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Do climate engineering experts display moral-hazard behaviour?

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ABSTRACT

Discourse analyses and expert interviews about climate engineering (CE) report high levels of reflectivity about the technologies' risks and challenges, implying that CE experts are unlikely to display moral hazard behaviour, i.e. a reduced focus on mitigation. This has, however, not been empirically tested. Within CE experts we distinguish between experts for radiation management (RM) and for carbon dioxide removal (CDR) and analyse whether RM and CDR experts display moral hazard behaviour. For RM experts, we furthermore look at whether they agree to laboratory and field research, and how they perceive the risks and benefits of one specific RM method, Stratospheric Aerosol Injection (SAI). Analyzing experts' preferences for climate-policy options, we do not find a reduction of the mitigation budget, i.e. moral hazard, for RM or CDR experts compared to climate-change experts who are neither experts for RM nor for CDR. In particular, the budget shares earmarked for RM are low. The perceptions of risks and benefits of SAI are similar for RM and climate-change experts. Despite the difference in knowledge and expertise, experts and laypersons share an understanding of the benefits, while their perceptions of the risks differ: experts perceive the risks to be larger.

Key policy insights

- Experts surveyed all prioritize mitigation over carbon dioxide removal and in particular radiation management.
- In the views of the experts, SAI is not a viable climate policy option within the next 25 years, and potentially beyond, as global field-testing (which would be a precondition for long-term deployment) is widely rejected.
- In the case of SAI, greater knowledge leads to increased awareness of the uncertainty and complexity involved. Policy-makers need to be aware of this relationship and the potential misconceptions among laypersons with limited knowledge, and should follow the guidelines about communicating risks and uncertainties of CE that experts have been advised to follow.

1. Introduction

The scientific discourse on climate engineering (CE) technologies is very careful to avoid framing the issue in a way that suggests that radiation management (RM) or carbon dioxide removal (CDR) could be a substitute for mitigation (Anshelm & Hansson, 2015).[1] In this regard, studies on expert opinions (Bellamy, Chilvers, Vaughan, & Lenton, 2013; Bellamy & Healey, 2018; Himmelsbach, 2017; Mercer, 2014; Winickoff, Flegal, & Asrat, 2015) have found that stratospheric aerosol injection (SAI), which comes under the heading of RM, is perceived as the most problematic technology, while CDR approaches are evaluated more positively. Experts rate the risks involved as high, especially with SAI, and generally emphasize that decarbonization should be the main priority. An

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important concern is that engagement with CE might in future shift the attention of the public, of economic enterprises, and of political decision-makers away from the reduction of greenhouse gas emissions and towards the use of CE. This concern is also called moral hazard (Baatz, 2016; Lawrence & Crutzen, 2017; Lin, 2013; McLaren, 2016; Morrow, 2014).

There is an ongoing debate about the actual existence of moral hazard and the effect of information about CE on the mitigation levels of different actors. In this debate, the experts, who are researchers from academia, figure predominantly in the role of scientific communicators bent on stressing the risks and uncertainties, warning against exaggerated confidence in the technologies, and trying to prevent decreases in mitigation levels by indicating the attendant hazards in no uncertain terms (Lin, 2013; Morrow, 2014). So far, the moral-hazard debate has not discussed the risk that experts themselves could display moral-hazard behaviour as a response to CE. It is, however, true that perception biases like overconfidence, over-optimism, or the affect heuristic, can act as psychological channels promoting the occurrence of moral-hazard behaviour (Lin, 2013) and experts are not immune to these biases (for an overview, see Montibeller & von Winterfeldt, 2015; Savadori et al., 2004). Over-confidence breeds a misguidedly positive view of the precision of technology assessments. Optimism bias fosters an underestimation of risks. For example, Hansson and Bryngelsson (2009) find overly optimistic evaluations of carbon capture and storage (CCS) in expert interviews. Tichy (2004) finds in technology Delphis[2] that top-rated experts are more prone to optimism bias with regard to the realization and economic exploitation of technologies. The term 'affect heuristic' refers to the evaluation of risks and benefits based on feelings. Positive feelings cause an overestimation of benefits and an underestimation of risks, negative feelings the opposite (Finucane, Alhakami, Slovic, & Johnson, 2000). In other words, perceptions of risks and benefits are negatively correlated. Laypersons have already been found to use the affect heuristic in evaluating SAI (Merk & Pönitzsch, 2017).

Although the literature suggests that experts are fully aware of the problems besetting the relevant technologies (Anshelm & Hansson, 2014), there are nonetheless important reasons for analysing potential moral hazard among experts through empirical analysis, and thereby closing the gap in theoretical work. Firstly, despite generally strong reservations against SAI, experts have advocated for SAI (and CDR) research in all studies based on expert opinions (Bellamy et al., 2013; Bellamy & Healey, 2018; Himmelsbach, 2017; Mercer, 2014).

Secondly, because the uncertainties and risks are substantial, it is unclear at which point an assessment of SAI could actually be regarded as overconfident. Even the currently cautious evaluations could already be overconfident. Moriyama et al. (2017), for example, found that cost estimates for SAI in previous studies were often too low because the underlying assumptions about the cooling efficiency and the direct costs were too optimistic. As overconfidence is often greater in specialized experts (Tichy, 2004), we shall be comparing RM experts to climate-change experts more broadly.

Thirdly, so far, the moral-hazard discussion has focused on SAI, where the costs appear to be low and the risk are high (Baatz, 2016; McLaren, 2016; Reynolds, 2014). However, CDR technologies, which are seen as more expensive and a more benign technologies, may in fact be more likely to cause moral hazard. For SAI, focus group studies (Shepherd, 2009; Wibeck, Hansson, & Anshelm, 2015) and a revealed-preference experiment (Merk, Pönitzsch, & Rehdanz, 2016) find that after learning about SAI, laypersons advocate increasing mitigation or buy more voluntary carbon offsets. Information about SAI also increases the perceived seriousness of climate change (Kahan, Jenkins-Smith, Tarantola, Silva, & Braman, 2015). For CDR, however, Campbell-Arvai, Hart, Raimi, and Wolske (2017) find a drop in support for mitigation policies as the perceived threat of climate change decreased after learning about CDR. Anderson and Peters (2016) warn against relying on the feasibility of CDR technologies. Also, Larkin, Kuriakose, Sharmina, and Anderson (2018) see a risk of dominant integrated assessment modelling further postponing mitigation, while Sugiyama, Arino, Kosugi, Kurosawa, and Watanab (2018) contend that the set of scenarios currently used does not reflect the full range of social choices.

Fourthly, researchers are the main source of information about CE for societies and decision-makers, and the multitude of assessment reports published during the past decade show just how strong the demand for expert assessment actually is (Morrow, 2017). Though the idea of using SAI to modify the climate has already been discussed for decades, the number of research publications was very low before the early 2000s (Lawrence & Crutzen, 2017). In 2006, Nobel prize winner Paul Crutzen called for research on the 'feasibility and environmental consequences of climate engineering', especially SAI (Crutzen, 2006, p. 214). Since then, the field has developed

very dynamically with a major upsurge in research publications (Lawrence & Crutzen, 2017) and heightened public interest (Tingley & Wagner, 2017). Also negative emission technologies, as CDR methods are often called, have gained substantial traction in the climate policy debate over the past years. In its fifth assessment report, the IPCC mentioned SRM and CDR technologies have already been included in integrated assessment models (IPCC, 2013, 2014). Since then, a multitude of articles have pointed out that limiting warming to 1.5°C or staying well below 2°C, as aimed for in the Paris Agreement, is strongly contingent on the use of CDR to achieve net negative emissions and the number of research articles has grown considerably (for an overview see Minx, Lamb, Callaghan, Bornmann, & Fuss, 2017). As the attention paid to CE technologies increases, perception biases and susceptibility to moral hazard of expert assessments become more important because the research experts report on, the scenarios they choose, and the priorities they set in their research are likely to influence climate policy.

Our analysis is the first to discuss whether CE experts themselves display moral-hazard behaviour, and the degree to which experts support field experiments on SAI. It also analyses the way they perceive the risks and benefits of one specific SRM method, SAI. We compare the SAI and CDR experts with climate-change experts who are not experts on either CE approach and with laypersons. The aim is to show whether CE experts are more receptive or more optimistic, whether they advocate a stronger reduction in mitigation levels, and whether their perception is prone to biases similar to those identifiable in laypersons. In contrast to earlier work (Bellamy et al., 2013; Bellamy & Healey, 2018; Himmelsbach, 2017; Mercer, 2014; Winickoff et al., 2015), our sample is very large, assembling 253 international experts. This enables us to assess expert perceptions more broadly than would be the case with only a small number of experts.

2. Data description and procedure

Between 2012 and 2015, we conducted one survey with international experts and two surveys with German laypersons on their perceptions of SAI. The surveys contained identical items that we compare in this paper (for an overview, see Table A1 in the Appendix). A summary of the statistics can be found in Table A2, also in the Appendix. The language of the surveys was German for the laypersons and English for the experts.

2.1. Experts

2.1.1. Sample characteristics
The expert survey was administered in April 2015. The invitation to participate in the survey was sent via e-mail to 883 researchers in the field of CE or climate change. Half of the invitations were based on affiliations to German research programmes (DFG Priority Program Climate Engineering, DFG Cluster of Excellence 'Integrated Climate System Analysis and Prediction' (CliSAP), BMBF funding priority 'Economics of Climate Change') or membership in associations (Standing Field Committee for Environmental and Resource Economics (AURÖ)). The other half were invited based on affiliations with modelling initiatives (CMIP5), participation in CE Summer Schools, or authorship of research articles.

A total of 310 experts (35%) completed the survey. As we are interested in expert judgements on CE, we excluded from further analysis both those participants who indicated that they were actually neither working in the field of CE research nor in the field of climate change research ($N = 15$) and those who had never heard of SAI ($N = 25$). Of the remaining participants, we excluded those who did not provide answers on all the items investigated in the paper ($N = 17$). The final sample thus consisted of 253 experts. 52% of the responses came from experts working at German research institutions.[3] As the German DFG Priority Program Climate Engineering explicitly focuses on the assessment of the technologies and not on their development (Oschlies & Klepper, 2017), the large number of responses from the German research community may over-represent the critical voices among CE experts. Also, German media discourse tends to be more critical of these technologies than is the case in English-speaking or Nordic countries (Anshelm & Hansson, 2015). We therefore include robustness checks taking account of differences between experts from international invitation lists and German invitation lists.

Respondent expertise is diverse. 25% indicate a high level of expertise in RM, 19% in CDR, 17% in adaptation. 32% claim a high level of expertise in mitigation. We define those with a self-reported high level of expertise as experts in the respective categories.[4] The categorization is not mutually exclusive. Respondents could indicate a high level of expertise in any number of fields. CE experts have a high level of expertise in RM and/or CDR.

All experts have ample experience in the field of climate-change research. 51% of all experts have been working on climate change for 11 years or longer. Most CE experts have comparable experience on climate change (Chi^2 test:[5] $p = 0.165$) and have shifted to research on CE at some point in their career. About half of the CE experts have been working in the field for 3 years or less and 80% have been working in the field for 6 years or less. As noted earlier, this reflects the fact that CE is a relatively young research field.

Most experts have a background in the natural sciences (60%). Other backgrounds include the social sciences (28%), engineering (4%), and the humanities (4%). 4% indicated that they have an interdisciplinary background. Among the CDR experts there are fewer social scientists (17%) and more researchers with an interdisciplinary background (15%) than in the other groups (Chi^2 test: $p = 0.001$). The backgrounds of the RM experts, however, are similar to those of the other experts (Chi^2 test: $p = 0.299$).

2.1.2. Survey design

To increase the response rate, we kept the expert survey short and focused on the most relevant aspects. We included general questions on the years spent working in climate change or CE research, disciplinary background, and expertise in RM, CDR, adaptation, and mitigation. To ensure anonymity, we did not ask about the experts' nationality, age or gender. The median time taken to complete the survey was 6 minutes.

The survey focused on the following three issues: (1) perceptions of the risks and benefits of SAI in general, (2) perceptions of SAI research, and (3) the distribution of a global climate-policy budget between RM, CDR, adaptation and mitigation.

We elicited perceptions of SAI research along two dimensions: (a) the scale of experimentation and the attendant intervention into the environment, from no intervention when research is done in the laboratory or with computer simulations, to local small-scale field experiments and global field experiments involving the release of particles into the environment; (b) the intention behind the research: either investigating effectiveness and side effects (we refer to this as 'research') or developing the technology necessary for deployment (we refer to this as 'development'). We asked our experts whether or not they would be in favour of research along these two dimensions in the next 25 years.

Finally, we broadened the focus of the survey and looked at CE methods in general and their relationship to mitigation and adaptation. We asked experts to imagine that it was their job to develop a global climate strategy for the period up to 2030. This involved distributing the total budget for managing climate change and its impacts and for researching and developing technologies, extending from mitigation and adaptation to RM and CDR. The experts were asked to distribute 100% of the total budget. We pointed out that higher budget shares indicated higher priority for the respective strategy. The order in which strategies appeared was randomized.

2.2. Laypersons

Our data on laypersons' perceptions come from two different surveys. In 2012 and 2013, we conducted surveys among the overall German population using the YouGov online panel. The data are representative for Germany's online population with respect to age, gender, and federal state. None of the subjects participated more than once in the surveys. In both surveys, respondents were informed about climate change, its consequences, SAI using sulfate particles, and the technology's risks and benefits. The information was provided by a short video operating with animated infographics. For further information on design and procedure, we refer our readers to the original publications (2012 survey: Merk, Pönitzsch, Kniebes, Rehdanz, & Schmidt, 2015; Merk & Pönitzsch, 2017; 2013 survey: Braun, Merk, Pönitzsch, Rehdanz, & Schmidt, 2018).

We compared the expert perceptions of the risks and benefits of SAI to the 2012/2013 layperson data. From 2012 there are 1,040 and from 2013 577 observations. We combined the data from these two layperson surveys, since their structure and the information video were very similar, and there were no significant differences

between the two surveys in terms of risk perception (Wilcoxon rank-sum test:[6] $p = 0.265$) and benefit perception ($p = 0.623$). The laypersons' initial awareness of SAI was slight. In 2012/2013, 17% of respondents had previously heard at least a little about SAI, while 3% had heard a lot about it.

3. Results

We first report on the experts' perceptions of SAI risks and benefits and compare them to the laypersons' perceptions. Second, we look at the experts' perceptions of SAI research and development. Third, we look at similarities and differences in reported uncertainty, i.e. the share of 'don't know' answers, for the perception of risks, benefits, and research. Fourth, we analyse experts' allocations of the climate-policy budget between RM, CDR, mitigation, and adaptation. Finally, we check the robustness of our results with respect to the nationality of the experts' affiliations.

3.1. Perceptions of risks and benefits of SAI

3.1.1. Experts
Experts agree that the risks of SAI are large, but they are divided in their assessment of its benefits (Figure 1). A large majority think that the risks of SAI are very large (59%) or somewhat large (35%). Only a few think the risks are somewhat small (6%) or very small (1%). The benefits of SAI are assessed to be very large by 30% and somewhat large by 13%, while a slight majority think the benefits are either somewhat small (35%) or very small (22%).

The perception of benefits depends on the level of expertise. 27% of RM experts think that the benefits are very large, while only 8% of non-RM experts share this assessment (rank-sum test: $p = 0.031$). There are no differences in the perception of risks. The majority in both groups perceive the risks of SAI as very large (RM experts: 64% vs. non-RM experts: 57%; rank-sum: $p = 0.331$).

3.1.2. Comparing experts and laypersons
Compared to laypersons, experts perceive SAI as riskier (rank-sum test: $p < 0.001$). While 93%[7] of experts think the risks are at least somewhat large, the share among laypersons is 86%. Experts also use the category 'very large' more often (59% vs. 46%). For benefit perception, experts and laypersons form similar judgements
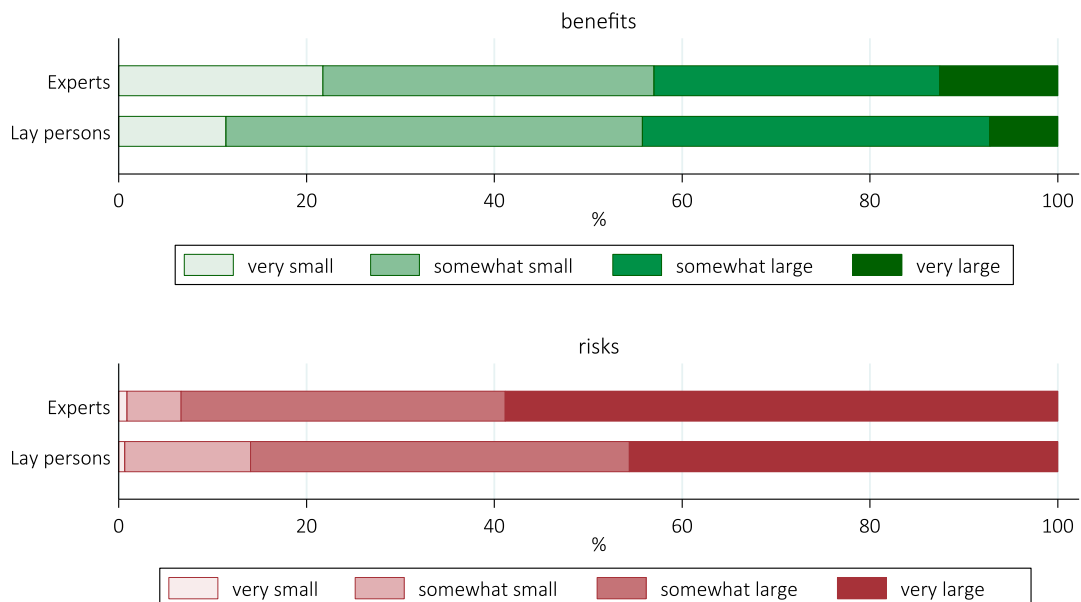

Figure 1. Overall perception of risks and benefits of SAI for laypersons and experts.

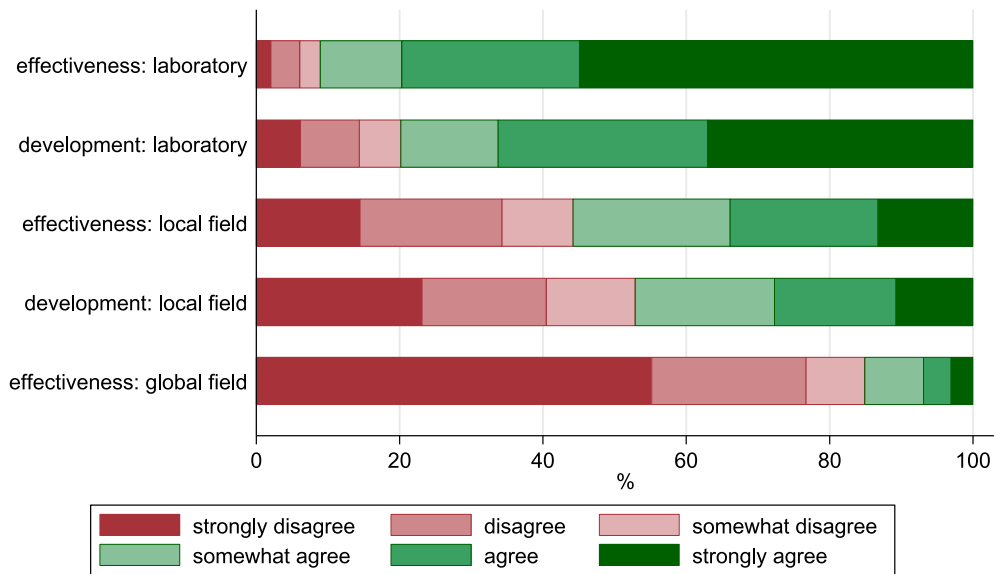Note: Laypersons from the surveys in 2012 and 2013 are pooled.

Figure 2. Perception of different intentions and scales of SAI research/development (experts).

(rank-sum test: $p = 0.271$). 56% of laypersons regard the benefits as somewhat small or smaller, the percentage of experts is 57%. Experts, however, are more heterogeneous in their assessments (Chi^2 test: $p < 0.001$). They use the extreme categories very small (22%) and very large (13%) more often than laypersons (11% and 7%).

Investigating whether respondents' perceptions of risks correlates with their perceptions of benefits, we find no such correlation for experts. Their risk and benefit perceptions are independent of each other (Spearman's ρ = -0.049; $p = 0.484$). This also holds for the sub-groups RM experts and others (Spearman's $\rho = -0.020$; $p = 0.895$ and $\rho = -0.081$; $p = 0.315$). For laypersons, however, risks and benefits are negatively correlated (Spearman's $\rho = -0.366$; $p < 0.001$). When they perceive risks as relatively large, they perceive benefits as relatively small and vice versa. This suggests that the affect heuristic may guide laypersons' judgements, whereas this is not the case for expert judgements on SAI.

3.2. Perception of different forms of research

Experts agree that research should be done on SAI in the next 25 years, but acceptance of research decreases with an increase in experimentation scale, i.e. the area that particles are released into, and with the focus on technology development (Figure 2). Agreement[8] for laboratory research[9] without the release of particles or development of the technology is high (36% agree, 55% agree strongly). Agreement drops slightly for developing the technology in the laboratory (80%), drops strongly for local small-scale field experiments involving the release of particles (56%), and drops further for local small-scale field tests for technology development (47%; Wilcoxon signed-rank test:[10] $p < 0.001$ for all comparisons). A large majority of 85% disagree with global field research.

RM experts tend to agree more strongly with research on, and development of, SAI than non-RM experts (rank-sum tests: each $p < 0.053$) but resemble non-RM experts in their rejection of global field research (rank-sum test: $p = 0.314$). The difference in opinion is most noticeable in connection with laboratory research, to which 77% of RM experts but only 47% of other experts strongly agree.

3.3. Uncertainty in risk, benefit, and research perceptions

Judgements about SAI are difficult because they involve risk-risk trade-offs and large uncertainties. Accordingly, both experts and laypersons could choose the category 'don't know' if they did not know how to respond to the questions on risks, benefits and research. We use these answers as an indicator for uncertainty.

Experts are more certain about risks than about benefits. 11% choose 'don't know' for the perception of risks, while 18% choose 'don't know' for the perception of benefits (signed-rank test: $p < 0.001$). RM experts show the same level of uncertainty as other experts in their perception of the risks and benefits of SAI (rank-sum test: $p > 0.513$ each).

Interestingly, experts are more likely than laypersons to answer 'don't know' for risk and benefit perception (rank-sum tests: $p < 0.002$ each). Among laypersons, 5% and 7% answer 'don't know' for risk and benefit perception, respectively.

Experts' uncertainty about whether to accept research on the effectiveness of SAI increases with the scale of experimentation from researching the effectiveness in the laboratory (2%) to global field-testing (8%, signed-rank test: $p < 0.001$). RM experts are not significantly more or less certain than non-RM experts about the various forms of research (rank-sum test: $p > 0.067$ each).

3.4. Allocation of the global climate-policy budget

In the following, we investigate the determinants of experts' funding priorities for global climate policy. We asked the experts how they would distribute the entire climate-policy budget for research, development and deployment between the four domains mitigation, adaptation, CDR, and RM (Figure 3).[11]

On average, they allocate the largest share – 54% of the total budget – to mitigation (std. dev. 19.78), followed by 28% for adaptation (std. dev. 15.89) and 12% for CDR (std. dev.: 12.36). The smallest share, 5%, is allocated to RM technologies including SAI (std. dev.: 6.92). Overall, however, experts' opinions on the relative importance of the four domains differ, as we can see from the large spread of responses.

Many experts are reluctant to allocate any of the budget to CE in general: 41% refuse to assign any of the budget to RM. Among CE researchers as well, scepticism vis-à-vis RM is substantial: 28% of RM experts and 37% of CDR experts do not allocate any of the budget to RM. CDR is more widely included in the policy mix. Only 19% of all the experts do not assign any of the budget to CDR, a percentage that is similar across expert groups (Fisher's exact test: $p = 0.838$).

Finally, we use Tobit regressions to analyse how expertise in a specific field influences budget shares (Table 1).[12] The regressions reveal that, on average, experts allocate higher budget shares to their own area of expertise than other experts. RM experts allocate 1 percentage point more to RM (t-test,[13] $p = 0.046$) and
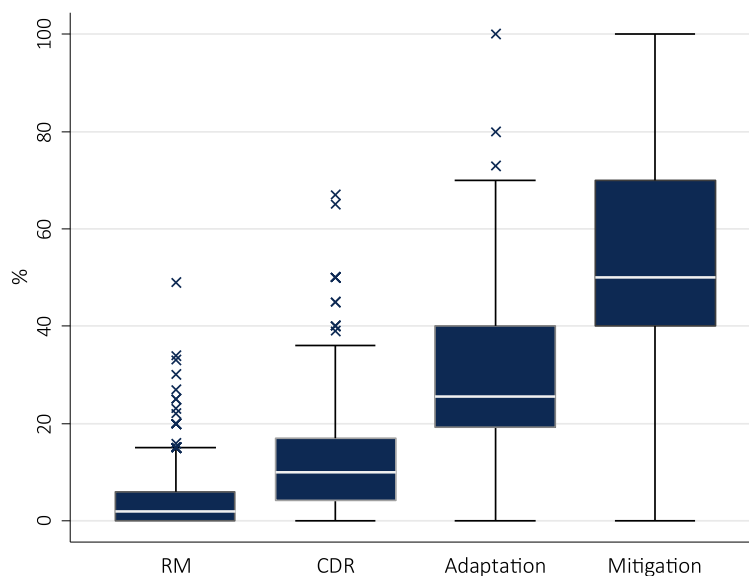

Figure 3. Distribution of the budget between RM, CDR, adaptation, and mitigation up to 2030.

Table 1. Average marginal effects (AME) from Tobit estimation, standard errors in parentheses.

	Budget shares for			
	RM	CDR	Adaptation	Mitigation
RM expert	1.327*	−1.656	−0.861	3.242
	(0.668)	(1.234)	(2.002)	(2.707)
CDR expert	−0.055	2.830*	−0.192	−3.649
	(0.782)	(1.435)	(2.327)	(3.139)
Adaptation expert	0.177	−2.989*	13.223***	−11.215***
	(0.806)	(1.489)	(2.312)	(3.146)
Mitigation expert	−0.188	−3.290**	−1.911	8.099**
	(0.673)	(1.232)	(1.971)	(2.645)
N	253	253	253	253

Note: $*p < 0.05$; $**p < 0.01$; $***p < 0.001$.

do not cut down on mitigation to pay for it (one-sided, $p = 0.884$). CDR experts allocate 3 percentage points more to CDR ($p = 0.048$), cutting down on the budget in all other areas. Adaptation experts spend 13 percentage points more on adaptation ($p < 0.001$) and compensate for this by reducing the mitigation budget by 11 percentage points ($p < 0.001$) and also cutting down on the CDR budget ($p = 0.044$). Mitigation experts spend 8 percentage points more on mitigation ($p = 0.002$) and 3 percentage points less on CDR ($p = 0.007$).

From the budget allocations we see that experts favour their own area of expertise. However, the statistical evidence for preference of one's own field is stronger for adaptation and mitigation experts than for RM and CDR experts. Neither RM experts nor CDR experts allocate significantly lower shares to mitigation. In other words, our data on preferences for climate response options do not support the moral-hazard argument with regard to RM or CDR experts.

3.5. Robustness check for nationality of experts' affiliation

About half of our experts work at German research institutions. This may put a bias on our results since, as set out earlier, the CE discourse in Germany tends to be more critical than elsewhere, implying a possible over-representation of scepticism vis-à-vis CE in our expert and layperson samples. To check for robustness, we analyse whether experts from German research institutes ($N = 133$) and international experts ($N = 118$) show the same patterns of perception and compare them with German laypersons. The analysis largely confirms our previous findings.

Again in the German sample, experts perceive SAI as riskier than laypersons (rank-sum test: $p = 0.017$), but in contrast to the overall sample, they regard the benefits as smaller (rank-sum test: $p = 0.002$). But we find no evidence of the affect heuristic, the negative correlation between risk and benefit perception (Spearman's $\rho = -0.001$; $p = 0.920$). In addition, these experts express more uncertainty than laypersons about evaluating risks and benefits (rank-sum tests: $p < 0.006$ each). They are also more firmly opposed to research than the international experts. About 5% of them express uncertainty in their evaluation of research, a score similar to the overall expert sample.

Thus, we see that our results are not significantly skewed by the over-representation of experts from Germany. German experts only differ from their international counterparts in the stronger scepticism they display in the evaluation of the benefits of SAI and the lower degree of support they express for research on the technology.

4. Discussion and conclusion

We have compared CE experts, notably RM experts, with climate change experts, who are not experts on CE, and laypersons to analyse whether RM and CDR experts are more willing to accept or more optimistic about RM or CDR respectively, whether their expertise prompts them to focus less on mitigation, and whether their perceptions are prone to biases similar to those entertained by laypersons.

We find no indication that, in comparison with other experts, RM experts are more liable to cut down on the mitigation budget, i.e. moral hazard. RM experts do indeed allocate higher budget shares to RM at the

expense of CDR, adaptation, or mitigation, but they do not systematically discriminate against any of these strategies. The result for CDR experts is similar. They allocate higher shares to CDR but do not systematically reduce the share of the budget earmarked for mitigation. Our results on budget allocation should, however, be interpreted with a degree of caution. The answers are expressed in shares of a total budget which itself remains undefined. We cannot gauge whether experts would allocate lower amounts in absolute terms. This means that, even though experts do not reduce the relative share allocated to mitigation, they might still reduce the absolute climate-policy budget, which in turn would be a case of moral hazard. Furthermore, offering more options for choice, that is, adding CE technologies, in itself reduces the shares assigned to mitigation and adaptation when respondents assign non-zero shares to CE. This could be interpreted as moral hazard. Despite these drawbacks, the question of budget allocation affords interesting insights into the spread of opinion among experts and the trade-offs between climate-policy options.

Mitigation is the experts' clear funding priority for climate research and climate policy up to 2030. They assign especially low budget shares to RM. This low budget share can either be interpreted as reluctance to invest in RM (research) or as a reflection of the assumption that the costs of SAI deployment would be low (Barrett, 2008). A clear sign of scepticism vis-à-vis RM, however, is the high percentage of experts (40%) who assign no funds to this option. The majorities in both groups, RM experts and non-RM experts, perceive the risks of SAI to be very large. RM experts are, however, more optimistic about the benefits. While RM experts think more favourably about research on SAI in the laboratory or developing the technology in small-scale field-tests, they reject global field testing just as unambiguously as other experts. Furthermore, RM experts are just as likely as other experts to be uncertain about how to judge the risks and benefits of SAI. We interpret this uncertainty among RM experts as indicating a low level of overconfidence.

Laypersons seem to be somewhat more confident than experts about SAI. They share a similar understanding of the benefits, but their perceptions of the risks differ: experts perceive the risks to be higher. Furthermore, we find that laypersons rely on affect in evaluating risks and benefits, while experts' perceptions are not biased by the affect heuristic. In addition, laypersons are less likely than experts to respond with 'don't know' when asked about their perceptions of the risks and benefits despite their less detailed knowledge about the technology. This implies that, in the case of SAI, more knowledge does not reduce uncertainty but rather increases awareness of the uncertainty and complexity inherent in SAI. Policy-makers need to be aware of this relationship and the potential misconceptions among laypersons and should follow the guidelines about communicating risks and uncertainties that experts have been advised to follow. This is especially important because the information we presented to the laypersons was very explicit about risks and uncertainties. The bias might be larger if the information provided were less explicit.

While our results confirm previous findings characterizing the CE research community as (self-) reflective about the risks of SAI (Anshelm & Hansson, 2014; Himmelsbach, 2017; Mercer, 2014), future research should continue to monitor the development of expert perceptions, as in the course of time overconfidence or moral hazard might evolve as the research taboo from the past loses influence. Like other moral-hazard studies we focus on SAI; we believe, however, that the moral hazard connected with CDR should also be addressed more thoroughly as it is already much more prominent in integrated assessment modelling and has gained substantial traction since the Paris Agreement in 2015.

Notes

1. CE encompasses two approaches: CDR technologies remove carbon dioxide from the atmosphere, while RM technologies modify the Earth's albedo to reflect either more sunlight (Solar Radiation Management, SRM) or more thermal radiation back into space (Thermal Radiation Management, TRM). SAI is an RM approach that would increase the albedo and reflect sunlight.
2. The aim of the Delphi-method is to 'obtain the most reliable consensus of opinion of a group of experts […] by a series of intensive questionnaires interspersed with controlled opinion feedback' (Dalkey & Helmer, 1963, p. 458).
3. We do not know the respondents' identity, but we know to which group of invitees they belong (see groups in first paragraph of this section).
4. Expertise was measured on a 5-point scale from low (1) to high (5). Category 5 is defined as a self-reported high level of expertise.

5. The Chi² test checks whether a categorical variable has the same distribution across samples. For all tests, we use the conventional significance level of 0.05. Accordingly, $p < 0.05$ indicates a statistically significant difference.
6. The Wilcoxon rank-sum test compares an ordinal outcome across samples without making assumptions about distributions. For the sake of brevity, we refer to it here as rank-sum test.
7. Small differences are due to rounding.
8. Disagreement, when not further specified, refers to the summed share of the three categories 'somewhat disagree', 'disagree', and 'strongly disagree'. Correspondingly, agreement denotes the summed share of the categories 'somewhat agree', 'agree', and 'strongly agree'.
9. Research into effectiveness and side effects in the laboratory and with computer simulations.
10. The Wilcoxon signed-rank test compares ordinal outcomes within the same sample without making assumptions on distributions. For the sake of brevity, we refer to it as signed-rank test.
11. The following definitions were used and explained: RM – technologies that modify the earth's radiation budget; CDR – technologies that remove CO_2 from the atmosphere; mitigation – options for reducing greenhouse gas emissions; adaptation – actions that help humans and ecosystems to cope with a changing climate. The definitions were all listed on the same page. Note that our definitions categorize CCS as mitigation.
12. The Tobit regressions enable us to identify the impact of expertise (exogenous variables) on the budget share allocated to a specific domain (endogenous variables). They take into account the fact that the budget share must lie between 0% and 100%. As before, experts with a 'high' (as opposed to 'low', 'somewhat low', 'medium', and 'somewhat high') level of expertise in a field are coded as experts in that field. Expertise enters the regression as a dummy variable. The coefficients in Table 1 report average marginal effects (AME), i.e., expected differences in the budget share (for shares strictly between 0 and 100) across different expert groups.
13. The t-tests are based on average marginal effects and indicate whether being a specific expert has an influence on budget allocations.

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References

Anderson, K., & Peters, G. (2016). The trouble with negative emissions. *Science*, *354*(6309), 182–183.

Anshelm, J., & Hansson, A. (2014). Battling promethean dreams and Trojan horses: Revealing the critical discourses of geoengineering. *Energy Research & Social Science*, *2*, 135–144.

Anshelm, J., & Hansson, A. (2015). Has the grand idea of geoengineering as plan B run out of steam? *The Anthropocene Review*, *3*(1), 64–74.

Baatz, C. (2016). Can we have it both ways? On potential trade-offs between mitigation and solar radiation management. *Environmental Values*, *25*(1), 29–49.

Barrett, S. (2008). The incredible economics of geoengineering. *Environmental and Resource Economics*, *39*(1), 45–54.

Bellamy, R., Chilvers, J., Vaughan, N. E., & Lenton, T. M. (2013). 'Opening up' geoengineering appraisal: Multi-criteria mapping of options for tackling climate change. *Global Environmental Change*, *23*(5), 926–937.

Bellamy, R., & Healey, P. (2018). 'Slippery slope' or 'uphill struggle'? Broadening out expert scenarios of climate engineering research and development. *Environmental Science & Policy*, *83*, 1–10.

Braun, C., Merk, C., Pönitzsch, G., Rehdanz, K., & Schmidt, U. (2018). Public perception of climate engineering and carbon capture and storage in Germany: Survey evidence. *Climate Policy*, *18*(4), 471–484.

Campbell-Arvai, V., Hart, P. S., Raimi, K. T., & Wolske, K. S. (2017). The influence of learning about carbon dioxide removal (CDR) on support for mitigation policies. *Climatic Change*, *143*(3), 321–336.

Crutzen, P. J. (2006). Albedo enhancement by stratospheric sulfur injections: A contribution to resolve a policy dilemma? *Climatic Change*, *77*(3), 211–220.

Dalkey, N., & Helmer, O. (1963). An experimental application of the DELPHI method to the use of experts. *Management Science*, *9*(3), 458–467.

Finucane, M. L., Alhakami, A., Slovic, P., & Johnson, S. M. (2000). The affect heuristic in judgments of risks and benefits. *Journal of Behavioral Decision Making*, *13*(1), 1–17.

Hansson, A., & Bryngelsson, M. (2009). Expert opinions on carbon dioxide capture and storage—a framing of uncertainties and possibilities. *Clean Cooking Fuels and Technologies in Developing Economies*, *37*(6), 2273–2282.

Himmelsbach, R. (2017). How scientists advising the European commission on research priorities view climate engineering proposals. *Science and Public Policy*, *43*(6), 872–873.

IPCC. (2013). *Climate change 2013: The physical science basis. Working group I contribution to the fifth assessment report of the intergovernmental panel on climate change*. Geneva: Cambridge University Press.

IPCC. (2014). *Contribution of working group III to the fifth assessment report of the intergovernmental panel on climate change*. Cambridge: Cambridge University Press.

Kahan, D. M., Jenkins-Smith, H., Tarantola, T., Silva, C. L., & Braman, D. (2018). Geoengineering and climate change polarization: Testing a two-channel model of science communication. *The Annals of the American Academy of Political and Social Science*, *658*(1), 192–222.

Larkin, A., Kuriakose, J., Sharmina, M., & Anderson, K. (2018). What if negative emission technologies fail at scale?: Implications of the Paris agreement for big emitting nations. *Climate Policy*, *18*(6), 690–714.

Lawrence, M. G., & Crutzen, P. J. (2017). Was breaking the taboo on research on climate engineering via albedo modification a moral hazard, or a moral imperative? *Earth's Future*, *5*(2), 136–143.

Lin, A. C. (2013). Does geoengineering present a moral hazard. *Ecology Law Quarterly*, *40*, 673.

McLaren, D. (2016). Mitigation deterrence and the "moral hazard" of solar radiation management. *Earth's Future*, *4*(12), 596–602.

Mercer, A. (2014). *An examination of emerging public and expert judgments of solar radiation management* (*Ph.D. Thesis*).

Merk, C., & Pönitzsch, G. (2017). The role of affect in attitude formation toward new technologies: The case of stratospheric Aerosol injection. *Risk Analysis*, *37*(12), 2289–2304.

Merk, C., Pönitzsch, G., Kniebes, C., Rehdanz, K., & Schmidt, U. (2015). Exploring public perceptions of stratospheric sulfate injection. *Climatic Change*, *130*(2), 299–312.

Merk, C., Pönitzsch, G., & Rehdanz, K. (2016). Knowledge about Aerosol injection does not reduce individual mitigation efforts. *Environmental Research Letters*, *11*(5), 054009.

Minx, J. C., Lamb, W. F., Callaghan, M. W., Bornmann, L., & Fuss, S. (2017). Fast growing research on negative emissions. *Environmental Research Letters*, *12*(3), 035007.

Montibeller, G., & von Winterfeldt, D. (2015). Cognitive and motivational biases in decision and risk analysis. *Risk Analysis*, *35*(7), 1230–1251.

Moriyama, R., Sugiyama, M., Kurosawa, A., Masuda, K., Tsuzuki, K., & Ishimoto, Y. (2017). The cost of stratospheric climate engineering revisited. *Mitigation and Adaptation Strategies for Global Change*, *22*(8), 1207–1228.

Morrow, D. (2017). *International governance of climate engineering: A survey of reports on climate engineering, 2009*–2015 (FCEA working paper series no. 01). Retrieved from https://ssrn.com/abstract=2982392

Morrow, D. R. (2014). Ethical aspects of the mitigation obstruction argument against climate engineering research. *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, *372*(2031).

Oschlies, A., & Klepper, G. (2017). Research for assessment, not deployment, of climate engineering: The German research foundation's priority program SPP 1689. *Earth's Future*, *5*(1), 128–134.

Reynolds, J. (2014). A critical examination of the climate engineering moral hazard and risk compensation concern. *The Anthropocene Review*, *2*(2), 174–191.

Savadori, L., Savio, S., Nicotra, E., Rumiati, R., Finucane, M., & Slovic, P. (2004). Expert and public perception of risk from biotechnology. *Risk Analysis*, *24*(5), 1289–1299.

Shepherd, J. G. (2009). *Geoengineering the climate: Science, governance and uncertainty*. Royal Society. Retrieved from http://eprints.soton.ac.uk/156647/1/Geoengineering_the_climate.pdf

Sugiyama, M., Arino, Y., Kosugi, T., Kurosawa, A., & Watanabe, S. (2018). Next steps in geoengineering scenario research: Limited deployment scenarios and beyond. *Climate Policy*, *18*(6), 681–689.

Tichy, G. (2004). The over-optimism among experts in assessment and foresight. *Technological Forecasting and Social Change*, *71*(4), 341–363.

Tingley, D., & Wagner, G. (2017). Solar geoengineering and the chemtrails conspiracy on social media. *Palgrave Communications*, *3*(1), 211.

Wibeck, V., Hansson, A., & Anshelm, J. (2015). Questioning the technological fix to climate change – lay sense-making of geoengineering in Sweden. *Energy Research & Social Science*, *7*, 23–30.

Winickoff, D. E., Flegal, J. A., & Asrat, A. (2015). Engaging the global south on climate engineering research. *Nature Climate Change*, *5*(7), 627–634.

Appendix

Table A1. List of items and sources.

Knowledge about SAI	
Have you ever heard about stratospheric aerosol injection before or have you never heard about it before?	• No, I have never heard about it. • Yes, I have heard a little about it. • Yes, I have heard a lot about it.
Risk and benefits of Stratospheric Aerosol Injection	
Overall, what do you think about the benefits of SAI?	Very small (1) – Very large (4); Don't know
Overall, what do you think about the risks of SAI?	
Research on SAI	
Currently not all chemical and physical effects of stratospheric aerosol injection (SAI) are known. Furthermore, technologies available today are unsuitable for injecting sulfate aerosols into high layers of the atmosphere over long time periods. Research can have two aims that can be pursued independently: • Better understand the chemical and physical effects of SAI and thereby learn more about its effectiveness and side-effects. • Develop technologies necessary to inject sulfate into the stratosphere.	
Do you agree or disagree that the following forms of SAI research should be conducted within the next 25 years?	Strongly disagree (1) – Strongly agree (6); Don't know
Research on the <u>effectiveness and side-effects</u> *of stratospheric aerosol injection …* … with computer models and in the laboratory; no particles are released into the atmosphere … with local small-scale field tests; particles are released into the atmosphere … with large-scale field tests across national borders; particles are released into the atmosphere <u>Development and test of technologies</u> *needed for stratospheric aerosol injection …* … with computer models and in the laboratory; no particles are released into the atmosphere … with local small-scale field tests; particles are released into the atmosphere	
Budget allocation	
We are interested in your opinion on which options should be used to manage global climate change and its impacts. Please imagine that it was your task to develop a global climate strategy for the next 25 years. You do so by distributing the total amount of money to be spent on managing global climate change and its impacts between different options. The higher the share of money you assign to an option, the more priority you give to that option in the strategy. The money will be used for research and development as well as implementation. *What percentage of the total budget would you allocate to each of the following options?* *Please distribute 100% of the total budget.* • Radiation Management (Technologies that modify the earth's radiation budget. They aim to either reduce incoming solar radiation or to increase outgoing terrestrial radiation.) • Carbon Dioxide Removal (Technologies that remove CO_2 from the atmosphere. The CO_2 is stored in the ocean, in geological formations, in the soil, or in biomass.) • Mitigation (Options to reduce emissions of greenhouse gases.) • Adaptation (Actions that help humans and ecosystems to cope with a changing climate.)	
Level of expertise	
Please indicate your level of expertise for each of the following options • Radiation Management • Carbon Dioxide Removal • Mitigation • Adaptation	Low (1) – High(5)

Table A2. Summary statistics.
Experts only (N = 253).

	Mean	Standard deviation	Minimum	Maximum
Allocated budget shares				
RM	4.78	6.88	0	49
CDR	12.49	12.09	0	67
Adaptation	28.42	15.87	0	100
Mitigation	53.52	19.43	0	100
Respondents with high level (= 5) of expertise in … (%)				
RM	24.50			
CDR	18.58			
Adaptation	16.60			
Mitigation	31.62			

Years in climate change research (%)	
3 years or less	14.23
4–6 years	17.79
7–10 years	17.00
11 years or more	50.99
Working in CE research (%)	
52.57	
Discipline (%)	
Humanities	3.56
Engineering	3.95
Interdisciplinary	4.35
Social Sciences	27.67
Natural Sciences	60.47

	Effectiveness		Development		
	Lab	Small-scale, field	Global-scale, field	Lab	Small-scale, field
Perception of research on different scales and with different intentions (%)					
Strongly disagree	1.98	13.89	51.00	5.98	22.22
Disagree	3.97	19.05	19.92	7.97	16.67
Somewhat disagree	2.78	9.52	7.57	5.58	11.90
Somewhat agree	11.11	21.03	7.57	13.15	18.65
Agree	24.21	19.84	3.59	28.29	16.27
Strongly agree	53.57	12.7	2.79	35.86	10.32
Don't know	2.38	3.97	7.57	3.19	3.97

Experts and lay persons.

	Experts	Lay persons
Risks of SAI (%)		
Very small	0.79	0.62
Somewhat small	5.14	12.68
Somewhat large	30.83	38.16
Very large	52.57	43.17
Don't know	10.67	5.38
Benefits of SAI (%)		
Very small	17.79	10.64
Somewhat small	28.85	41.25
Somewhat large	24.9	34.38
Very large	10.28	6.74
Don't know	18.18	6.99