests. On the other hand, the demand for stakeholder participation depends on the characteristics of problems, whether there is high or low agreement of knowledge and values (Jahn et al. 2012). If there were a high agreement of knowledge and values, the participation would be recommendable, but not mandatory, while if the agreement of both knowledge and values was low, the case of "wicked problem", it would necessitate the wide participation throughout the course of research. As we believe that the latter is the case of climate engineering, particularly field tests, securing sufficient participation from diverse stakeholders is essentially important. We must find effective mechanisms of stakeholder engagement.

In this paper, we intended only to provide the outcome of our exercise of co-designing research agendas; therefore, we only scratched the surface of reflection on this exercise. Such reflexive elaboration will shed light on the limitations and societal implications of our exercise. Moreover, it may ultimately lead to further transdisciplinarity in the co-production and co-delivery of knowledge. Given the dynamic nature of climate change and policy responses, relevant research agendas of climate engineering cannot be static. Therefore, research agendas should be periodically and iteratively reviewed and updated through transdisciplinary processes.

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