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SPECIAL FEATURE: ORIGINAL ARTICLE

Citizens' Attitudes, Preferences, Willingness-to-pay for Climate Change Mitigation Options in Asia

Public attitude toward solar radiation modification: results of a two-scenario online survey on perception in four Asia–Pacific countries

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Abstract
Solar geoengineering or solar radiation modification (SRM) is increasingly looming large as a potential response to human-induced climate change. However, it is deeply mired in controversies surrounding environmental risks and social governance challenges. Given the high stakes and uncertain characteristics of SRM, it is essential to understand public perception. However, previous studies on public perception have not explicitly utilized scenarios to frame SRM as an option in the future and mostly have been conducted in the Global North. Here, we present the results of an online survey conducted in Australia, India, Japan, and the Philippines in 2022. In our survey, we showed two different SRM scenarios in which SRM would play different roles in the policy response to the possibility of climate tipping points. Overall, respondents in India and the Philippines were more concerned about climate change and more supportive of SRM, and tended to feel that future scenarios with SRM deployment were more plausible than those in Japan and Australia. Nonetheless, public support of SRM was ambivalent, and many voiced concerns about the environmental and governance risks of SRM. Our findings suggest the significance of explicitly communicating the policy contexts in which SRM might be deployed in the future for capturing more nuanced understandings of SRM among the public.

Keywords Solar radiation modification · Climate engineering · Geoengineering · Public perception · Governance

Introduction

The latest IPCC Sixth Assessment Reports have confirmed that the human influence on climate change is "unequivocal"; impacts of climate change are worsening, and climate change might exceed the limit of adaptation; and limiting global warming to 1.5 °C above the pre-industrial level requires CO_2 emissions reduction to net zero in the 2050s. The remaining carbon budget for a global warming of 1.5 °C, a goal adopted in the Paris Agreement of 2015 and reaffirmed in the 2021 Glasgow Climate Pact, is approximately 500 $GtCO_2$, and the world may soon see the temperature exceeding this threshold because it could run out of the carbon budget with an annual emission rate of ~ 60 $GtCO_2$ eq (IPCC 2023). Scholars and stakeholders are increasingly worried about the risks of temperature overshoot, that is, a period of temperature exceedance beyond the temperature goal.

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Against this backdrop, solar radiation modification (SRM), sometimes called solar geoengineering or climate engineering (CE), is now looming large as a potential option that could alleviate the risks of climate change (National Academies of Sciences, Engineering, and Medicine 2021; Patt et al. 2022; UNEP (United Nations Environment Programme) 2023). Directly cooling the climate system has the potential to reduce some of climate change risks. However, this poses new risks to society and the climate. The “cure” might be worse than the “disease.” Therefore, SRM is very controversial, and there is an ongoing debate about this technology (Buck 2022; Biermann et al. 2022; Doherty and Coauthors 2023; Wieners et al. 2023). At the international level, governments are also taking different positions, as evidenced at the United Nations Environment Assembly (UNEA) held in Nairobi, Kenya, in February–March 2024. A group of countries led by Switzerland submitted a draft resolution on SRM, calling for assessment of SRM by the United Nations Environment Programme (UNEP). However, many countries objected, and the proposal was eventually withdrawn.

According to a recent report (National Academies of Sciences, Engineering, and Medicine 2021), it is crucial to engage the public prior to decision-making regarding research and development. There are at least three reasons for broad public engagement with science and technology issues (Fiorino 1990; Stirling 2008): normative (it is democratically desirable to listen to the public), substantive (the public may come up with broader issues than domain experts), and instrumental (engagement may make the process of decision-making smoother as relevant stakeholders are informed and consulted). On SRM, specifically, it is often argued that public engagement with people in the Global South and vulnerable communities is necessary and even desirable (Winickoff et al. 2015; Rahman et al. 2018). Based on these three reasons, scholars have argued for global public engagement (Carr et al. 2013). Similarly, a case was made for the need for an equal level of participation of various stakeholders and publics (including vulnerable communities), based on the theory of recognitional justice (Hourdequin 2019).

To date, SRM perception studies have been conducted using multiple methods such as qualitative interviews, deliberative workshops, quantitative surveys, or experimental approaches. They have investigated general attitudes (Mercer et al. 2011), sensemaking strategies across different countries (Wibeck et al. 2017), support for different types of research (Merk et al. 2015; Sugiyama et al. 2020), moral hazard (reduced incentives due to the knowledge on SRM) (Merk et al. 2016; Cherry et al. 2021), the role of affect (Merk and Pönitzsch 2017), climate change communication channels (Kahan et al. 2015), the influence of framing (Corner and Pidgeon 2015; Bolsen et al. 2022), and ambivalent attitudes (Asayama et al. 2017). There are several articles that reviewed and synthesized the results of the literature of SRM perception research (Scheer and Renn 2014; Burns et al. 2016; Cummings et al. 2017; Flegal et al. 2019; McLaren and Corry 2021; Raimi 2021; Patt et al. 2022).

From those reviews, some general conclusions can be drawn. First, the public is largely unaware of the option of SRM. Most of the studies therefore provided information about SRM to elicit opinions from the public, and the framing of SRM does matter to their responses. Second, people are mostly against the deployment of SRM, but cautiously and conditionally support research with a mechanism of international governance in place. Also, many factors influence their perceptions, including trust in scientists, perceived naturalness, affect, and value.[1]

Despite significant numbers of research conducted in understanding public views on SRM so far, there are some limitations to these existing studies. First and foremost, studies have been concentrated on high-income countries and biased toward the Global North or Western democracies. More studies on diverse areas, including the Global South and vulnerable communities, are needed (Winickoff et al. 2015; Visschers et al. 2017; Rahman et al. 2018; Buck 2018; Sugiyama et al. 2020; Hussain et al. 2023); the publics in those regions might have different perceptions on SRM than those surveyed already. One of such studies beyond the Global North is our own previous study (Sugiyama et al. 2020), which conducted an online survey in six Asia–Pacific countries (Australia, China, Japan, India, the Philippines, and South Korea). A recent study (Hussain et al. 2023) conducted a similar survey with mostly undergraduate and graduate students in Kenya, Nigeria, and Pakistan. However, the samples of these studies were mostly restricted to students. Students might have different opinions from the rest of the country’s population. More recently, a large-scale survey on SRM and carbon dioxide removal (CDR) was conducted in 30 countries and 19 languages (Baum et al. 2024a). They found that the respondents from the Global South were more supportive of SRM and CDR and identified differences in support for different SRM and CDR options. While these new publication trends are welcome, more work is desirable to understand nuanced perspectives from the Global South.

Another important limitation of previous literature is that most studies did not delve into the characteristics of SRM as a *future* option. Since SRM would not be used—if ever used—in isolation, its assessment needs to be done in the

[1] While the earlier literature (Shepherd et al. 2009; Lawrence et al. 2018) lumped SRM and carbon dioxide removal (CDR) under the umbrella term such as geoengineering and CE, we treat them separately, following recent IPCC reports (IPCC 2018, 2022). We thus do not review an expanding literature on CDR perceptions.

context of different scenarios of deployment (Talberg et al. 2018b; Parson and Reynolds 2021), and the choice of scenarios strongly frames and affects the evaluation of SRM (Talberg et al. 2018a; Sugiyama et al. 2018; Patt et al. 2022; Lockley et al. 2022; MacMartin et al. 2022). The methodological choice of futures affects the political perspective on SRM (Low and Schäfer 2019), and the rationale for SRM governance is closely tied to how future pathways are conceived and articulated (Gupta et al. 2020). Anticipation is a key element of the proposed governance framework of responsible research and innovation (Burget et al. 2017), which some scholars have attempted to apply to SRM (Stilgoe et al. 2013; Stilgoe 2015; Low and Buck 2020).

More specifically, publics might show different attitudes toward the framings of different SRM scenarios, since a scenario avoids a partial view on SRM. The potential use or rejection of SRM should be placed in the context of the progress of climate change mitigation, the increasing concern about gradual climate damages and tipping points, and/or how local communities are adapting to worsening extreme events. Given the totality of information, the public may perceive SRM differently in different scenarios. For instance, how would the public see SRM under a scenario of worsening climate change impacts or the imminent unfolding of a tipping point? Or, how would they see SRM in light of rapidly evolving mitigation technologies such as solar panels, wind turbines, and electric vehicles? More importantly, which scenario would the public prefer? In sum, it is crucial to explore how public perceptions of SRM could vary with different scenarios of SRM deployment in the future.

Lastly, whether the attitudes toward SRM have stayed similar or changed over time is a crucial question. Especially, the COVID-19 global pandemic affected every corner of our life through health damages, lockdowns, and economic recessions. The pandemic also brought to the fore numerous science and policy issues, including the trust in scientists and politicians, risk perceptions of COVID-19 itself and vaccination. Whether and how such a shock affected people's attitudes toward climate change and SRM is an important question.

In order to fill the gap in the existing literature, this paper presents the results of an online survey experiment conducted in four Asia–Pacific countries (Australia, India, Japan, and the Philippines) about public attitudes toward climate change and SRM, using future scenarios as a framing device. The survey featured two scenarios differing in terms of the level of global mitigation efforts and the possibility of climate tipping points.

The remainder of this paper is organized as follows. "Method" describes the survey instruments and sampling strategy. This is followed by the results presented in "Results". "Discussion and Conclusions" concludes the study.[2]

Method

Sample and survey experiment

We conducted a series of online surveys in four target countries: Japan, Australia, the Philippines, and India. These countries were selected as a subset of our previous study (Sugiyama et al. 2020). The sample size was approximately 600 for each country (approximately 300 per scenario–country combination). The survey was pretested with a Japanese sample, and the actual survey was conducted from February to March 2022. We used a panel maintained by Cross Marketing Inc., a survey firm based in Japan, and its international partners. Age and sex distributions were adjusted to the averages of the target countries. Among Indian respondents, the number of survey participants with a graduate degree was extremely high (51%) [see the Appendix, Q20 of Sugiyama et al. (2023)], which might lead to a bias in the results. We therefore take into account education in the regression analysis.

To test the effects of the scenarios, we randomly assigned each respondent to one of the two scenarios developed. The survey experiment with text was similar to previous studies (Corner and Pidgeon 2015; Fairbrother 2016), but differed in that the passage given to the respondents was explicitly presented as a future scenario.

Survey instrument

Our survey instrument has been informed by previous research. In order to clarify the relative importance of scenarios and potential factors for SRM attitudes, our survey instrument includes questions on the attitudes toward climate change and SRM as well as questions on factors that are found to be related to the risk and benefit perceptions of SRM in the literature, including general attitudes toward the environment, science, and technology, and trust in institutions and scientists. The design of our survey instrument is broadly consistent with the previous literature (Mercer et al. 2011; Merk et al. 2016; Sugiyama et al. 2020).

Specifically, it consists of:

1. Six questions (Q1–Q6) on attitudes toward climate change (van der Linden et al. 2017; Bell et al. 2021)

[2] An earlier version, along with descriptive statistics, has been reported in Sugiyama et al. (2023).

(e.g., Q2, "On a scale from 1 to 7, how worried are you about climate change?").
2. Question (Q7) on prior SRM knowledge (Q7, "Have you ever heard of proposed large-scale engineering technology that is designed specifically to combat climate change, known as either 'geoengineering' or 'climate engineering'? …, on a scale from "know a lot" to "know nothing").
3. One randomly chosen SRM scenario out of the two prepared (see below).
4. Three questions (Q8–Q10) regarding scenarios (e.g., Q10, "Do you think that this "Future Scenario 2030" is realistic or unrealistic?" Q10_3, "After 2030, the International Earth Cooling Programme is planned for future climate engineering use.", on a scale from "very realistic" to "very unrealistic").
5. Four questions (Q11–Q14) on attitudes toward SRM, including questions on support for research and deployment (Mercer et al. 2011; Mahajan et al. 2018; Sugiyama et al. 2020) (e.g., Q11, "Suppose it is the year 2030 and 'Future Scenario 2030' has become a reality. What is your opinion of each of the following statements related to the future use of climate engineering (CE)?" Q11_3, "I am willing to accept the use of CE if it would help to avert massive and irreversible impact of global warming.").
6. Four questions (Q15–Q18) on attitudes toward the environment, society, and science, based on and adapted from an earlier work (Braun et al. 2018) (e.g., Q16, "To what extent do you agree or disagree with each of the following statements?", Q16_1, "The Earth is like a spaceship, with very limited room and resources." on a scale from "strongly agree" to "strongly disagree").
7. One question (Q19) on trust of institutions (Mercer et al. 2011; Merk et al. 2015) (e.g., Q19, "How much do you trust the following groups as a source of information about society and the environment?" Q19_3, "United Nations and other international organisations").
8. One question (Q20) on respondent's highest academic degree.
9. One question (Q21) on simple math to assess concentration levels.

We excluded respondents who did not provide the correct answer to the concentration check (Q21) and those who provided repeated answers (e.g., 1, 1, 1, 1,…) to multiple questions. See the working paper (Sugiyama et al. 2023) for the full documentation of the survey instrument.

As for the terminology in the survey instrument, because SRM is not well known to the public, we chose to use the term "climate engineering" (CE), which sounds more intuitive and less technical than the term "SRM." This is consistent with our previous study (Sugiyama et al. 2020). As noted above, CE is sometimes used as an umbrella term for both SRM and CDR, but here CE is used to indicate only SRM. Hereafter, we use these two terms interchangeably. In the survey instrument, CE is described as a "[t]echnology that uses airplanes and other devices to sow sunlight-reflecting particles into the atmosphere."

Scenarios

SRM is a putative technology and an SRM system at the scale envisaged by researchers does not currently exist. This requires some form of scenario assumptions about how SRM might be deployed for scientific assessment and policy discussions, be they explicit or implicit.

The existing literature has developed and utilized many different SRM scenarios with varying objectives. In quantitative scenarios for modeling studies, various scientific objectives have been identified, including the assessment of the overall climate response (Kravitz et al. 2011, 2015), the effect of the magnitude of deployment (Matthews and Caldeira 2007; Kosugi 2013; Sugiyama et al. 2018), and the role of strategies and feedback (Kravitz et al. 2016; Lee et al. 2020). Some scholars also developed qualitative narrative scenarios, with varying actors and governance frameworks (Parson and Reynolds 2021). These scenarios do not only provide scientific basis for SRM assessment, but they might also have significant effects on public views on SRM. However, they have rarely been used directly to inform public engagement nor has their framing effect been examined in previous public perception research.

We designed our scenario narratives based on the following considerations: first, SRM has increasingly been invoked in the context of the Paris Agreement temperature goal of either well below 2 degrees or 1.5 degrees (MacMartin et al. 2018, 2022). Second, there is increasing concern regarding climate tipping points (Lenton et al. 2008, 2019; Armstrong McKay et al. 2022) and the possibility of containing them with SRM (Moore et al. 2019; Chen et al. 2020). Therefore, we developed the following two scenarios (Table 1): (1) "supplement," where SRM supplements mitigation efforts to reach the 1.5-degree goal and avoid climate tipping points and (2) "salvage," where SRM is invoked to salvage the 1.5-degree goal in case of the failure of efforts on global mitigation policy. For simplicity, we assumed a globally coordinated deployment program, and did not explore the aspect of actors who would deploy SRM. In our scenario description, this hypothetical, global SRM deployment program was called the "International Earth Cooling Programme". The scenario also mentioned global cooling benefits and risks of heterogeneous impacts of SRM. Because of the simplification, our scenario did not mention any distributional impacts (benefits and risks) of SRM. We come back to this point in the discussion section.

Table 1 Scenario A ("Supplement") and Scenario B ("Salvage")

Scenario A ("Supplement")	Scenario B ("Salvage")
Future Scenario 2030	
Increases in carbon dioxide (CO_2) in the atmosphere, which are mainly from burning fossil fuels (coal, oil, and natural gas), are causing global warming by trapping more heat in the Earth's atmosphere, which increases the number of extreme weather events (heat waves, wildfires, floods, droughts, etc.)	
Studies have shown that by limiting the increase in global average temperature to 1.5 °C since pre-industrial times, we can reduce the risk of extreme weather events and manage to maintain our way of life	
In 2021, the international community agreed to work toward limiting the temperature rise to 1.5 °C, with the goal of significantly reducing CO_2 emissions to virtually zero by mid-century by [curbing / reducing] fossil fuel use	
As of 2030, as a result of the concerted efforts of the international community to reduce emissions, it is more likely that we will be able to limit the temperature increase to 1.5 °C	As of 2030, large emitters and developing countries with rapidly growing economies and populations have not reduced their emissions, and the temperature increase is expected to exceed 1.5 °C in the near future
However, the latest research shows that, even if the temperature increase is limited to 1.5 °C, the melting of large ice sheets in Antarctica and Greenland could accelerate sea level rise, and the melting of Arctic permafrost could release large amounts of methane (a powerful greenhouse gas), which would accelerate global warming	If this trend continues, there are fears that in the near future, the melting of the large Antarctic and Greenland ice sheets could accelerate sea level rise. In addition, the melting of Arctic permafrost could release large amounts of methane (a powerful greenhouse gas), which would accelerate global warming
Against this backdrop, a new method [to artificially cool/for artificially cooling] the Earth, known as 'climate engineering', [has been/is being] considered to combat global warming	
The International Earth Cooling Programme was launched with the [aim/goal] of starting to implement climate engineering in 2035	
Technology that uses airplanes and other devices to sow sunlight-reflecting particles into the atmosphere is under consideration	
While [research/research conducted] during the past 20 years has confirmed that this technology does produce a cooling effect, there are some concerns about its environmental side effects, including precipitation changes in some areas and [the potential for ozone/potential ozone] layer destruction	
The International Earth Cooling Programme aims to safely use small-scale climate engineering to prepare for the potential melting of ice sheets and permafrost, while simultaneously reducing CO_2 emissions	The International Earth Cooling Programme aims to ensure the safe use of large-scale climate engineering to prevent the melting of ice sheets and permafrost because concerted emission reduction efforts by the international community are unlikely

Note that during the translation between Japanese and English, a few errors were introduced and some parts of Scenarios A and B do not match perfectly. Those parts are marked with square brackets, with the phrases in the left of the slash corresponding to Scenario A

A version in Japanese is presented in Appendix 2 of a working paper (Sugiyama et al. 2023)

Results

Attitudes toward climate change

Respondents were generally worried about climate change and believed in the need for more action; however, the degree of concern varied by country. About 80% or more of the respondents in all countries were very worried, worried, or somewhat worried about global climate change, with the fractions in India and the Philippines reaching about 95% (Q2) (Fig. 1). In terms of climate action, more than 60% of all respondents said that people and governments should do much more or more, with the highest share from the Philippines and the lowest from Japan (Q5). The responses from Australia and India are somewhat similar to each other (Fig. 2). These responses differed significantly according to the Kruskal–Wallis test, which show statistical tests on other questions as well (Table 2).

Attitudes toward SRM

A statistically significant division was found between the Global North (Australia and Japan) and Global South (India and the Philippines) regarding prior knowledge of SRM (Table 2). (We recognize the diversity within the Global North and Global South, but we use these two terms to enhance readability.) 71% of Indian respondents and 53% of Philippine respondents knew either a lot or a little about SRM, whereas in Japan and Australia, this was 18% and 27%, respectively (Fig. 3). A similar pattern was observed in our previous study (Sugiyama et al. 2020). It is not clear if this has to do with the amount of media coverage in respective countries, or if it might be related to some biases (e.g., Indians and the Filipinos being overly confident or Australian and Japanese being overly conservative), or misinterpretation of the term climate engineering, as was found in Mercer et al. (2011).

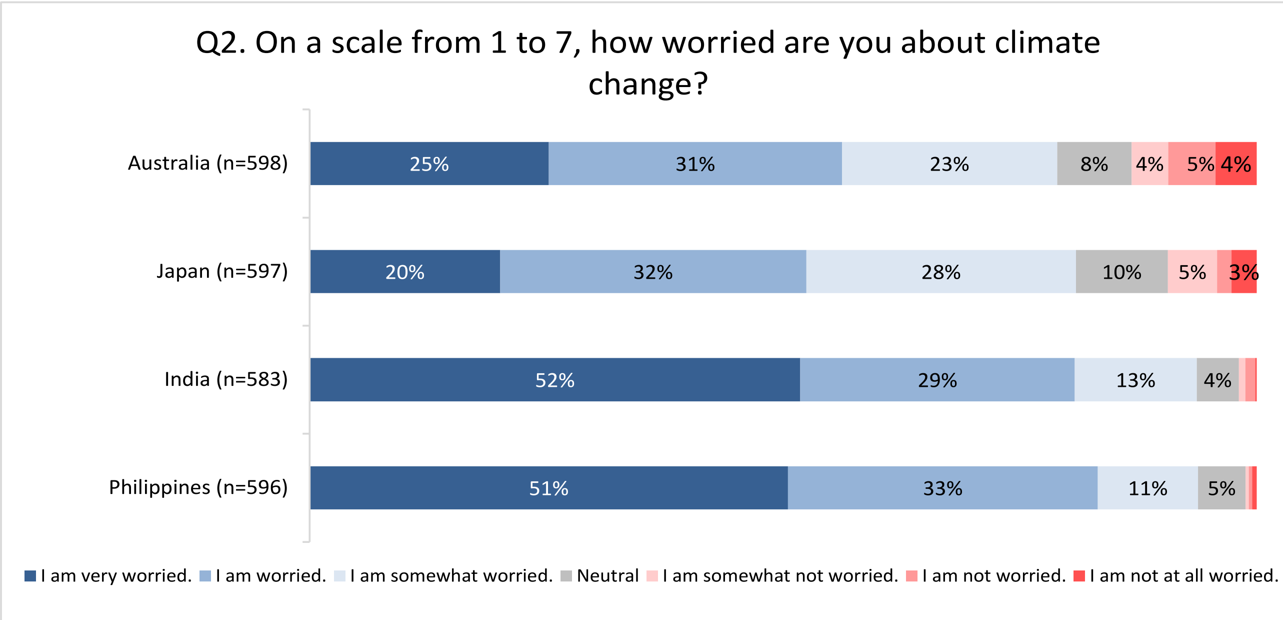

Fig. 1 Responses to Q2. On a scale from 1 to 7, how worried are you about climate change?

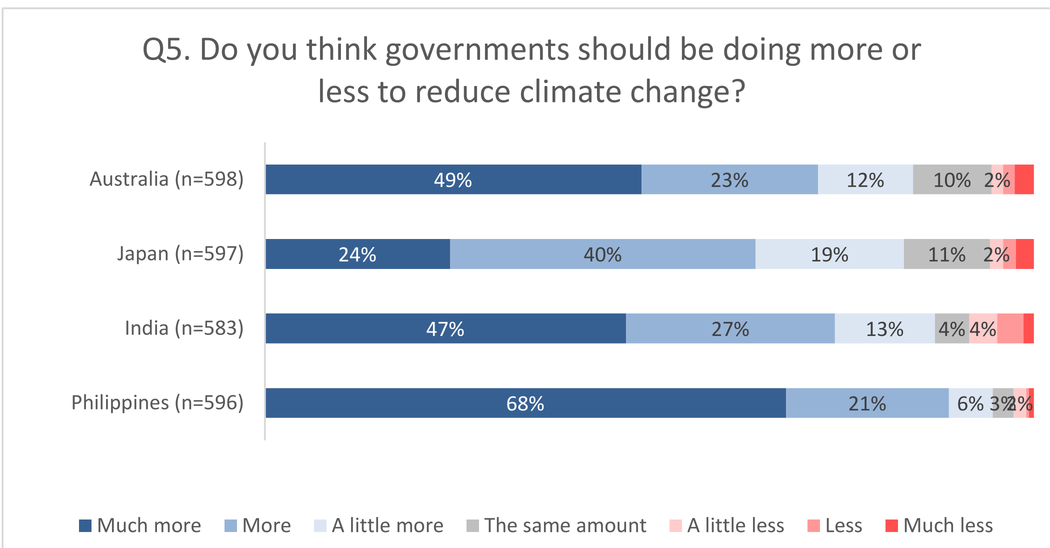

Fig. 2 Responses to Q5. Do you think governments should be doing more or less to reduce climate change?

Analysis of the open-ended questions did not provide a simple interpretation (supplementary Fig. 3).

After asking about prior knowledge of SRM, we presented two SRM scenarios: Scenario A (SRM as a supplement) and Scenario B (SRM as a salvage). We then asked participants questions regarding their comprehension of the elements of the scenarios. Although comprehension is not a prerequisite for forming attitudes toward SRM, it would be useful to examine which aspects of SRM are more difficult to communicate. These results will inform the design of information materials for future research and outreach activities.

The level of comprehension varied with the questions and scenarios presented, although it was generally low. We grouped comprehension questions into five categories: progress in emissions reduction (Q8_1 and Q8_2), temperature exceeding beyond 1.5 degrees (Q8_3 and Q8_4), melting of ice sheets and permafrost (Q8_5 and Q8_6), consideration of SRM or lack thereof (Q8_7), and scale of SRM to

Table 2 One-way, non-parametric analysis of variance on attitudes toward climate change

Country	Questions on climate change						Questions after SRM scenario	
	Q1 Human activities causing climate change	Q2 Worry about climate change	Q3 Personal harm from climate change	Q4 More efforts needed from people	Q5 More efforts required from governments	Q6 Willingness to change life and work to reduce climate change	Q7 Prior knowledge on SRM	Q9 Importance of 1.5-degree goal
Japan	1080.0(a)	938.2(a)	896.8(a)	935.3(a)	922.5(a)	716.6(a)	818.0(a)	970.7(a)
Australia	1069.8(a)	988.4(a)	863.5(a)	1145.4(b)	1184.6(b)	1063.5(b)	982.5(b)	1086.4(b)
India	1219.9I	1412.1(b)	1487.6(b)	1214.7(b)	1181.0(b)	1501.7(c)	1610.4(d)	1352.5(c)
Philippines	1171.2(b)	1417.3(b)	1510.1(b)	1455.7(c)	1462.2(c)	1476.2(c)	1349.6(c)	1344.8(c)
χ^2 (df)	23.2(3)***	283.8(3)***	582.1(3)***	195.5(3)***	212.0(3)***	620.5(3)***	524.1(3)***	196.1(3)***

The results of the Kruskal–Wallis test were all significant at $p < 0.001$, as shown by the significance symbol ***. Mean ranks for the same question (in the same column) with different symbols (a, b, and c) are significantly different at $p < 0.01$ with a post hoc Steel–Dwass test. Q1 is on a 6-point scale (excluding the "don't know" response), Q2, Q4, Q5 on a 7-point scale, and Q3, Q6, Q7 and Q9 on a 4-point scale. A larger value of the mean rank indicates the direction for more concerns/efforts. Note that Q7 and Q9 were asked after the scenario

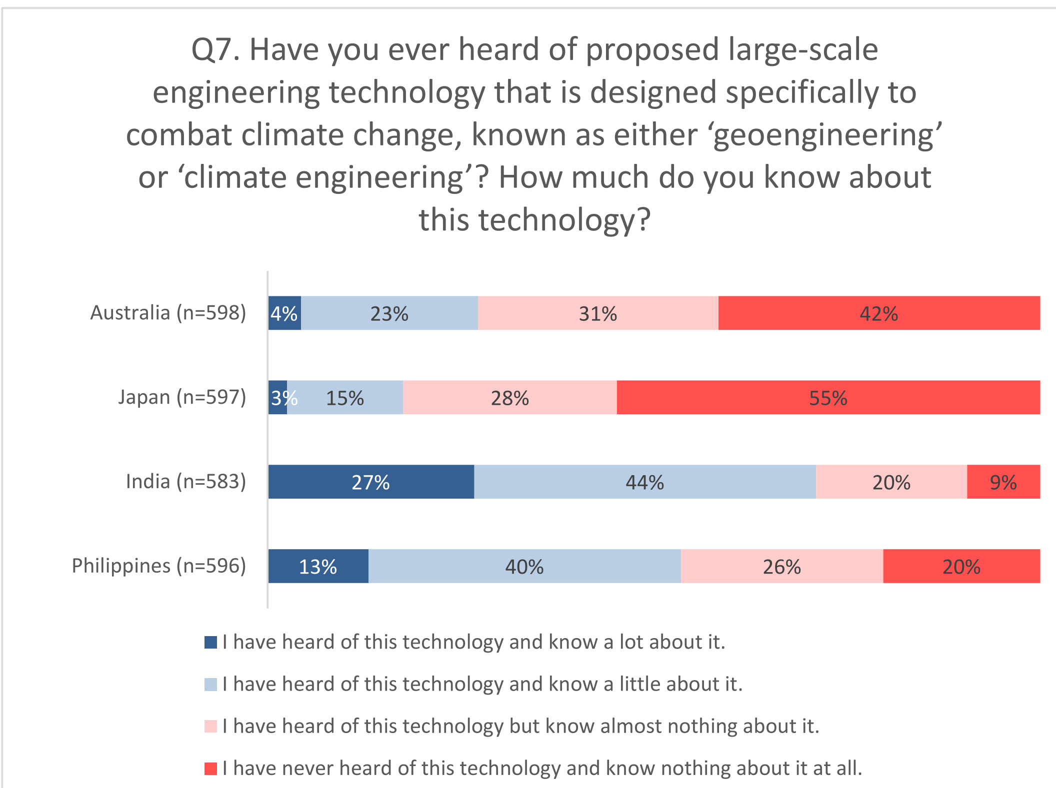

Fig. 3 Have you ever heard of the proposed large-scale engineering technology that is designed specifically to combat climate change, known as either 'geoengineering' or 'climate engineering'? How much do you know about this technology?

be deployed (Q8_8 and Q8_9). Supplementary Fig. ESM 1 shows the proportion of respondents who chose the correct descriptions that matched the scenarios they had read. In general, their comprehension level was low, often less than 50%. Supplementary Fig. ESM 2 shows the distribution of the correct pairs by scenario. The distribution was skewed toward a low number, regardless of the scenario. Random responses should lead to correct answers to a pair of questions with a 25% probability and to a single question with a 50% chance of a correct answer. Some responses were below this threshold. In particular, the share of correct responses for the SRM scale in the supplement scenario was

Table 3 χ^2 independence test between the questions and scenario

Question	Brief description	χ^2	p
Q9	Importance of the 1.5-degree goal	2.75	0.431
Q10_1	Perceived plausibility of ice sheet melting	7.50	0.112
Q10_2	Perceived plausibility of permafrost melting and methane release	2.66	0.617
Q10_3	Perceived plausibility of SRM planning	4.33	0.363
Q10_4	Perceived plausibility of SRM deployment	2.95	0.567
Q11_1	We should use SRM as soon as possible	3.20	0.524
Q11_2	No SRM no matter what	7.75	0.101
Q11_3	Use SRM to contain global warming	10.40	0.034
Q11_4	Use SRM to save time for mitigation	5.62	0.229
Q11_5	No SRM because of environmental impacts	10.24	0.037
Q11_6	No SRM because of moral hazard concern	8.90	0.064

Q9 (importance of the 1.5-degree temperature goal), each of the Q10s (perceived plausibility of SRM scenarios) and Q11s (attitudes toward SRM) were analyzed. The degree of freedom is 4 and the sample size is 2374 for all the questions

consistently lower than 25%, implying difficulty in communication with a moderate level of SRM deployment.

We examined how the responses varied according to the scenario. Table 3 shows the results of a series of χ^2 independence tests between the scenario (supplement vs. salvage) and questions. Included are Q9 (importance of the 1.5-degree goal), Q10 (perceived plausibility or realism of SRM scenarios), and Q11 (attitudes toward SRM). Only a few questions (Q11_3 and Q11_5) exhibited a weak relation with the scenario ($p < 0.05$). The respondents under the salvage scenario tended to support SRM in averting climate change (Q11_3) and did not exclude it from the options, even if there were environmental side effects (Q11_5).

Though the importance of the 1.5-degree temperature goal did not differ between scenarios, there was a between-country difference. It was higher in India and the Philippines than in Australia and Japan (Table 2).

Next, we investigated the plausibility of different aspects of the two scenarios. Again, the between-country differences were much larger than the between-scenario differences, and we present the pooled results. Note that unlike the previous comprehension questions, there is no "correct" response to the plausibility questions. The Indian and Philippine respondents consistently found the scenario elements realistic, including massive ice sheet melting, permafrost melting, planning, and deployment of SRM (Fig. 4 and supplementary Fig. ESM 4). For instance, more than 85% of the respondents in India and the Philippines answered that SRM deployment in the scenarios was either very or somewhat realistic (Fig. 4). The level of perceived plausibility was lower in Australia and Japan. Also, the percentage of respondents giving neutral answers "Neither realistic nor unrealistic" was much higher in Australia and Japan. The differences are statistically significant for the SRM deployment and other aspects (Table 4), with respondents in the Global South feeling that SRM deployment would be more realistic than those in the Global North.

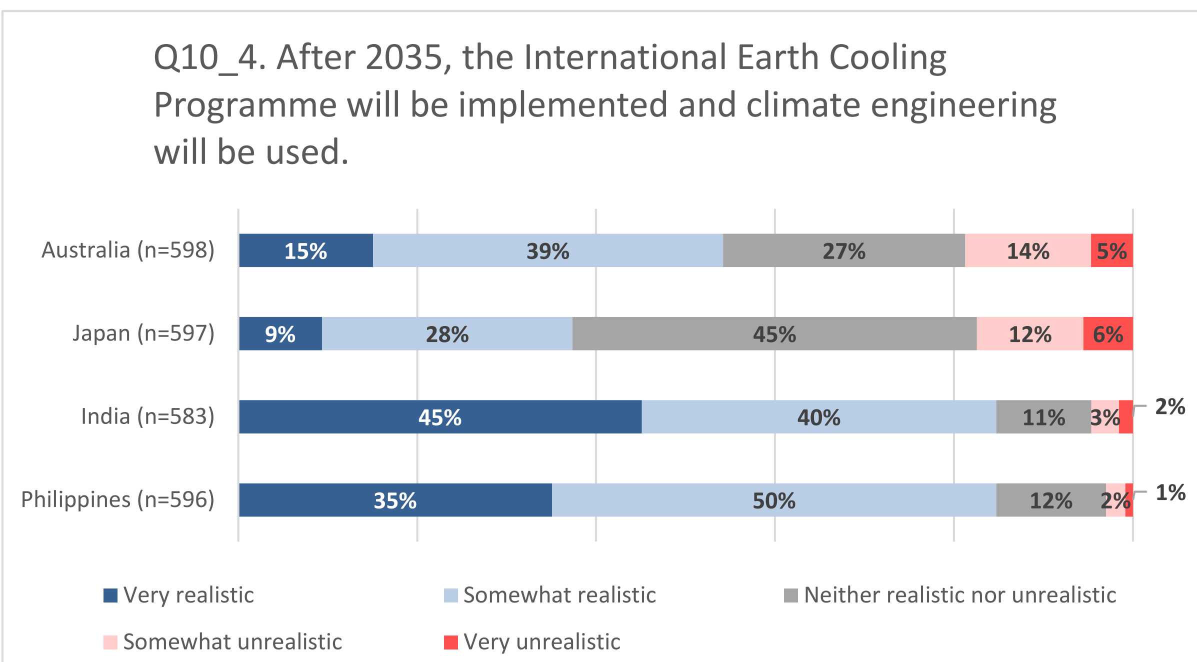

Fig. 4 Responses to Q10 about realism of different aspects of scenarios

Table 4 One-way, non-parametric analysis of variance on scenario elements

Country	Question			
	Q10_1, Ice sheet melting	Q10_2, Permafrost melting	Q10_3, SRM planning	Q10_4, SRM deployment
Japan	982.8(a)	980.2(a)	811.6(a)	823.9(a)
Australia	1124.0(b)	1089.5(a)	1007.3(b)	989.7(b)
India	1332.4(c)	1362.6(b)	1478.0(c)	1507.6(c)
Philippines	1314.5(c)	1322.2(b)	1460.7(c)	1437.0(c)
χ^2 (df)	118.9(3)***	143.0(3)***	462.2(3)***	466.6(3)***

The results of the Kruskal–Wallis test were all significant at $p<0.001$, as shown by the significance symbol ***. Mean ranks for the same question (in the same column) with different symbols (a, b, and c) are significantly different at $p<0.01$ with the post hoc Steel–Dwass test. The ordering of the countries is kept the same as in previous tables, though the mean ranks of India are often larger than those of the Philippines. The directionality is such that a higher mean rank value indicates a higher level of perceived realism

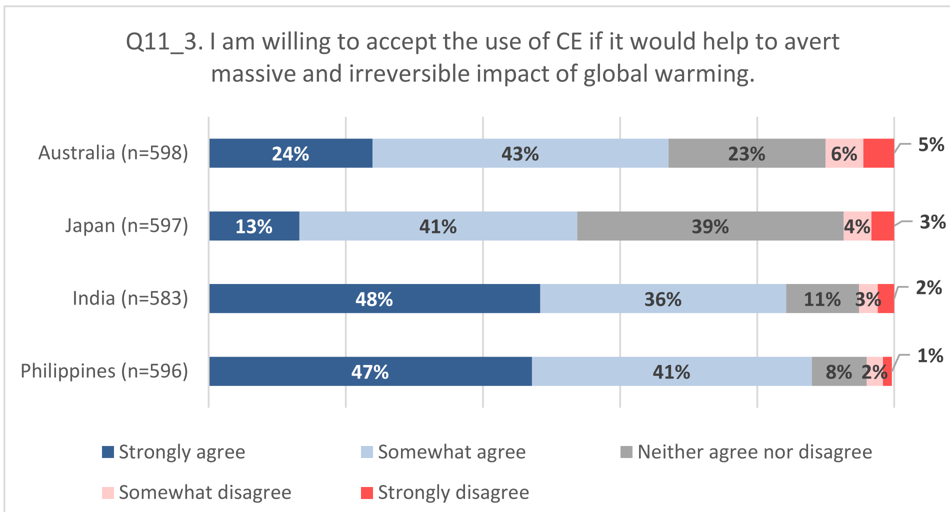

Fig. 5 Responses to Q11_3 about the conditional support for SRM

After questions on the scenarios, we posed questions regarding attitudes toward SRM. Here again, between-country differences stand out compared to between-scenario differences. As in the previous question, respondents from India and the Philippines showed more positive responses to questions about SRM support than did those from Australia and Japan (Q11_1, Q11_3, and Q11_4; Fig. 5 and supplementary Fig. ESM 5). For instance, the share of respondents who either strongly agreed or somewhat agreed with the immediate use of SRM was highest in India (79%), followed by the Philippines (72%), Australia (48%), and Japan (35%) (Q11_1, Supplementary Fig. ESM 4). Notably, more than 50% of the Japanese respondents chose "neither agree nor disagree." In addition, the responses to questions regarding conditional acceptance (Q11_3 and Q11_4) were more favorable than those regarding unconditional deployment (Q11_1), although the magnitude of the differences varied across countries.

Responses were actually ambivalent, however, particularly in India; though 79% of the survey participants either strongly agreed or somewhat agreed with the immediate use of SRM (Q11_1), 44% either strongly or somewhat agreed to the statement "we should never use CE, no matter the situation" (Q11_2). More than 50% of the respondents either strongly or somewhat agreed with not using SRM because of environmental side effects (Q11_5) and moral hazard or reduced incentives for reducing CO_2 emissions (Q11_6). The general tendencies are similar in other countries, though Japanese and Australians tended to choose "neither agree nor disagree" more often.

A statistical analysis showed that there were statistically significant splits between the Global North and the Global South in response to SRM support questions (Q11_1, 3, 4), but the results were not clear for the SRM opposition questions (Q11_2, 5, and 6) (Table 5).

Table 5 One-way, non-parametric analysis of variance on attitudes toward SRM

	Q11_1 We should use SRM as soon as possible	Q11_2 No SRM no matter what	Q11_3 Use SRM to contain global warming	Q11_4 Use SRM to save time for mitigation	Q11_5 No SRM because of environmental impacts	Q11_6 No SRM because of moral hazard concern
Japan	902.1(a)	1156.1(b)	872.6(a)	845.6(a)	1076.4(a)	1028.7(a)
Australia	1015.5(a)	1215.3(b)	1052.1(b)	1007.3(b)	1224.8(c)	1166.9(b)
India	1494.0(c)	1265.7(c)	1403.2(c)	1445.5(c)	1326.5(d)	1367.7(c)
The Philippines	1346.0(b)	1114.6(a)	1427.8(c)	1458.4(c)	1125.5(b)	1190.9(b)
χ^2 (degrees of freedom)	315.3(3)***	17.7(3)***	314.7(3)***	406.2(3)***	50.2(3)***	77.7(3)***

The results of the Kruskal–Wallis test were all significant at $p < 0.001$, as shown by the significance symbol ***. Mean ranks for the same question (in the same column) with different symbols (a, b, and c) are significantly different at $p < 0.01$. A higher value of the mean rank value implies a higher level of agreement of each statement

Factors affecting attitudes toward SRM

For the regression, we combined the responses to similar questions and constructed the following variables after conducting Cronbach's alpha analyses to assess the validity of combining different questions.[3]

For climate change concerns and willingness for action, we used the following two variables:

- The climate concern scale on a 7-point scale (1: I am not at all worried to 7: I am very worried) (Q2).
- The propensity for climate action (two items on a 7-point scale ranging from 1 "much less" to 7 "much more"; Q4, Q5) (Cronbach's α = 0.838).

For SRM, we created a variable that measures the perceived safety of SRM by combining Q12_1 ("CE will help the planet more than it will hurt it."), Q12_2 ("With enough research, I believe CE will turn out to be safe and effective."), and Q12_9 ("If scientists find that CE can reduce the impacts of global warming with minimal side effects, then I would support its use."). The perceived safety of SRM (Q12_1, Q12_2, and Q12_9, each on a 5-point scale (1 = strongly disagree to 5 = strongly agree)) (Cronbach's α = 0.811).

We also included the perceived effectiveness of SRM in rapid cooling (Q13_1, Q13_2, Q13_3, each on a 4-point scale; ranging from 1 (unimportant) to 4 (important)) (Cronbach's α = 0.766).

Variables on values are constructed, following Braun et al. (2018):

- Altruistic values (Q17_1 to Q17_4, each on a 4-point scale from 1 = strongly dissimilar to 4 = very similar; e.g., Q17, "The following gives descriptions of various people. To what extent do you think you are similar or dissimilar to the people described below?" Q17_1, "They believe it is important for everyone to have equal opportunities in life.") (Cronbach's α = 0.79).
- Egoistic value (Q17_5 to Q17_8, each on a 4-point scale from 1 = strongly dissimilar to 4 = very similar) (Cronbach's α = 0.834) (similar to questions on altruistic values).
- Security value (Q18_1 to Q18_4, each on a 4-point scale from 1 = strongly dissimilar to 4 = very similar) (Cronbach's α = 0.764) (similar to questions on altruistic values).

Although we included questions on ecological values (Q16), we excluded them due to their low Cronbach's alpha value (0.526).

Trust in institutions is also found to be related to the SRM support. Since levels of trust in different institutions are well correlated, we developed an indicator of trust in environmental institutions. This combination, for instance, can describe organizations such as the IPCC (environmental and science organization which includes many university researchers as authors):

- Trust in independent bodies (Q19_3 environmental organizations, Q19_5 researchers at universities or government institutions, Q19_6 United Nations and other international organizations; 5-point scales from 1 "strongly distrust" to 5 "strongly trust") (Cronbach's α = 0.848).

Also, for the dependent variables, we use responses to Q11, "Suppose it is the year 2030 and 'Future Scenario 2030' has become a reality. What is your opinion of each

[3] The scale of some variables has been reversed to enable more intuitive interpretation. The scales presented here are those used in the regression analysis.

Table 6 Results of ordinary least square regressions of the composite support variable onto attitudes toward climate change and SRM, values and trust, and sociodemographic variables

Independent variables	Dependent variable		
	Support for SRM		
	Model S1	Model S2	Model S3
Scenario dummy (salvage = 1)	0.148	0.095	0.056
Education dummy (college or above = 1)		0.09	0.062
Gender dummy (female = 1)		− 0.052	− 0.025
Age		− 0.009**	− 0.001
Country dummy (India)		0.799***	0.016
Country dummy (Japan)		0.193	− 0.046
Country dummy (Philippines)		0.821***	0.032
Risk aversion		− 0.140***	− 0.033*
Altruistic values		0.166***	− 0.044*
Egoistic values		0.106***	0.022
Security values		0.143***	0.022
Trust in NGO, researchers, and UN			0.074***
Concern about harms from climate change			0.090*
Belief in the need for further climate action			0.044*
SRM can be used safely			0.611***
SRM can cool fast			0.163***
Constant	11.558***	7.050***	1.297***
Observations	2261	2261	2261
Adjusted R^2	0.0004	0.233	0.56
F statistic	1.921 (*df* = 1; 2259)	63.512*** (*df* = 11; 2249)	180.618*** (*df* = 16; 2244)
Note:	+$p<0.1$; *$p<0.05$; **$p<0.01$; ***$p<0.001$		

of the following statements related to the future use of climate engineering (CE)?" Responses are based on on a 5-point scale from "strongly disagree = 1" to "strongly disagree = 5". We use one scale for the support of SRM, which is a combination of responses to:

- Q11_1 ("We should use CE as soon as possible");
- Q11_3 ("I am willing to accept the use of CE if it would help to avert massive and irreversible impact of global warming."); and
- Q11_4 ("I am willing to accept the use of CE if it would help to give us more time to cut CO2 emissions.") (α = 0.829).

We constructed another scale for the opposition to SRM, which bundles:

- Q11_2 ("We should never use CE, no matter the situation" on the same scale);
- Q11_5 ("We should not use CE because CE may cause harmful impacts on the environment"); and
- Q11_6 ("We should not think of using CE because it will take away people's motivation to reduce CO_2 emissions.") (α = 0.812).

Tables 6 and 7 show the multiple regression results of the three models for SRM support and opposition, respectively. Different blocks were sequentially added: (1) the model based on the type of scenario (SRM as supplement vs. SRM as salvage), (2) model with additional variables on sociodemographic characteristics, values, and trust, and (3) full model that includes attitudes toward climate change and SRM.

The scenario is only weakly statistically significant for opposition to SRM, but not for support (Models S1 and O1). This did not change with the inclusion of the additional variables.

When variables on sociodemographic characteristics were added (Models S2 and O2), age and some of the country dummies and values were found to be statistically significant. Females tended to oppose SRM (Model O2). For Model S2, the Indian and Philippine dummies are

Table 7 Results of ordinary least square regressions of the composite opposition variable onto attitudes toward climate change and SRM, values and trust, and sociodemographic variables

Independent variables	Dependent variable		
	Opposition to SRM		
	Model O1	Model O2	Model O3
Scenario dummy (salvage = 1)	− 0.215 +	− 0.234*	− 0.219 +
Education dummy (college or above = 1)		− 0.03	− 0.028
Gender dummy (female = 1)		0.335**	0.329**
Age		− 0.015**	− 0.017***
Country dummy (India)		− 0.195	− 0.022
Country dummy (Japan)		− 0.474**	− 0.339 +
Country dummy (Philippines)		− 0.663***	− 0.430*
Risk aversion		0.017	− 0.024
Altruistic values		− 0.056 +	0.003
Egoistic values		0.277***	0.294***
Security values		− 0.03	0.007
Trust in NGO, researchers, and UN			0.071*
Concern about harms from climate change			− 0.008
Belief in the need for further climate action			− 0.069*
SRM can be used safely			− 0.272***
SRM can cool fast			− 0.02
Constant	9.460***	8.384***	10.510***
Observations	2261	2261	2261
Adjusted R^2	0.001	0.099	0.133
F statistic	2.929 + (*df* = 1; 2259)	23.644*** (*df* = 11; 2249)	22.681*** (*df* = 16; 2244)
Note	+$p<0.1$; *$p<0.05$; **$p<0.01$; ***$p<0.001$		

statistically significant and positively related to SRM support. In Model O2, the Japan and Philippines dummies were negatively related to opposition. Taken together, Philippine respondents in particular tend to support SRM. Risk aversion is negatively related to SRM support (Model S2). The directionality of the egoistic value is complicated, as it is related to both the support of and opposition to SRM in a statistically significant manner.

In the full models (Models S3 and O3), some of the coefficients of the sociodemographic and value variables no longer become statistically significant, but their signs do not change, except for the altruistic value for SRM support (Model S3). The attitudes toward SRM were as expected; respondents who were more concerned about climate change and believed in SRM safety and effectiveness were inclined to support SRM and vice versa (note the sign for Model O3). The adjusted R^2 significantly improved from Models S2 to S3, whereas the improvement was modest between Models O2 and O3. The adjusted R^2 for Model S3 is much higher than that for O3.

Sensitivity analysis on the inclusion of the scenario comprehension variable showed that the overall results were not affected by this variable (although the statistical significance of some variables changes) (supplementary Tables ESM 1 and 2).

Discussion and conclusions

This study presents the results of a 2022 online survey on public attitudes toward SRM in four Asia–Pacific countries: Australia, Japan, India, and the Philippines. We present two SRM scenarios that differ in the level of global mitigation efforts and risk of climate tipping points (e.g., ice sheet melting). The level of comprehension of the scenario details was generally low.[4] Scenarios were found to have only a small effect on opposition to SRM. As with the results of our previous, pre-pandemic study conducted in 2016 (Sugiyama et al. 2020), those from emerging and developing economies (India and the Philippines) were more supportive of SRM

[4] Although in a different context, a recent survey experiment study also found that varying the framing of SRM in media-style articles had a limited effect on the respondents' attitudes toward SRM (Baum et al. 2024b).

than those from Australia and Japan. However, their attitudes were ambivalent, as the majority simultaneously exhibited support for SRM and concerns about various risks.

In this research, explanatory variables other than the presented scenario that could influence support for, or opposition to, SRM were selected in accordance with the literature. However, the general caveat regarding this type of study, that potentially important explanatory factors may have been omitted (omitted variable bias), may also apply to this case. The lower adjusted R^2 value for Model O3 compared to Model S3 suggests that the above concerns should be taken into account, especially when analyzing the explanatory factors for dissenting opinions. Although prior research has tended to focus more on the analysis of explanatory factors for approval, it is expected that there are mechanisms at work in the formation of oppositional attitudes that are not merely the reverse of those for support. However, further exploration of this point is left for future research.

One interesting observation from the survey was that the respondents struggled to comprehend the details of the scenarios. In particular, the small scale of SRM deployment featured in the "supplement" scenario seems not to be understood well by survey respondents. This suggests that while a scale of deployment is a significant aspect of SRM scenario design (Kosugi 2013; Keith and MacMartin 2015; MacMartin et al. 2018; Sugiyama et al. 2018), especially for modeling research (Irvine et al. 2019; MacMartin et al. 2022), it is difficult for the general public to grapple with a difference in scale of SRM deployment and its implication for side effects and governance challenges.

One possible reason why the respondents struggled to understand the details of the scenarios may be the low level of awareness about abrupt or irreversible damage from climate change. A recent UK survey study (Bellamy 2023) found that the general public is largely unaware of climate tipping points. As our study hinged on the concept of tipping points for scenario descriptions, a lack of public awareness of tipping point risks might explain partly the low level of scenario comprehension in our survey.

Likewise, our study is limited by the narrow focus of scenario narratives regarding potential SRM deployment in the future. As a first attempt to incorporate scenario assumptions into public perception research on SRM, our scenario descriptions do not encompass a wide range of possible deployment strategies. The focus was rather on the level of global mitigation efforts and the role of SRM in prevention of climate tipping points. The limited effect of scenarios on SRM perception might be due to this narrow focus of our scenario narratives. Besides, our scenarios did not present any information on distributional impacts of SRM across different countries (e.g., the country of residence vs. the Global North vs. the Global South), which might have led to reduced salience of our scenarios to the respondents.

For future research, it will be interesting to explore the effect of a different set of possible SRM deployment scenarios which consider more diverse socio-political dimensions of deployment strategies including key actors, geopolitical contexts, and distributional implications, based on the existing studies of qualitative scenario development (Boettcher et al. 2016; Parson and Reynolds 2021). Of course, such scenarios should be mindful of taking into account physical impacts and damage of climate change including the potential risks of climate tipping points. But they could also consider diverse mitigation options such as demand-side solutions and large-scale CDR because SRM deployment cannot exist in isolation from other climate solutions. It is, however, challenging to appropriately examine public perceptions of such complex scenarios with delicate trade-offs and synergies between different policy options through survey experiment methods. A methodological innovation in survey research would probably be needed for further research.

While SRM remains a highly politically controversial topic, the urgency of climate change would likely increase public attention to SRM as a potential policy option in the future. Nevertheless, whether or not to research on SRM is still deeply contested and there is now a call by high-level political figures for adopting a moratorium on the deployment and large-scale outdoor experiment on SRM (Climate Overshoot Commission 2023). But public opinions are never set in stone. Attitudes toward SRM are susceptible to changes in social, political and environmental contexts. Although it is hard to say how public attitudes toward SRM will evolve in the future, some unexpected events might shift public opinion from skepticism to enthusiasm. Usually public perception research is designed to capture a snapshot of public views and understandings of certain issues at a certain point of time but it could also be designed to anticipate a potential shift in public attitudes by including possible future scenarios into survey experiments. Such survey research might be able to inform policymakers about how people might react to future SRM debates when they start to consider more seriously SRM as a potential option and have broader public discussions over the governance of SRM development and deployment in the years to come.

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Declarations

Conflict of interest The authors have no competing interests to declare that are relevant to the content of this article.

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