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Public opinion about solar radiation management: A cross-cultural study in 20 countries around the world

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Abstract
Some argue that complementing climate change mitigation measures with solar radiation management (SRM) might prove a last resort to limit global warming to 1.5 °C. To make a socially responsible decision on whether to use SRM, it is important to consider also public opinion, across the globe and particularly in the Global South, which would face the greatest risks from both global warming and SRM. However, most research on public opinion about SRM stems from the Global North. We report findings from the first large-scale, cross-cultural study on the public opinion about SRM among the general public (N=2,248) and students (N=4,583) in 20 countries covering all inhabited continents, including five countries from the Global South and five 'non-WEIRD' (i.e. not Western, Educated, Industrialised, Rich, and Democratic) countries from the Global North. As public awareness of SRM is usually low, we provided participants with information on SRM, including key arguments in favour of and against SRM that appear in the scientific debate. On average, acceptability of SRM was significantly higher in the Global South than in the 'non-WEIRD' Global North, while acceptability in the 'WEIRD' Global North was in between. However, we found substantial variation *within* these clusters, especially in the 'non-WEIRD' Global North, suggesting that countries do not form homogenous clusters and should thus be considered individually. Moreover, the average participants' views, while generally neither strong nor polarised, differed from some expert views in important ways, including that participants perceived SRM as only slightly effective in limiting global warming. Still, our data suggests overall a conditional, reluctant acceptance. That is, while on average, people think SRM would have mostly negative consequences, they may

Extended author information available on the last page of the article

still be willing to tolerate it as a potential last resort to fight global warming, particularly if they think SRM has only minor negative (or even positive) impacts on humans and nature.

Keywords Climate engineering · Public opinion · Perceived risks · Perceived benefits · Perceived justice · Technology acceptance

1 Introduction

Even if we succeeded in mitigating climate change[1] immediately and drastically, global warming will most likely reach 1.5 °C above pre-industrial levels by 2040 and surpass 1.5 °C in the decades thereafter, with severe consequences for human and non-human life around the world (IPCC 2018, 2022, 2023). Therefore, some propose to complement climate change mitigation measures with solar radiation management[2] (SRM; Crutzen 2006; MacMartin et al. 2018). SRM technologies would reflect a small amount of sunlight back into space, for example, by injecting reflective aerosols into the stratosphere, resulting in reduced global temperatures (Crutzen 2006). Model experiments indicate that SRM, specifically stratospheric aerosol injection, could limit warming to 1.5 °C (Jones et al. 2018; Tilmes et al. 2020) and reduce severe climate risks in almost all regions worldwide (Irvine and Keith 2020).

However, SRM also raises serious concerns (e.g. Robock 2016; see also IPCC 2022, 2023). First, SRM does not address the root cause of global warming, greenhouse gas (GHG) emissions (Kiehl 2006; Owen 2014), nor its secondary effect of ocean acidification (MacMartin et al. 2018), which threatens marine ecosystems and related ecosystem services (Doney et al. 2020). Further, experts are concerned that using or even only considering the use of SRM might deflect both politicians and the public from immediate and drastic climate change mitigation – so called 'mitigation deterrence' (Lin 2013; McLaren 2016). Additionally, SRM poses multiple risks, including rapid temperature increases if SRM was suddenly stopped, and changes in precipitation (IPCC 2018, 2022, 2023; cf. Parker and Irvine 2018). These risks – along with the benefit of reduced temperatures – would cross borders and affect countries beyond those deploying SRM (Brent et al. 2015; Robock et al. 2008). Moreover, the effects of SRM would be unequally distributed: some countries would primarily benefit from moderate temperatures, while others – including those that contributed least to global warming (Carr and Yung 2018; Rahman et al. 2018) – would disproportionally suffer from changes in precipitation (Jones et al. 2018; Tilmes et al. 2013; cf. Irvine and Keith 2020).

The fact that the effects of SRM would be transboundary and unequally distributed raises important ethical concerns about distributive justice and the governance of SRM (Macnaghten and Szerszynski 2013; Táíwò and Talati 2021). Notably, experts mostly agree that decisions around SRM should be taken multilaterally (Barrett 2014; Ghosh 2018; Morrow 2020) and include those countries and ethnic groups that might suffer disproportionately from SRM, particularly countries from the Global South (Carr and Yung 2018; Rahman

[1] Mitigation measures include greenhouse gas emission reductions and carbon dioxide removal (e.g. IPCC 2018).

[2] The IPCC (e.g. IPCC 2018) refers to the group of technologies discussed here as Solar Radiation Modification.

et al. 2018; Táíwò and Talati 2021). Further, to ensure that non-technical decisions around SRM are made in a democratic and socially responsible manner, and because public acceptance is one pre-condition for implementation, these decisions should consider not only the opinions of SRM experts but also of the public (Carr et al. 2013; Carr and Yung 2018; Wieners et al. 2023).

Among the emerging literature on public opinion about geoengineering in general (see Cummings et al. 2017), only few studies have examined public opinion about SRM in particular, and these have several limitations. First, many studies are based on qualitative data with small samples (e.g. Carr and Yung 2018; Corner et al. 2013), which are less suitable for describing prevalent public opinion (Wright et al. 2014). Second, multiple studies have examined perceived risks and benefits of SRM (e.g. Mercer et al. 2011; Sütterlin and Siegrist 2017; Visschers et al. 2017), yet few studies have researched impacts of perceived distributive justice of SRM (Gregory et al. 2016; Klaus et al. 2020; see also McLaren et al. 2016). Third, most research on public opinion about SRM stems from a few 'WEIRD' (i.e. Western, Educated, Industrialised, Rich, and Democratic; Henrich et al. 2010) countries from the Global North, especially the UK (see Burns et al. 2016; Cummings et al. 2017; IPCC 2022). Only two publications (Sugiyama et al. 2020; Visschers et al. 2017) focused on non-specialist[3] public opinion about SRM in the Global South, even though they are arguably the most relevant public perspectives as the Global South is most vulnerable to risks from both global warming and SRM (Carr and Yung 2018; Rahman et al. 2018). The two studies suggest that public opinion on SRM in the Global South might be more positive than public opinion in the 'WEIRD' Global North (Sugiyama et al. 2020; Visschers et al. 2017). In general, there is concern that despite the majority of the world's population being 'non-WEIRD', psychological research more generally is mainly conducted in 'WEIRD' countries, even though evidence suggest that key cognitive and motivational processes might differ between 'WEIRD' and 'non-WEIRD' populations (Henrich et al. 2010).

1.1 Overview of the present study

To address these limitations, we, researchers from all around the world, joined forces to conduct the first large-scale, quantitative, cross-cultural study on public opinion about SRM, specifically stratospheric aerosol injection, targeting also countries from the Global South and 'non-WEIRD' countries. As public awareness of SRM is usually low (e.g. Mercer et al. 2011; Pidgeon et al. 2012), we provided participants with information on SRM, including key arguments in favour of and against SRM that appear in the scientific debate. Then, we investigated people's beliefs about global warming (as SRM aims at limiting global warming) and perceptions about the implementation and use of SRM (hereinafter called perceptions about SRM), which reflected the key arguments in favour of and against SRM. Next, we investigated whether and to what extent belief in global warming and perceptions about SRM are associated with and uniquely explain the acceptability of the implementation and use of SRM (hereinafter called acceptability of SRM). The main focus of our study was on whether belief in global warming and perceptions about SRM and their associations with acceptability of SRM differed across country clusters (see subsection 2.1). Specifically, we grouped the countries along two dimensions, (a) Global North versus Global South (Sugi-

[3] For specialists' (e.g. climate change specialists or environmental leaders) opinions about SRM from the Global South, see Carr and Yung (2018); Delina (2021); Winickoff et al. (2015).

yama et al. 2020; Visschers et al. 2017) and (b) 'WEIRD' versus 'non-WEIRD' countries (Henrich et al. 2010), as these groups are likely to differ in their opinions on SRM.

2 Methods

2.1 Selection of countries and country clusters

In 2018, the Dutch core team invited through their network research teams from 31 countries with the aim to include at least one country from each inhabited continent to achieve geographically comprehensive data that captures opinions around the globe (see Supplementary Information A [SI-A]). The contacted teams were from three North American, three South American, five African, two Australian/Oceanian, eight Asian, two Eurasian, and eight European countries (including the Netherlands). Of these, eleven countries (including six from the Global South) dropped out because the country team declined our invitation, because the minimally required sample size was not achieved or because of low data quality (see SI-A). Our final sample included 20 countries spanning all inhabited continents.

To compare between country clusters, we grouped the 20 countries along two dimensions, Global North versus Global South (Solarz 2019) and 'WEIRD' versus 'non-WEIRD' (Henrich et al. 2010). For information on how we assigned the countries to the clusters, see SI-A. The three resulting clusters were: (a) five 'non-WEIRD' countries from the Global South (hereinafter referred to as the Global South); (b) five 'non-WEIRD' countries from the Global North (hereinafter referred to as the 'non-WEIRD' Global North); and (c) ten 'WEIRD' countries from the Global North (hereinafter referred to as the 'WEIRD' Global North; see Fig. 1; Table 1).

2.2 Country characteristics

To help interpret potential differences in opinions about SRM between countries, we collected secondary data about the countries sampled. We included climate change vulnerability (see Fig. 7.2 in IPCC 2022) as research suggests that vulnerable populations might be more open to SRM because they are desperate to limit global warming (Carr and Yung 2018). In our sample, vulnerability ranged from very high (in Nigeria) to very low (in most of the 'WEIRD' Global North; see Table 1).

Next, we considered two cultural dimensions that could affect public opinion about SRM, namely technology affinity (World Values Survey; Inglehart et al., 2017–2021) and uncertainty avoidance (The Culture Factor Group 2023; see also Hofstede et al. 2010). While, on average, the Global South, the 'non-WEIRD' Global North, and the 'WEIRD' Global North differed with regard to these cultural dimensions, heterogeneity within these clusters was at least as substantial (see Table 1).

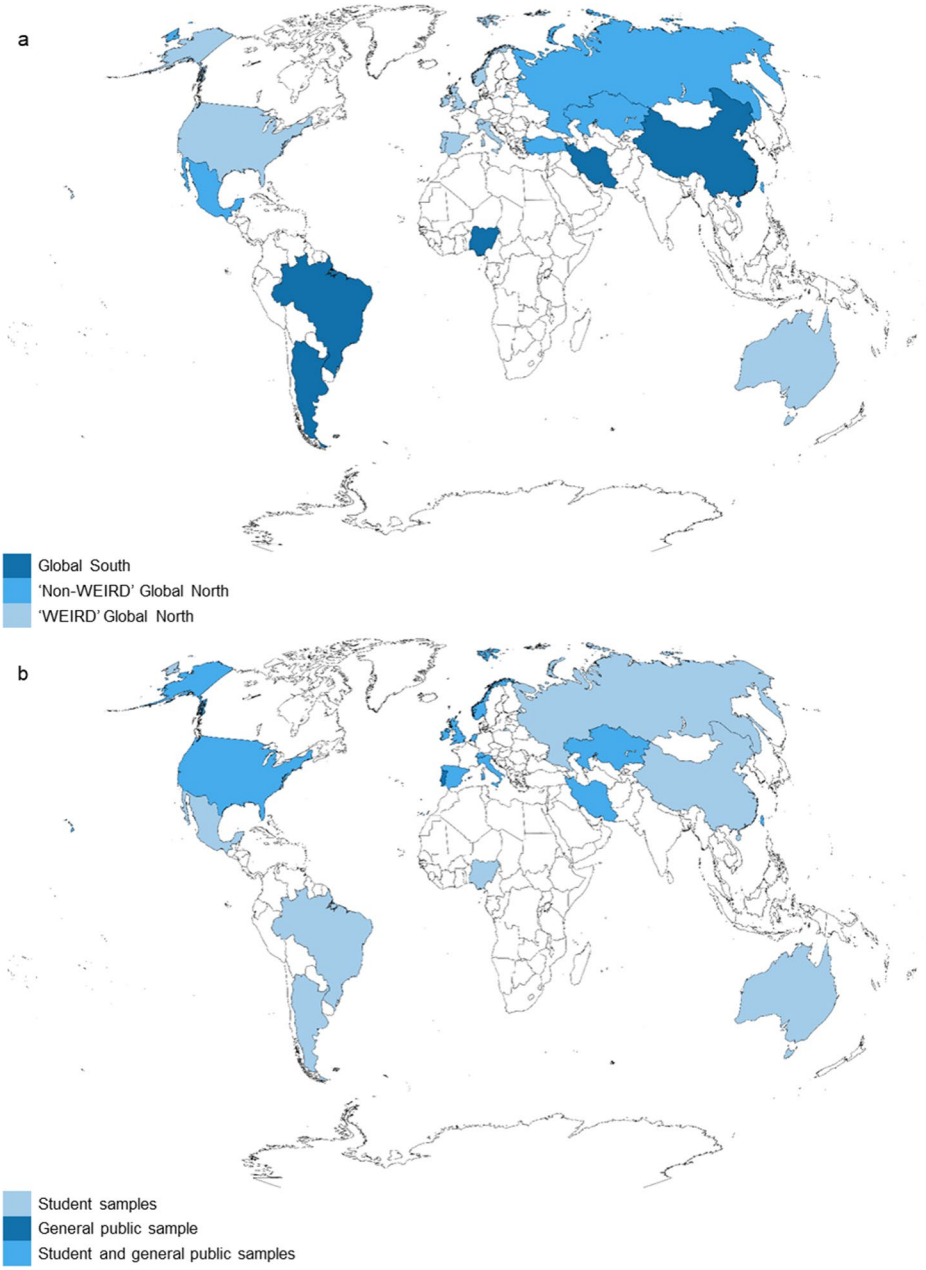

Fig. 1 Countries included in our study. **a**: Countries categorised according to the Global North-South divide (Solarz 2019; The Group of 77, n.a.) and their 'WEIRD'ness (Henrich et al. 2010). **b**: Countries categorised according to type of sample. Graphs prepared with MapChart (https://www.mapchart.net/)

Table 1 Overview of sampled countries, sample sizes, and background variables per country

Cluster	Country	Sample sizes		Background variables		
		Students	General public	Climate change vulnerability[1]	Technology affinity[2]	Uncertainty avoidance[3]
Global South	Argentina	210	--	Low	43.0%	86
	Brazil	210	--	Low	66.9%	76
	China	187	--	Medium	92.5%	30
	Iran	193	170	Medium	86.2%	59
	Nigeria	175	--	Very high	83.8%	55
	Overall / Average	975	170	Low to very high	74.48%	61.2
'Non-WEIRD' Global North	Kazakhstan	160	141	Very low to low	72.6%	88
	Mexico	208	--	Medium	56.9%	82
	Russia	217	--	Low	73.9%	95
	Taiwan	260	232	Medium	79.8%	69
	Turkey	410	--	Medium	54.6%	85
	Overall / Average	1,255	373	Very low to medium	67.56%	83.8
'WEIRD' Global North	Australia	114	--	Very low	49.4%	51
	Ireland	139	191	Very low	n.a.	35
	Italy	173	168	Very low	n.a.	75
	Netherlands	211	262	Very low	48.1%	53
	Norway	441	207	Very low	n.a.	50
	Portugal	--	167	Very low	n.a.	99
	Spain	198	195	Very low	n.a.	86
	Switzerland	222	96	Very low	n.a.	58
	UK	194	187	Very low	56.6%	35
	USA	661	232	Low to very low	54.2%	46
	Overall / Average	2,353	1,705	Very low to low	52.08%	58.8
Total		4,583	2,248			

Note.[1] Based on Fig. 7.2. of the IPCC report 'Climate Change 2022: Impacts, Adaptation and Vulnerability' (IPCC 2022). [2] Based on wave 7 of the World Values Survey (Inglehart et al., 2017–2021). Presented are the percentage of participants selecting the response option "good thing" to question 44 whether more emphasis on technology in future is a good or a bad thing. [3] Scores in uncertainty avoidance, as measured by The Culture Factor Group (2023) and building on research by Hofstede et al. (2010), reflect "the extent to which the members of a culture feel threatened by ambiguous or unknown situations and have created beliefs and institutions that try to avoid these". n.a. = not available.

2.3 Data collection procedure

In spring and autumn 2019, we conducted a quantitative online questionnaire among the general public and/or among students[4] in the 20 countries studied (and in the four countries excluded during or after data collection, see SI-A). The approaches for participant recruitment and rewarding differed between subsamples (see SI-A). Recruitment methods included panel services, email lists, and social media. If rewards were given, they included course credits, cash tokens, and vouchers.

[4] For pragmatic reasons, we also collected data among students, as some of the co-authors, especially from the Global South and from the 'non-WEIRD' Global North, did not have the opportunity to collect data from the general public. Doing so also enabled us to examine whether opinions about SRM of students and the general public differed.

Study participation was voluntary and followed informed consent protocols. The study received ethical clearance by the Ethical Committee of Psychology at the University of Groningen, where the first author of the study was based. In each country, additional ethical clearance (or an exemption thereof) was attained for data collection among the specific subsample, with five exceptions, namely Norway, with no requirement to obtain additional clearance, and Argentina, China, Iran, and Nigeria, where we had no option to seek ethical clearance.

2.4 Samples

Information on the excluded data in the 20 countries studied is presented in SI-A. The final student sample consisted of 4,583 participants, with 2,972 women and 1,547 men; 61 participants did not indicate their gender. Their mean age was 22.26 years ($SD = 5.60$). The majority (61.5%) studied a subject from social sciences and humanities, followed by engineering and natural sciences (28.0%), medical and health sciences (11.4%), and any other field (4.3%; students could follow more than one subject). Prior knowledge about SRM was limited with 63.5% of participants knowing 'nothing at all' and 25.3% knowing only 'a little'. For the demographics and knowledge levels per student subsample, see SI-A.

The general public sample consisted of 2,248 participants (see SI-A for the demographics and knowledge levels per sample). While somewhat more women (55%) participated in our study than men did (44%), the vast majority of the subsamples had similar gender distributions as the respective population. In general, younger people were overrepresented across the samples ($M = 41.70$ years; $SD = 15.47$), except in the subsamples from the UK and the USA, which were representative with regard to age. Participants had mostly a higher (55.5%) or a medium (35.2%) level of education and people with lower education were underrepresented in all countries, except in the US subsample, which was also representative in terms of education levels. With 60.8% of participants knowing 'nothing at all' about SRM and 24.5% knowing only 'a little', prior knowledge about SRM was limited. Given that the samples are not fully representative of the respective population, and because countries might differ from each other with regard to these demographics, we examined whether this might have affected our findings. For age and gender this seems not to be the case as belief in global warming as well as perceptions about and acceptability of SRM were only weakly related with age and gender (i.e. mostly small effects; Cohen 1992). Education levels, however, were substantially related to some of these variables (i.e. medium to large effects; Cohen 1992; see SI-D). To reduce a potential bias in our findings, we thus controlled for education levels in the ANCOVAs we ran (see subsection 2.6 and SI-C).

We ran sensitivity power analyses (Faul et al. 2009) with G*Power 3.1.9.7 to specify the effect size we were able to detect with the achieved sample sizes, given a power of 0.80 and analysis-specific α-levels (see SI-A). In the most demanding type of analysis used (i.e. the omnibus F-test of the multiple regression analyses; see SI-C), the smallest effect sizes we were able to detect with the achieved sample sizes ranged from $f^2 = 0.04$, which is a small effect, to $f^2 = 0.26$, which is a medium effect (Cohen 1992; for the details, see SI-A). This is satisfactory as studies analysing the explanatory factors of public acceptability of SRM found large effects in the omnibus F-test (e.g. Visschers et al. 2017).

2.5 Questionnaire

We prepared the questionnaire in English. In non-English speaking countries, the local researchers translated the questionnaire to the dominant local language and back to English. See SI-B for the language used per country. Completion of the questionnaire took around 20 min. Below we outline the information on SRM provided to participants and the measures used in this study. Detailed information on the content of the questionnaire, including information on the measures not used in this study, are presented in SI-B.

2.5.1 Information on SRM

The complete information on SRM we provided is presented in SI-B. First, we explained the aim of SRM (i.e. cool the earth) and how it could be achieved through stratospheric aerosol injection. Then, we presented the key arguments in favour of and against SRM that appear in the scientific debate. The arguments in favour of SRM included that SRM could limit global warming to below 1.5ºC and could thus help reduce some of the worst consequences of global warming (IPCC 2018; Jones et al. 2018; Tilmes et al. 2020). The arguments against SRM included that it would not address the main cause of global warming (Kiehl 2006; Owen 2014), could change precipitation patterns (Jones et al. 2018; Tilmes et al. 2013; cf. Irvine and Keith 2020), cause mitigation deterrence (Lin 2013; McLaren 2016), and that its effects would differ significantly across regions with some countries also suffering (Robock et al. 2008; Tilmes et al. 2013). We closed with information on governance issues related to SRM.

The information was based on information texts used in previous cross-cultural research (Visschers et al. 2017) and on the section on SRM of the 2018 IPCC report (IPCC 2018). It was carefully reviewed by co-author AR, an expert on SRM who contributed to the section on SRM in the 2018 IPCC report, and pretested among lay-people with regard to its comprehensibility.

2.5.2 Measures

Detailed information on the measures and, in case of multi-item measures, on the internal consistencies are presented in SI-B. We adapted existing scales to measure belief in global warming (van Valkengoed et al. 2021) and acceptability of SRM (Contzen et al. 2021) and designed new items to assess the different perceptions about SRM. These concerned the key arguments in favour of and against SRM. Specifically, items reflected the perceived impact of SRM on global warming (IPCC 2018; Jones et al. 2018; Tilmes et al. 2020), on the cause of global warming (Kiehl 2006; Owen 2014), on mitigation efforts (Lin 2013; McLaren 2016), and on humans and nature (IPCC 2018, 2022, 2023). Moreover, we measured the perceived monetary costs of SRM, and beliefs related to the distribution of the costs and benefits of SRM between countries (Robock et al. 2008; Tilmes et al. 2013).

All scales applied bipolar response scales ranging from −3 (representing the negative pole) to +3 (representing the positive pole) with 0 being “neither nor”. All response options were labelled with words to ensure that all participants had the same understanding of the different response options.

2.6 Analysis approach

Detailed information on the analyses is presented in SI-C. We first assessed people's belief in global warming and their perceptions about and acceptability of SRM, and whether beliefs, perceptions and acceptability differed across countries and country clusters. To this end, we ran several ANCOVAs for both the student and the general public sample.

Next, we investigated whether and to what extent belief in global warming and the six perceptions about SRM were significantly associated with acceptability of SRM and whether these associations differed across countries and clusters. For this, we ran simple regression analyses per country, separately for students and the general public. For both full samples and for each country cluster, we ran Generalised Estimating Equations (GEEs; Zeger and Liang 1986) that accounted for the nested structure of the data (i.e. participants nested in countries).

We then tested to what extent belief in global warming and the six perceptions about SRM *uniquely* explained acceptability of SRM (when controlling for all other beliefs) and whether these unique relationships differed across countries and country clusters. For each country, we ran a multiple regression analysis for students and/or the general public. For both full samples and for each country cluster, we ran a GEE.

Additional ANCOVAs, regression analyses and GEEs were run to investigate potential differences in findings between the general public and student samples. These comparisons are presented in SI-G.

All analyses were performed using IBM SPSS Statistics for Windows, Versions 27 and 29. With exception of the GEEs, for which bootstrapping is not available, all CIs were estimated with bias-corrected and accelerated (BCa) bootstrapping based on 5,000 resamples.

3 Results

3.1 Belief in global warming and perceptions about SRM differed somewhat between country clusters

We first examined belief in global warming and people's perceptions about SRM and whether these beliefs and perceptions differed across country clusters. The results are displayed in Fig. 2 and the detailed results in SI-D.

In all countries, participants on average believed that global warming is happening, human-made, and harming humans and nature. In the 'WEIRD' Global North, belief in global warming was, on average, significantly higher than in the Global South, while beliefs in the 'non-WEIRD' Global North were in between. Heterogeneity within country clusters was substantial. For example, participants in the Global South were among those who believed in global warming least strongly (i.e. students in Nigeria) and most strongly (i.e. students in Argentina).

In most countries, participants perceived SRM as only (very) slightly effective in limiting global warming. While heterogeneity between countries was low overall, in the Global South (i.e. Iran), the general public perceived SRM as significantly more effective than the general public in the 'WEIRD' and 'non-WEIRD' Global North, in particular Kazakhstan.

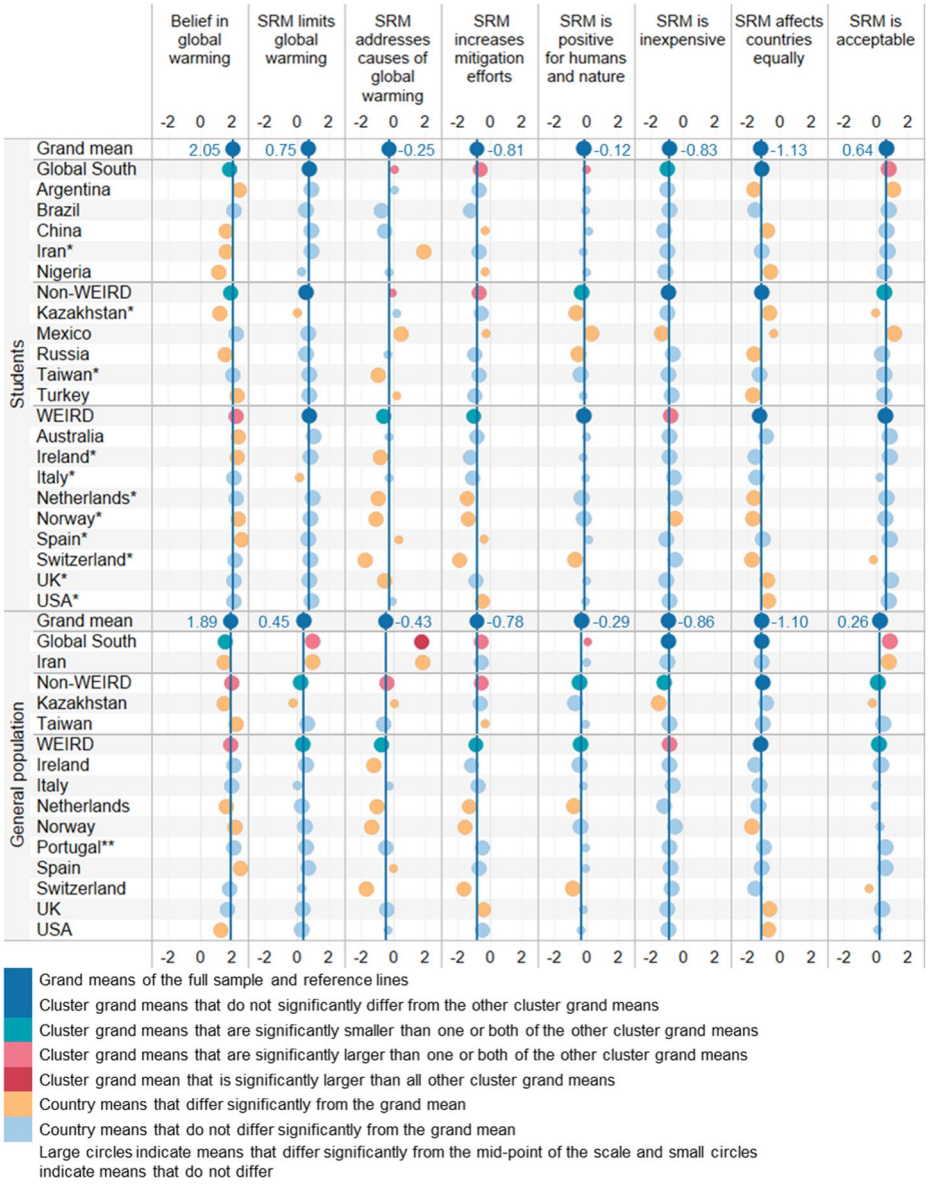

Fig. 2 Mean scores for belief in global warming, perceptions about SRM and acceptability of SRM among students (N=4,583) and the general public (N=2,245[1]), for the full sample, per country cluster and per country. Belief in global warming and all perceptions about and acceptability of SRM were measured with bipolar response scales ranging from −3, representing the negative pole, to +3, representing the positive pole, with 0 being "neither nor". For both samples, the means were controlled for time of data collection (spring versus autumn). For the general public, they were additionally controlled for education level. * Countries in which data were also collected among the general public. ** Data were collected among the general public only. [1] As n=3 participants did not report on their education level and had thus to be excluded from the mean comparisons, the size of the general population sample is N=2,245 (and not N=2,248). Graph prepared with Tableau (https://www.tableau.com/)

On average, participants perceived very slightly that SRM would not address the *causes* of global warming. Heterogeneity between country clusters was substantial. Participants in the 'WEIRD' Global North, especially Switzerland, thought more strongly that SRM would *not* address the causes of global warming than participants in the 'non-WEIRD' Global North and the Global South. Among the latter two clusters, there were even some samples (the Mexican and Iranian) that thought – at least to some extent – that SRM *would address* the causes of global warming. Moreover, in nearly half of the samples, the average was around the midpoint representing the response "SRM would neither address nor not address the causes of global warming". Interestingly, this was not because the majority of participants thought so but because in most countries participants had divergent perceptions. That is, some participants thought that SRM would not address the causes of global warming, while others thought the opposite (see SI-D).

On average, participants thought that SRM would slightly reduce politicians' and citizens' efforts to mitigate global warming. How strong this perception was differed between country clusters. Participants in the 'WEIRD' Global North (especially Switzerland) perceived more strongly that SRM would reduce mitigation efforts than participants in the 'non-WEIRD' Global North (especially students in Mexico and the general public in Taiwan) and the Global South. In fact, students in Mexico and the general public in Taiwan (along with students in China, Nigeria, and Spain) thought that SRM would neither increase nor reduce mitigation efforts. There was no country in which participants, on average, had the perception that SRM would *increase* mitigation efforts.

On average, participants thought that SRM would have *very* slight negative impacts on humans and nature. Yet, participants in the 'non-WEIRD' Global North perceived significantly stronger negative impacts on humans and nature than participants in the Global South did, while participants in the 'WEIRD' Global North were in between. While heterogeneity between countries was low overall, heterogeneity within the 'non-WEIRD' Global North was substantial, especially among students. Specifically, students in Kazakhstan and Russia were among the participants who thought most strongly that SRM would have negative impacts on humans and nature, while students in Mexico thought it least strongly. In fact, students in Mexico thought that SRM would have slightly *positive* impacts on humans and nature. It is noteworthy that in more than half of the countries – including all countries in the Global South – participants thought, on average, that SRM would have neither positive nor negative impacts on humans and nature.

In all countries, participants on average perceived SRM as somewhat expensive. While heterogeneity between countries was low overall, students and the general public in the 'WEIRD' Global North (especially students in Norway) perceived SRM as significantly less expensive than students in the Global South and the general public in the 'non-WEIRD' Global North (especially Kazakhstan).

On average, participants in all countries except Mexico thought at least to some extent that the costs and benefits of SRM would be unequally distributed between countries. While we found no differences in perceptions across country clusters, there was substantial disagreement within clusters (and across all countries) about the extent to which the distribution would be unequal, especially among students. For example, participants in the 'WEIRD' Global North were both among those who thought most strongly that the costs and benefits of SRM would be distributed unequally (e.g. students in Switzerland) and among those who thought this least strongly (e.g. students in the USA). Interestingly,

students in Mexico thought on average that the costs and benefits would be neither equally nor unequally distributed.

3.2 SRM is most acceptable in the global south

Next, we investigated to what degree people evaluated SRM as acceptable and whether acceptability differed across country clusters. The results are displayed in Fig. 2 and the detailed results in SI-D.

Overall, participants evaluated SRM as marginally acceptable, and in none of the countries was SRM evaluated as unacceptable on average. Acceptability of SRM was significantly higher in the Global South (especially among students in Argentina and the general public in Iran) than in the 'non-WEIRD' Global North (especially Kazakhstan), while the 'WEIRD' Global North was in between. While heterogeneity between countries was low overall, heterogeneity within the 'non-WEIRD' Global North was substantial, especially among students. Specifically, students from Mexico were among the participants who accepted SRM most strongly, while students (and the general public) from Kazakhstan were among the participants who accepted it least strongly. In fact, the latter (along with participants in Switzerland) judged SRM as neither acceptable nor unacceptable.

3.3 The associations between perceptions about and acceptability of SRM are fairly consistent across country clusters

We then tested the strength of association of belief in global warming and of the different perceptions about SRM with acceptability of SRM. The results are displayed in Fig. 3 and the detailed results in SI-E.

Overall, the results were fairly consistent across country clusters. Among students, there were no significant differences between clusters in the strength of the relationships between beliefs and perceptions with acceptability, and among the general public, there were only three significant differences between clusters. Specifically, the strength of the relationship between acceptability of SRM with the perceptions that SRM limits global warming, increases mitigation efforts, and has positive impacts on humans and nature was significantly weaker in the Global South (i.e. Iran) than in the 'WEIRD' and 'non-WEIRD' Global North (see Fig. 3).

Five of the perceptions about SRM were significantly and, in most cases, moderately strongly to strongly (Cohen 1992) associated with acceptability of SRM (see Fig. 3). Specifically, the more people thought that SRM would have negative impacts on humans and nature (large effect size [ES] in all countries), that it would not limit global warming (mostly large ES), that it would not address the causes of global warming (medium to large ES), that it would reduce our efforts to mitigate global warming (mostly medium to large ES) and that its costs and benefits would be unequally distributed between countries (mostly medium ES among students and large ES among the general public), the less they accepted SRM.

In contrast, belief in global warming and the perception that SRM is inexpensive were either non-significantly or only weakly to moderately strongly associated with acceptability of SRM. Specifically, the more participants perceived SRM as expensive (mostly small ES among students and mostly medium ES among the general public) and the less people believed in global warming (mostly small ES), the less they accepted SRM.

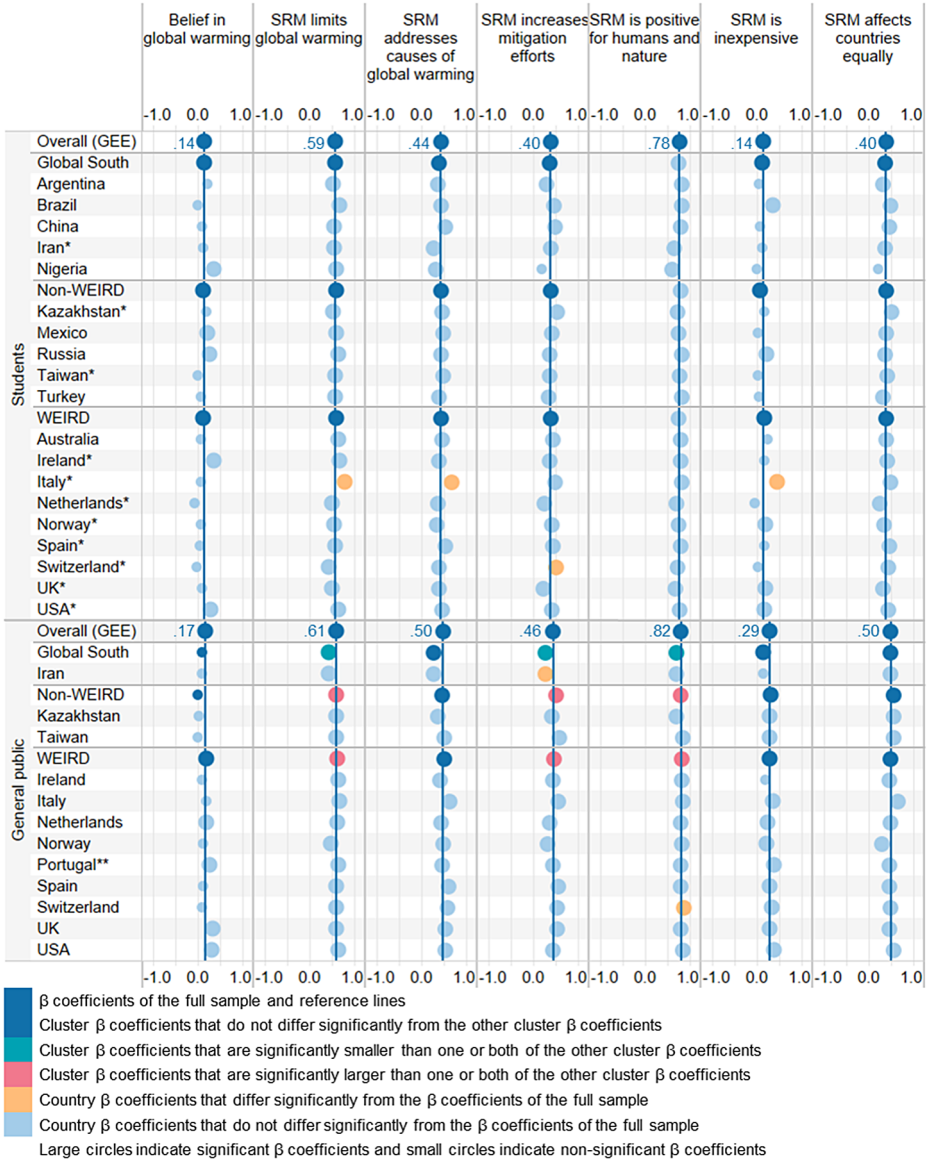

Fig. 3 Associations between belief in global warming and different perceptions about SRM with the acceptability of SRM among students (N=4,583) and the general public (N=2,248), for the full sample, per country cluster and per country. Standardised regression coefficients from GEEs on the full samples and from simple regression analysis per country are presented. * Countries in which data were also collected among the general public. ** Data were collected among the general public only. Graph prepared with Tableau (https://www.tableau.com/)

3.4 SRM is less acceptable, the more negative its impacts on humans and nature

Finally, we tested whether and how well belief in global warming and the different perceptions about SRM *uniquely* explained the acceptability of SRM (i.e. when controlling for the other explanatory factors). The results are displayed in Fig. 4 and the detailed results in SI-F.

The results were very consistent across country clusters. First, among students, there were no significant differences between clusters in the strength of the explanatory factors of acceptability, and among the general public, there were only two significant differences between clusters. Specifically, belief in global warming and the perception that SRM would address the causes of global warming explained acceptability of SRM significantly better in the 'WEIRD' Global North than in the 'non-WEIRD' Global North, while the Global South was in between. Second, and more importantly, there was a single best explanatory factor[5] of the acceptability of SRM in all countries, all country clusters, and overall (strong ES in all countries): the more people thought that SRM would have negative impacts on humans and nature, the less they accepted it.

The second-best explanatory factor was the perception that SRM would limit global warming effectively: the more people thought that SRM would not limit global warming, the less they accepted it. Yet with a few exceptions, this perception uniquely explained the acceptability of SRM only weakly. The same was true for belief in global warming and the remaining perceptions about SRM, which uniquely explained acceptability either only weakly or even non-significantly.

4 Discussion

For the present paper, researchers from around the world joined forces to conduct the first large-scale, cross-cultural study on public perceptions and acceptability of SRM in 20 countries covering all inhabited continents, including five countries from the Global South and five 'non-WEIRD' countries from the Global North. As public awareness of SRM is usually low (e.g. Mercer et al. 2011; Pidgeon et al. 2012), we provided participants with information on SRM, including key arguments in favour of and against SRM that appear in the literature. While the scientific debate about SRM is increasingly polarised (see e.g. Doherty et al. 2023, and Wieners et al. 2023, versus Biermann et al. 2023), participants' views on SRM were generally neither strong (i.e. mean scores were oftentimes close to the midpoint) nor polarised (i.e. mostly non-opposing views). Interestingly, the average views of participants differed from the expert views they had been presented with in important ways. On the one hand, participants perceived only to a small extent the key advantage of SRM presented. That is, while many experts believe that SRM could limit global warming to 1.5 °C (IPCC 2018; Tilmes et al. 2020), in most countries, participants perceived SRM as only (very) slightly effective in limiting global warming. On the other hand, participants shared some of the key concerns they had been presented with to only a limited degree. Specifically, while experts agree that SRM would not address the causes of global warming (Kiehl 2006; Owen 2014), participants only *very* slightly perceived this, which contrasts qualitative research that suggested that laypeople clearly share this concern among experts (Pidgeon et al. 2013).

[5] That is, in all the multiple regression analyses and GEEs, the same explanatory factor had the highest standardised regression coefficient.

Fig. 4 Belief in global warming and different perceptions about SRM uniquely explaining the acceptability of SRM among students (N=4,583) and the general public (N=2,248), for the full sample, per country cluster and per country. Standardised regression coefficients from GEEs on the full samples and from multiple regression analysis per country are presented. * Countries in which data were also collected among the general public. ** Data were collected among the general public only. Graph prepared with Tableau (https://www.tableau.com/)

Moreover, while experts are concerned that SRM would cause mitigation deterrence (Lin 2013; McLaren 2016), participants perceived on average that SRM would only slightly reduce politicians' and citizens' efforts to mitigate global warming, which corroborates initial cross-cultural findings (Visschers et al. 2017). Next, according to experts, SRM could impact humans and nature positively by limiting global warming to 1.5 °C and reducing some of the worst consequences of global warming (IPCC 2018; Tilmes et al. 2020), but also negatively, for example, because of changes in precipitation (Jones et al. 2018; Tilmes et al. 2013; cf. Irvine and Keith 2020). Participants potentially integrated these diverging potential impacts they had been presented with and thought that SRM would have marginally negative impacts on humans and nature. Interestingly, similar to the expert views they had been presented with (Robock et al. 2008; Tilmes et al. 2013), participants perceived on average that the costs and benefits of SRM would be (slightly) unequally distributed between countries, which also corroborates initial evidence on public opinion (Gregory et al. 2016).

In sum, our cross-cultural study revealed that, on average, participants thought that SRM would have slightly negative consequences and could be only (very) slightly effective in limiting global warming. Nevertheless, they evaluated the use of SRM as marginally acceptable. While the perception that SRM could limit global warming significantly explained acceptability of SRM, in all countries another perception stood out as the main explanatory factor: the more participants believed that SRM would have negative impacts on humans and nature (or the less they believed it would have positive impacts), the less they accepted it. Interestingly, while the perception that costs and benefits would be unequally distributed between countries was the strongest (negative) view participants had about SRM, it appears not to be a key barrier to acceptance. When controlling for all other perceptions and belief in global warming, perceiving that the costs and benefits of SRM would be unequally distributed between countries did not explain acceptability of SRM.

Taken together, and corroborating previous findings (e.g. Carr and Yung 2018; Macnaghten and Szerszynski 2013; Sugiyama et al. 2020), our results suggest a conditional, reluctant acceptance of SRM among the public. Specifically, on average people think SRM would have mostly negative consequences, but they may be willing to tolerate it as a potential last resort to fight global warming, particularly if they think SRM has only minor negative (or even positive) impacts on humans and nature.

In line with initial cross-cultural findings, acceptability of SRM was significantly higher in the Global South than in the Global North (Sugiyama et al. 2020; Visschers et al. 2017). This was probably the case because participants in the Global South perceived significantly weaker negative impacts of SRM on humans and nature – which we identified as the single best explanatory factor of acceptability in our study (see above) – than participants in the Global North. Interestingly, the Global South's opinions about SRM differed especially from the average opinions in the '*non*-WEIRD' Global North, which accepted SRM least strongly and perceived most strongly that SRM would have negative impacts on humans and nature. The average opinions in the 'WEIRD' Global North was in between and, in case of the student samples, not significantly different from the opinions in the other two clusters. However, we also found substantial variation in opinions *within* these country clusters, especially in the '*non*-WEIRD' Global North. This cluster included countries that were among those with the most positive opinion about SRM (i.e. perceiving the least negative impacts on humans and nature and accepting SRM most strongly), namely Mexico, as well

as those with the most negative opinion about SRM (i.e. perceiving the highest negative impacts on humans and nature and accepting SRM least strongly), namely Kazakhstan. These variations in opinions in the 'non-WEIRD' Global North might be explained by differences in climate change vulnerability in the relevant countries, as research suggests that vulnerable populations are more desperate to limit global warming and therefore more willing to consider SRM (Carr and Yung 2018). Supporting this interpretation, Mexico is more vulnerable to climate change than Kazakhstan (see Table 1 and IPCC 2022). However, climate change vulnerability cannot explain all country differences in public opinion about SRM found in our study (possibly, because public perceptions of climate change vulnerability may not always be in line with actual vulnerability). For example, Nigeria is the country most vulnerable to climate change in our study, yet participants in Nigeria were not among those with the most positive opinion about SRM (nor among those with the most negative). Similarly, cultural differences between the countries sampled (see Table 1), namely differences in technology affinity (Inglehart et al., 2017–2021) and uncertainty avoidance (The Culture Factor Group 2023), cannot explain all the country differences in public opinion about SRM found in our study. For example, technology affinity is, on average, higher in the Global South, which had a more positive opinion about SRM, than in the 'non-WEIRD' Global North, which had a more negative opinion about SRM. Yet, Mexico scores lower on technology affinity than Kazakhstan, but participants in Mexico had more positive opinions about SRM than participants in Kazakhstan. In sum, we found (a) substantial variation within country clusters in both our data and the secondary data summarised in Table 1, indicating that countries do not form homogenous clusters (see Khan et al. 2022; Solarz 2019), and (b) that the secondary data cannot explain all country differences. Any generalisation about clusters should thus be made with caution and it seems equally important to look at differences between countries within these clusters.

It is worth noting that perceptions about the impact of SRM on humans and nature as well as acceptability of SRM varied relatively little across all countries and within clusters, while much more variation was found in belief in global warming and in other perceptions about SRM. These included the degree to which people thought SRM would not address the causes of global warming and would reduce efforts to mitigate global warming, and the degree to which they thought the effects of SRM would be unequally distributed between countries. These country and cluster variations might become more pronounced if SRM were to be developed further, people became more familiar with it and especially if an unequal distribution of the effects of SRM between countries became more evident. Future decisions about SRM should consider such variations (Barrett 2014; Ghosh 2018; Morrow 2020) and pay particular attention to the potentially varied opinions and concerns of different countries from the Global South (Carr and Yung 2018; Rahman et al. 2018; Táíwò and Talati 2021) and acknowledge potential variations between and within the 'WEIRD' and 'non-WEIRD' Global North.

As mentioned, participants' views were generally neither strong nor polarised. One possible explanation for this finding is that participants did not yet have a firm opinion about SRM, because they were not familiar with SRM before participating in our study (see SI-A). Precisely because public awareness of SRM is usually low (e.g. Mercer et al. 2011; Pidgeon et al. 2012), we provided participants with information on SRM, including the key arguments in favour of and against SRM that appear in the scientific debate. It is likely that participants strongly relied on this balanced information, which may further explain

why participants' views were generally neither strong nor polarised. At the same time, our data shows that participants did not follow the information provided unreflectively. As discussed earlier, the average views of participants differed from the expert views they had been presented with in important ways, which suggests that people do not simply adopt the arguments from experts presented, for example, in the media and public debate. Moreover, though everyone had been exposed to the same (balanced) information, we found substantial variation between as well as within countries in some perceptions about SRM, as well as meaningful co-variations between perceptions about and acceptability of SRM (see above).

Moreover, strong and polarised views have been found especially in some of the qualitative research about SRM (e.g. Carr and Yung 2018), including studies applying deliberative workshops (e.g. Corner et al. 2013). This may be due to (a) sampling approaches as some studies sampled specialists (e.g. climate change specialists or environmental leaders; Carr and Yung 2018; Winickoff et al. 2015), who may have stronger opinions about global warming and SRM than the general public, and (b) self-selection as people with stronger opinions on climate-related issues may be more likely to attend participatory events on such topics (e.g. Liu et al. 2022). Additionally, it is possible that in qualitative approaches participants may form stronger opinions as these approaches, compared to quantitative approaches as ours, might allow them to process the received information on SRM more deeply as participants usually have the opportunity to ask questions and discuss the information. In either case, the question remains whether and how public opinion on SRM might change if there is more public deliberation (Merk et al. 2019) and if people become aware of the rather controversial debate about SRM among experts (e.g. Biermann et al. 2023; Doherty et al. 2023; Wieners et al. 2023). Future research could investigate this by studying people's opinions about SRM at different levels of knowledge and intensities of deliberation (Merk et al. 2019; Sütterlin and Siegrist 2017) and when exposed to less balanced information about SRM or to the controversial debates among experts.

4.1 Strength, limitations and directions for future research

The present paper presents the geographically most comprehensive data on public opinion about SRM, including five countries from the Global South and five 'non-WEIRD' countries from the Global North. It extends the current evidence on public opinion on SRM, which stems mostly from a few 'WEIRD' countries from the Global North, especially the UK (see Burns et al. 2016; Cummings et al. 2017; IPCC 2022). Furthermore, in addition to public perceptions on risks and benefits of SRM, we considered public perceptions related to distributive justice, which have been understudied (e.g. Gregory et al. 2016; Klaus et al. 2020; see also McLaren et al. 2016), despite their prominence in the scientific debate (Robock et al. 2008; Tilmes et al. 2013).

However, our paper is not exempt from limitations. First, despite our samples' geographic comprehensiveness, our study includes only one country that is very highly vulnerable to climate change (see Table 1 and IPCC 2022), while the vulnerability of the other countries sampled ranged from medium to very low. While climate change vulnerability cannot (fully) explain the country patterns we found in public opinion about SRM,

future studies should aim at sampling more highly vulnerable countries and communities, which has been done in previous qualitative research (e.g. Carr and Yung 2018). However, this may present a challenge as we aimed at including further countries from Africa and Asia that are (very) highly vulnerable to climate change but were unsuccessful (see SI-A).

Next, in eight of the 20 countries studied, we had no access to general public samples, including four countries from the Global South and three 'non-WEIRD' countries from the Global North. Therefore, we combined the approaches of the two previous quantitative, cross-cultural studies on non-specialists opinions about SRM that considered countries from the Global South, which sampled students (Sugiyama et al. 2020) and the general public (Visschers et al. 2017). As may be expected, comparisons between the student and general public samples revealed some statistically significant differences, yet these were generally rather small (see SI-G): we did not find polarised perceptions between the samples, nor did the main explanatory factor of acceptability differ between the samples. This suggests that student opinions about SRM might serve as proxy for public opinion about SRM, which might be a good alternative to using the opinions of specialists (e.g. climate change specialists or environmental leaders) as a proxy, which has been done in some research on public perspectives on SRM in the Global South (e.g. Carr and Yung 2018; Delina 2021; Winickoff et al. 2015). Nevertheless, whenever feasible, future studies should focus on general public samples.

Relatedly, only one general public sample, the one from the USA, represented the respective population well with regard to gender, age, and education. In the other samples, women were somewhat overrepresented and older people and people with lower education were underrepresented, which may have affected our findings. With regard to age and gender this seems not to have been the case as these demographics were not substantially related with any of the variables we studied. Education levels, however, were substantially related to some of these variables (see SI-D). For example, people with lower (as compared to higher) education believed less strongly in global warming and thought less strongly that SRM would reduce efforts to mitigate global warming. To reduce a potential bias in our findings, we thus controlled for education levels in the ANCOVAs we ran. Future studies should aim at limiting such biases by collecting more representative samples.

The data used in this study was gathered in 2019. Global warming has been increasingly debated since then (e.g. Al Jazeera 2022), which may have increased people's belief in global warming. However, we do not expect that this has affected opinions about SRM as, according to our findings, belief in global warming explains acceptability of SRM only weakly. At the same time, it is possible that that part of the public that experiences increasing climate anxiety (Whitmarsh et al. 2022) may be increasingly desperate for solutions to global warming and thus more willing to consider SRM (see Carr and Yung 2018). Yet, the main concerns participants – as well as experts – have about SRM, especially about potential negative impacts on humans and nature, remain a challenge and might thus limit acceptability longer-term. To assess whether and how public opinion about SRM will change in future, it is critical to monitor public acceptability of SRM and the underlying perceptions to inform future decisions about SRM.

5 Conclusion

This paper presents the results from the first large-scale, cross-cultural study on public perceptions and acceptability of SRM. On average, acceptability of SRM was significantly higher in the Global South than in the 'non-WEIRD' Global North, while acceptability ratings of the 'WEIRD' Global North were in between. However, we found also substantial variation within these country clusters, especially in the 'non-WEIRD' Global North, which suggests that countries do not form homogenous clusters and should thus be considered individually. Moreover, the average participants' opinion on SRM, while generally neither strong nor polarised, differed from some expert views in important ways, including that participants perceived SRM as only slightly effective in limiting global warming. Still, our data suggests overall a conditional, reluctant acceptance. That is, while on average, people think SRM would have mostly negative consequences, they may still be willing to tolerate it as a potential last resort to fight global warming, particularly if they think SRM has only minor negative (or even positive) impacts on humans and nature. Our study makes an important contribution to the current discussion on whether or not SRM should complement climate change mitigation measures to limit global warming (e.g. Biermann et al. 2023; Doherty et al. 2023; Wieners et al. 2023) as a socially responsible decision on SRM should consider the opinions of people across the globe (Carr and Yung 2018; Rahman et al. 2018).

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Author contributions NC coordinated the study and initiated, conceived and designed it together with GP and LS. All co-authors provided feedback on the design and contributed to data collection. NC and SCR analysed the data. NC wrote the original draft of the manuscript and all co-authors contributed to revising and editing the manuscript.

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Data availability The datasets generated and/or analysed during the current study are available from the corresponding author on request.

Declarations

Competing interests The authors have no relevant financial or non-financial interests to disclose.

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