Presenting balanced geoengineering information has little effect on mitigation engagement

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Abstract

'Moral hazard' links geoengineering to mitigation via the fear that either solar geoengineering (solar radiation management, SRM) or carbon dioxide removal (CDR) might crowd out the desire to cut emissions. Fear of this crowding-out effect ranks among the most frequently cited risks of (solar) geoengineering. We here test moral hazard versus its inverse in a large-scale, revealed-preference experiment (n~340,000) on Facebook and find little to no support for either outcome. For the most part, talking about SRM or CDR does not motivate our study population to support a large U.S. environmental non-profit's mission, nor does it turn them off relative to baseline climate messaging, except when using extreme messengers and framings. Our results indicate the importance of actors and reasoned narratives of (solar) geoengineering to help guide public discourse.

Keywords: Geoengineering, moral hazard, mitigation deterrence, crowding out, crowding in

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Introduction

Mere mention of either solar geoengineering (solar radiation management, SRM) or carbon dioxide removal (CDR) might crowd out the desire to mitigate. This "moral hazard" phenomenon entered geoengineering discussions early on (Keith 2000). It is well-grounded theoretically (Lin 2013, Morrow 2014, Reynolds 2015). It is also a misnomer (Jebari et al 2021, Tsipiras 2022), or at least a misapplication of the strict economic definition of the term (Marshall 1976). Crowding-out of mitigation by geoengineering might be better described as a "lack of self-control" (Wagner and Weitzman 2015, p. 197) or "risk compensation" (Merk et al 2016). Either way, though, the idea looms large in geoengineering discussions (Crutzen 2006, Lawrence 2006, Lawrence and Crutzen 2016). It is often a leading cause of objection to even discussing CDR and especially SRM, lest it detracts from the need to cut emissions in the first place (McLaren 2016, Wagner and Zizzamia 2021).

Empirical evidence is mixed. A number of early studies with laypersons point to possible moral hazards, primarily relying on stated-preference surveys (Mercer et al 2011, Pidgeon et al 2012, Burns et al 2016, Cherry et al 2021). Those can fall prey to acquiescence bias (Mahajan et al 2019) and other framing issues (Raimi et al 2019). The earliest controlled revealed-preference analysis (n~650) shows 'inverse' moral hazard or 'crowding in', hypothesized to be linked to fear of SRM (Merk et al 2016), a conclusion since supported by some lab experiments (Cherry et al 2022) and contradicted by others in the context of CDR (Hart et al 2022).

We here conduct several large-scale social media experiments with a combined n~340,000 using the Facebook page of a large U.S. environmental non-profit organization (NGO). The group is broadly perceived by the wider public as standing for ambitious yet traditional climate policy.

We, thus, interpret 'likes' and newsletter signups, respectively, as public or somewhat more costly private signals of engagement with climate policies. This allows us to test the response to various messages around SRM and CDR in comparison with baseline climate mitigation messaging.

Methods

We analyze several framings with three large-scale social media experiments, with the number of observations ranging from ~90,000 to 170,000. We observe 'likes' (experiment 1 & 3) and newsletter signups (experiment 2) on the Facebook page of a major US environmental NGO. 'Likes' are a small yet socially costly signal in support of the NGO. Newsletter signups are arguably more costly yet almost entirely private. A clear limitation of using Facebook 'likes' and newsletter signups is that the actions are indeed small, compared for example to engagement in lab experiments (Andrews et al 2021, Cherry et al 2022) or spending one's own money on carbon offsets (Merk et al 2016) and even more so compared to real-life, long-term behavioral changes. The advantage of our study design is that both 'likes' and newsletter signups can be interpreted as engagement with and interest in climate policy, avoiding, for example, the need to use offset purchases as a proxy for climate mitigation more broadly. More specifically, 'likes' and newsletter signups are both proxies for user attention in a highly contested social media marketplace, where it is often hard to distinguish signal from noise (e.g. Guess et al 2023).

That is especially true for 'likes' of the environmental NGO's Facebook page. 'Liking' a Facebook page is low-cost, but it does send a public signal in the sense that one's name is now linked to the group's Facebook page, and displayed there to one's own Facebook friends and others. Newsletter signups, in contrast, are arguably costlier; they are also private. Both steps send a

signal of one's desire to engage with climate policies in small but measurable ways. Furthermore, we do not focus on the absolute level of engagement, which might indeed be considered small. Instead, we focus on the differences in likes and newsletter signups when different messages are sent. The large samples allow us to test any number of frames and messages.

We ran three distinct experiments. Experiment 1 explored reactions in the form of Facebook 'likes' to different framings—from carefully presenting SRM as a 'sensible' part of a balanced climate policy portfolio, to highly politicized 'madmen' and 'techno-fix' framings presenting it as anything but, while always comparing campaigns to baseline messages about cutting emissions or climate action that use the same framings and similar images. Furthermore, Experiment 1 targeted four different subgroups of the U.S. population on the platform, utilizing Facebook's ad targeting mechanism to identify interest groups. Experiment 2 & 3 only included the most responsive user group as identified in Experiment 1; they also add CDR treatments. Specifically, we analyze whether framing SRM and CDR as complementing or substituting emissions cuts attracts more or less attention compared to a message about technologies for emissions reduction. Experiment 2 looks at changes in the likelihood to sign up to the NGO's newsletter; experiment 3 at changes in the propensity to 'like' the NGO's public Facebook page. Both use the same messages and images.

We use specifically designed explainer graphics for SRM, CDR, and mitigation, combined with carefully chosen and repeatedly tested images, and match both with different messages. Each ad is marked as "sponsored", indicating that they were paid for by the environmental NGO

(example see Figure 1).[1] Importantly, each subject sees no more than one control or treatment variation on their Facebook timeline. That also excludes users who had already 'liked' the NGO's page or subscribed to the newsletter in the past.

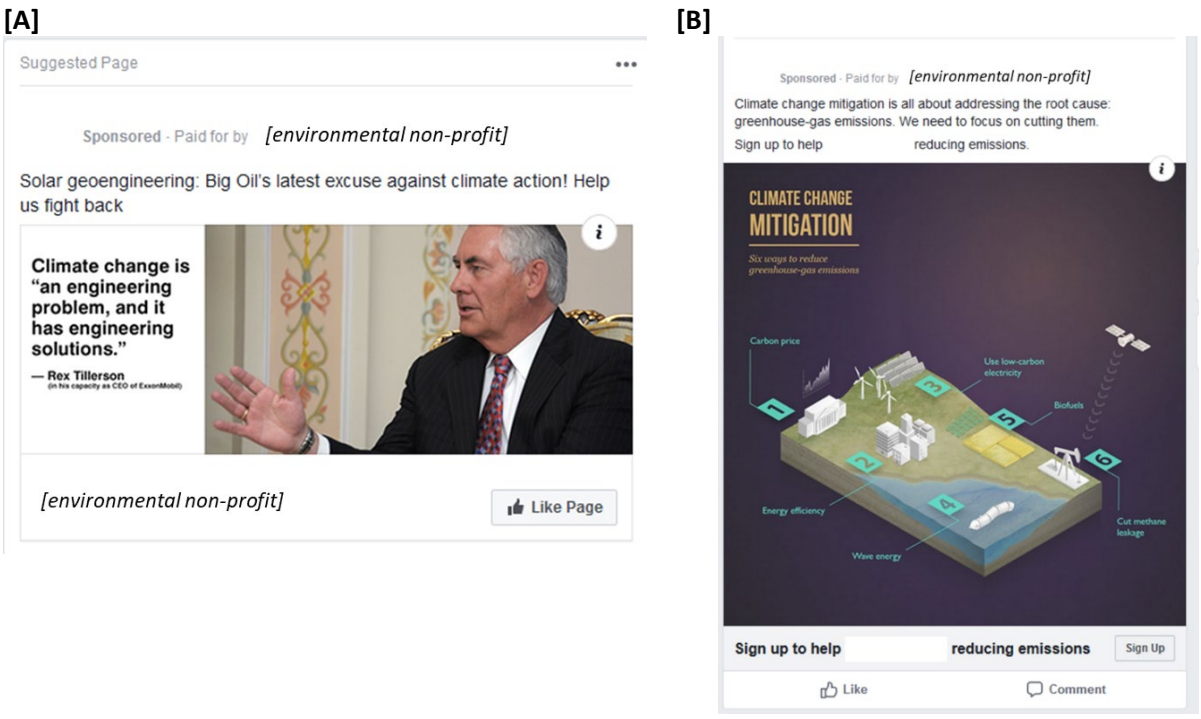


Figure 1: Example post to attract likes [A, experiment 1] or newsletter sign-ups [B, experiment 2] with message and graphic; name and logo of environmental NGO visible to Facebook users

Experiment 1

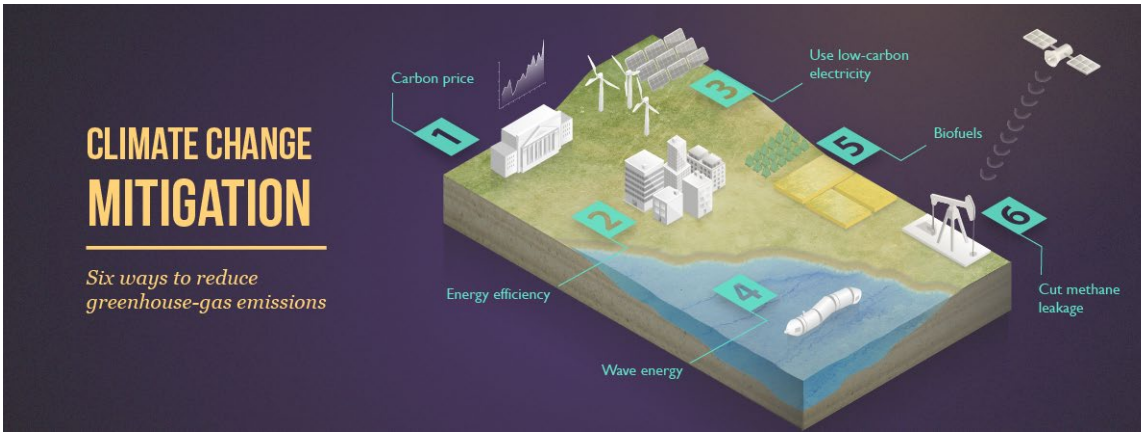
Experiment 1 was a Facebook 'like'-campaign over the course of 4 days in June 2018, testing the differences in engagement ('likes' per impression) in four framings comparing mitigation and

[1] We used the large US environmental NGO's Facebook page for this set of experiments in exchange for us compensating the NGO for the ad purchases, and under the condition of anonymity.

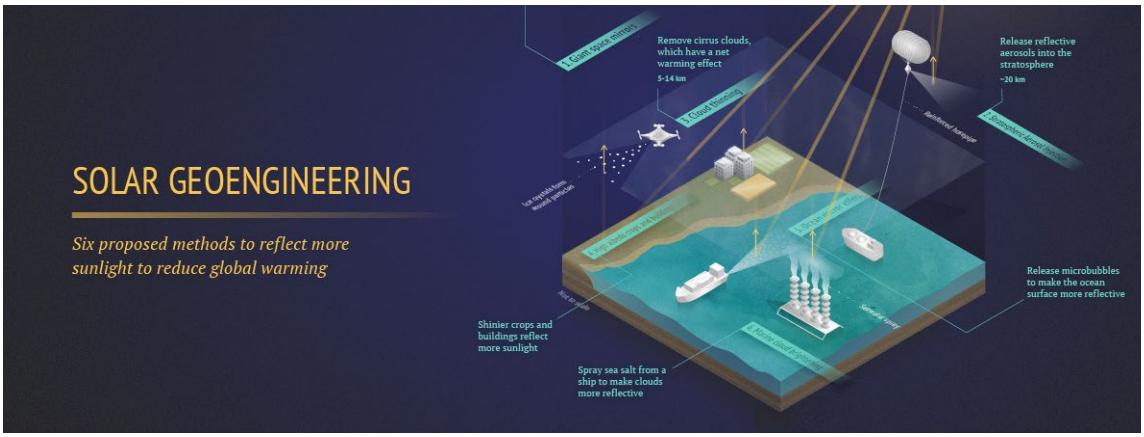
SRM. Figure 2 summarizes the experimental setup. The SRM framings are always compared to baseline messages about cutting emissions or climate action that use the same framings and similar images. In the control settings, the messages (Panel B) were either combined with the climate change mitigation graphic or the madmen graphic (Panel A). The treatment posts combined either the SRM graphic or the madmen graphic (Panel A) with various messages (Panel B).

The interpretation of *crowding in* versus *out* depends on the specific messages and framings. Two experimental settings frame SRM as part of a 'sensible' or 'rational' climate policy portfolio. Higher engagement rates in either of these two settings compared to the mitigation baseline would indicate *crowding out* of the desire to cut emissions by SRM. Two other experimental settings, in turn, are highly politicized, framing SRM as "Big oil's latest excuse" or as a 'techno-fix', calling on users to help fight back or to make an 'actual' contribution to solving climate change. Under this framing, higher engagement rates for either of the SRM framings compared to the mitigation baseline would imply *crowding in* of the desire to cut emissions by the temptation of SRM.

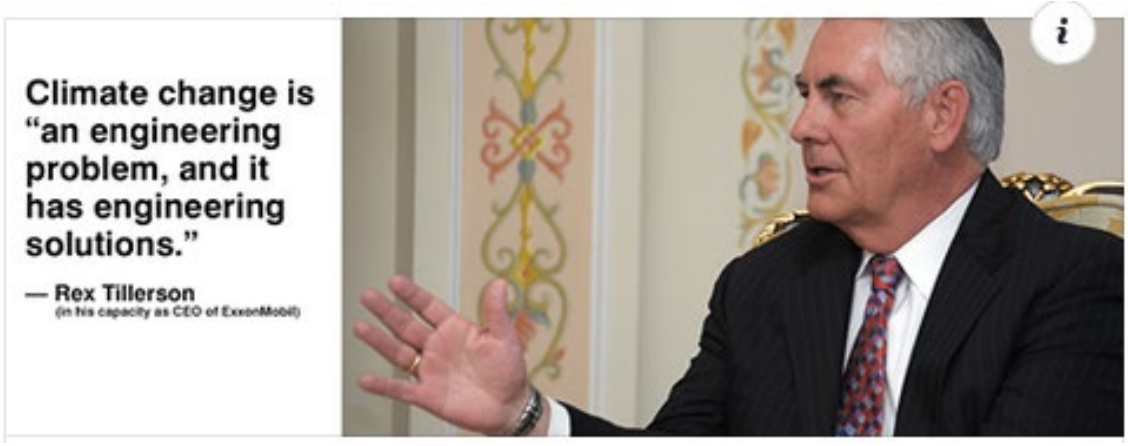
[A] graphics



Climate change mitigation (Note that our use of the term 'mitigation' focuses on reducing greenhouse-gas emissions, rather than encompassing a broader definition that might also include some CDR (IPCC 2022).)



Solar geoengineering (SRM)



Madmen

[B] messaging *[graphics]*

Control	***Treatment***
	Rational climate policy
Can clean technology help address climate change? Join us to promote rational policy *[Climate change mitigation]*	Can solar geoengineering help address climate change? Join us to promote rational policy *[Solar geoengineering]*
	Sensible climate policy
Can clean technology help address climate change? Join us to promote sensible policy *[Climate change mitigation]*	Can solar geoengineering help address climate change? Join us to promote sensible policy *[Solar geoengineering]*
	Technofix
Smart technology a fix to stabilize temperatures? Help us solve climate change *[Climate change mitigation]*	Solar geoengineering a techno-fix to stabilize temperatures? Help us solve climate change *[Solar geoengineering]*
	Madmen
Big Oil is still making excuses against climate action! Help us fight back *[Madmen]*	Solar geoengineering: Big Oil's latest excuse against climate action! Help us fight back *[Madmen]*

Figure 2: Experiment 1 - Like campaign, graphics [A] and messaging [B].

Experiment 1 included four distinct Facebook targets groups (Table A-1) which we created using Facebook's marketing platform. It contains a set of interests, actions, or attitudes that Facebook has observed in users' past engagement on the platform and beyond. We use these interests to define the four groups. For example, in June 2018 the interests 'climate engineering´ and 'chemtrail conspiracy theory´ had been identified for around 314,000 and 630,000 users, respectively. However, we do not know how much the groups overlap. We used these interests to create the subgroup 'chemtrailers´ and to exclude these users from the other groups. Beyond a general description, Facebook does not offer information on how they identify interests, necessitating, for example, us running the experiment in the subgroup 'chemtrailers' separately and dropping them in all other groups, even though doing so might also exclude some few with

genuine prior interest in geoengineering. Facebook reports engagement by gender and age groups, allowing further interpretation of these subgroups below.

Group 1, the *NGO optimization,* is a target group often used by the NGO as these are users with profiles similar to the NGO's super activists, they should, thus, be very likely to engage with the NGO's content. These users have shown an interest in environmental issues, donated to environmental and wildlife causes, and engaged with liberal political content in the past. They are most closely resembling highly active supporters of the environmental NGO. This is a setup used under realistic conditions for a 'like'-campaign run by the NGO itself.

In group 2, *Facebook optimization*, we let the platform optimize the distribution of the ads without restricting age, gender, or prior interests. This is akin to a test of how the FB-algorithm would distribute the treatments across gender and age groups without additional targeting, attempting to maximize 'likes' rather than reaching any one particular group. For this group we only know the gender and age group of the users who saw our ad. We assume that the FB-algorithm optimized the targeting by using additional information about users that is unobservable for us such as prior engagement with content on environmental issues.

In group 3, *Chemtrailers*, we target users who have shown an interest in geoengineering, climate engineering or the 'chemtrails' conspiracy theory before.[2] Beyond this interest, we only know

[2] While it might have been good to be able to distinguish genuine interest in geoengineering from conspiratorial content, social media discourse on geoengineering appears to be dominated by the latter (Tingley and Wagner, 2017). Hence, we analyze this group separately and excluded either form of prior engagement from the other groups.

users' gender and age group. This group is explicitly excluded in the three other target groups to keep Facebook from delivering the solar geoengineering treatments predominantly to these users.

In group 4, *Limited optimization,* we set up 48 audience groups to restrict the influence of Facebook's algorithm on the distribution of the treatments and to learn about the engagement with the ads among groups that are more difficult to reach, because they either have not shown any interest in similar content in the past or because they are in general less likely to engage with Facebook content. The 48 groups are defined by all possible combinations of the variables gender, age (in four groups, 18-24, 25-44, 45-64, and 65+), interest in environmental causes (yes, no), and 3 political leanings (conservative, moderate, and liberal). Engagement rates are reported by audience groups, and we allocated the same advertising budget to all 48 groups. Thus, in audience groups that are less likely to engage with the NGO and our content, Facebook shows the post to more users, raising the price per successful engagement.

At the time of the experiment, there were about 230 million Facebook user accounts in the US that could be classified by age and gender (Table 1). Accounts of organizations or institutions are excluded. Table 1 shows the share of observations by age and gender within the groups and compares them to all Facebook users at the time. In the NGO optimization and the Facebook optimization, women and older users are over-represented, while among Facebook users in general, these same groups are underrepresented. The highest share of users is between 25 and 44 years old, with some detectable patterns. For example, people in the 'Chemtrailers´ group tend to be male and between 25 and 64 years old. We can also see the effect of our limited

optimization setup in the distribution. There, we force Facebook to also target those with lower-than-average engagement rates, for example young adults. The share in the 18-24-years group is particularly high because they are less likely to engage with our ad, increasing the number of impressions to create any engagement. Conversely, the share of women above 65 is lower because fewer impressions are needed to create similar rates of engagement. This observation alone implies that the NGO and our content speak mostly to older women.

		Age			
		18-24	**25-44**	**45-64**	**65+**
NGO optimization	male	0.3%	3.0%	13.3%	15.7%
N=16,147	female	0.5%	5.5%	22.9%	38.8%
FB optimization	male	3.1%	13.7%	14.0%	10.1%
N=15,906	female	3.1%	13.2%	19.7%	23.1%
Chemtrailers	male	5.0%	27.4%	19.5%	6.3%
N=3,330	female	2.4%	16.8%	15.1%	7.6%
Limited optimization	male	17.3%	16.6%	11.6%	10.1%
N=136,224	female	16.5%	12.6%	8.0%	7.5%
Facebook users August 2018	male	8.7%	22.6%	11.7%	4.0%
N~230,100,000	female	8.7%	23.0%	15.2%	6.1%

Table 1: Distribution of age and gender in our sample in the four groups and among Facebook users in August 2018. The sample consists of all the users on whose timeline our ad appeared. The shares add up to 100% within the groups.

Table 2 shows engagement rates by treatment and target groups. Overall, the ads appeared on the timeline of 171,607 users and generated 3,229 likes for the NGO's page, implying an overall engagement rate of 1.88%. Engagement varies between 1% (limited optimization, non-environmentalists, 'rational', treatment) and 3.28% (NGO optimization, 'madmen', control). 'NGO optimization' and 'Facebook optimization' result in similar levels of engagement

(probability test: NGO = FB optimization, p=0.512) and they are significantly higher than the engagement rates among the 'Chemtrailers' and the limited targeting setup (pairwise probability tests: p<0.000). The low levels of engagement from 'Chemtrailers' and in the 'Limited optimization' setting, in turn, are not significantly different (p=0.352).

					Limited optimization		
		NGO optimization	**Facebook optimization**	**Chemtrailers**	**NON-environ-mentalists**	**environ-mentalists**	***Total***
Rational	treatment	2.43%	2.67%	1.21%	1.00%	2.46%	*1.61%*
		1,849	1,645	413	9,398	6,708	*16,106*
	control	3.32%	2.14%	0.54%	1.17%	2.59%	*1.76%*
		1,986	2,102	368	9,119	6,492	*15,611*
Sensible	treatment	2.71%	2.91%	0.73%	1.00%	2.20%	*1.51%*
		1,885	1,751	414	10,042	7,422	*17,464*
	control	2.95%	2.55%	1.44%	1.09%	2.37%	*1.68%*
		1,900	2,194	278	9,456	8,093	*17,549*
Technofix	treatment	2.29%	2.36%	2.17%	1.00%	2.26%	*1.53%*
		1,879	1,778	415	9,458	6,721	*16,179*
	control	2.62%	2.62%	0.92%	1.11%	2.33%	*1.61%*
		1,948	2,064	543	10,453	7,282	*17,735*
Madmen	treatment	2.90%	3.18%	2.83%	1.15%	2.53%	*1.77%*
		2,140	1,981	495	9,475	7,712	*17,187*
	control	3.28%	3.22%	1.73%	1.31%	2.71%	*1.96%*
		2,560	2,391	404	9,832	8,561	*18,393*
Total		2.84%	2.72%	1.47%	1.10%	2.44%	*1.68%*
		16,147	15,906	3,330	77,233	58,991	*136,224*

Table 2: Experiment 1, engagement rates in % and impressions by treatment groups and target groups

We run logit models to analyze the experimental effects in treatment and control groups separately in each of the four audience setups. Figure 3 shows the coefficients from logit regressions for liking the page dependent on the experimental setting, gender, and age

category. Table A-1 provides more detail on each. In the logit regressions for the 'Limited optimization' group we control for political leaning and interest in environmental topics in addition to gender and age to avoid omitted variable bias, as these were the characteristics our targeting was based on (Table A-2).

We do not find significant differences between the treatment and the control settings in any of the audience groups (Figure 3). Moreover, engagement rates do not vary significantly between treatments in the groups. The exception is among 'Chemtrailers', where, contrary to our expectation, overall engagement rates are low (1.47%, see Table 2). There is a marginally significant difference (probability tests: $p = 0.019$) between the 'sensible' framing (0.73%) that implies that solar geoengineering could play a part in sensible climate policy and the 'madmen' treatment (2.83%) that calls for engagement against SRM with the pugnacious message "Solar geoengineering: Big Oil's latest excuse against climate action! Help us fight back".

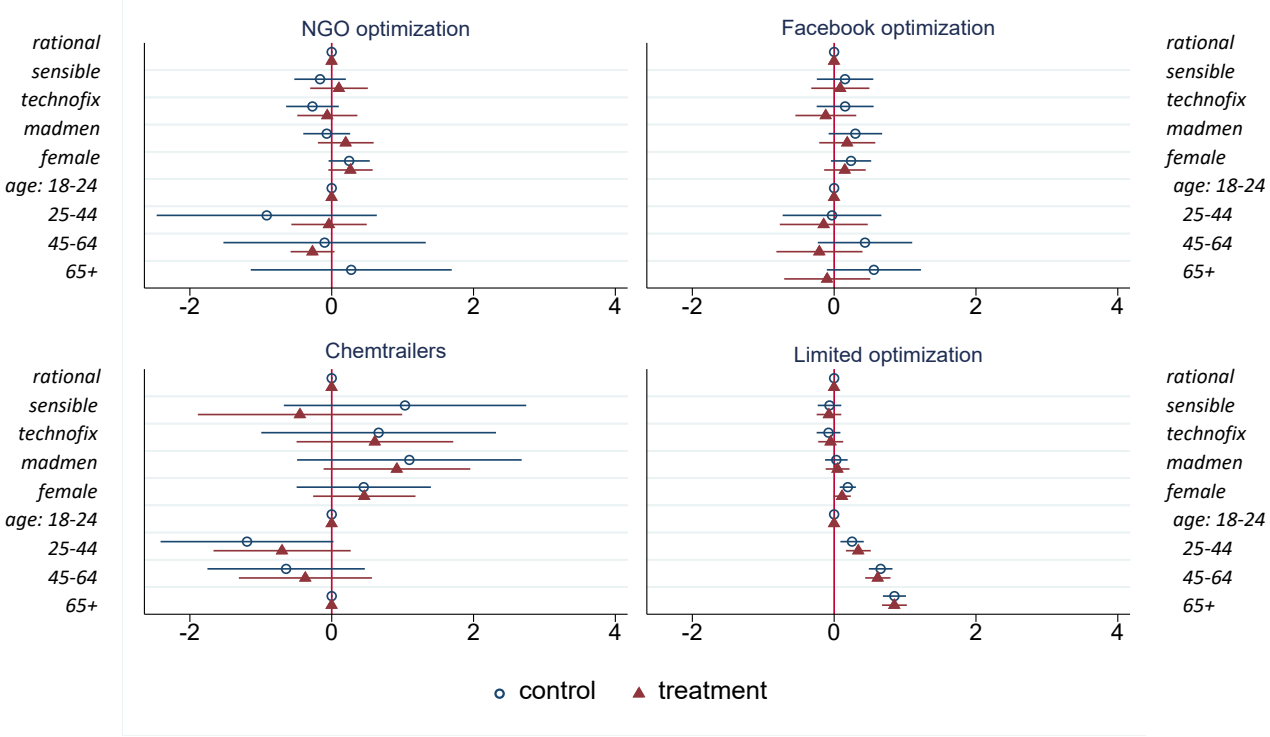


Figure 3: Coefficients from logit regression for no like vs. like (experiment 1) with 95%-confidence intervals for treatment and control groups by audience groups; treatment/control group-coefficients are relative to the base category 'rational'

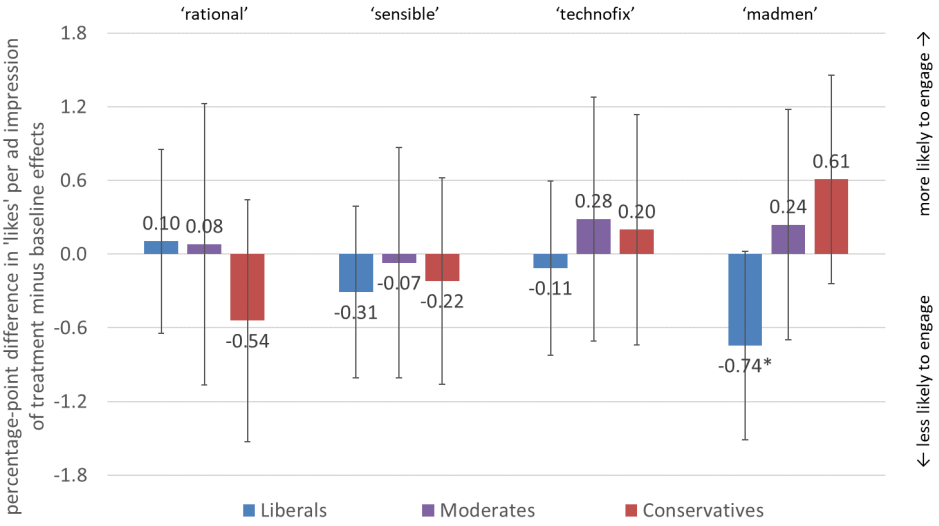
Note: Table A-1 shows detailed results for NGO optimization, Facebook optimization, and Chemtrailers. See Table A-2 for the 'limited optimization' group, where we also control for political leaning and interest in environmental topics. NGO optimization N=16,147; Facebook optimization N=15,906; Chemtrailers N=3,330; Limited optimization: N=136,224. 65+ is reference category in the Chemtrailers group when 18-24 group empty.

We now zoom in on the 'limited optimization' setup, as it allows us to observe political leanings and interest in environmental causes in addition to gender and age. Engagement rates among users that are not interested in environmental topics are comparatively low (~1.1% versus ~2.4% for users who have shown prior interest in environmental topics, Table 2) and do not vary substantially or significantly between treatments (Figure A-1). We, therefore, focus on users in the ´limited optimization' target groups that are interested in environmental topics, with n~59,000 (Table 2).

Figure 4**A** displays the differences in engagement rates between treatment and control settings by political leanings, the 95% confidence intervals and results for probability tests comparing the differences between groups. Figure 4**B** shows the logit coefficients relative to the respective base category by political leaning. The model setup is the same as before, controlling for gender and age.

Overall, we find that presenting balanced geoengineering information (Figure 2), describing it as part of 'rational' or 'sensible' climate policy, exhibits neither crowding in nor out, compared to calling for 'rational' or 'sensible' mitigation policy sans mention of 'geoengineering' (Figure 4**A**). The same goes for presenting SRM as a 'technofix'.

A



B

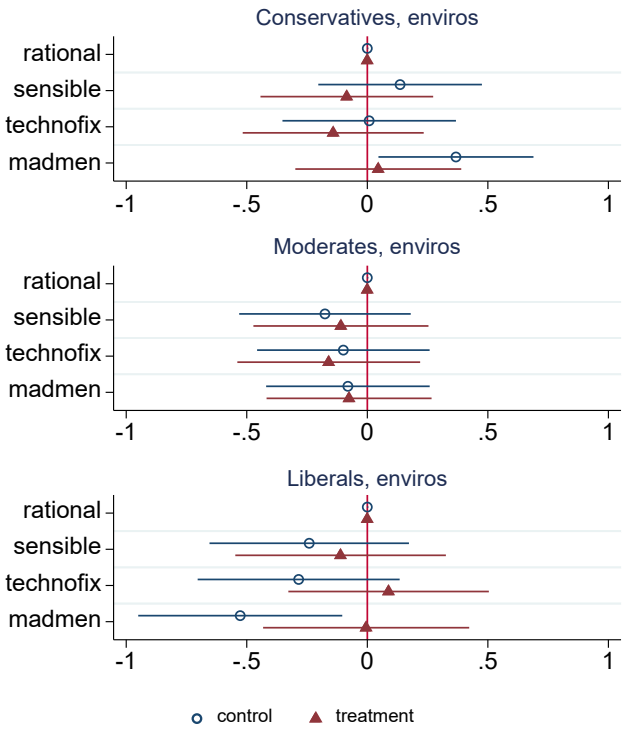


Figure 4—Treatment effect by framing and political leaning of Facebook 'like' campaign testing 'rational' and 'sensible' (Figure 2) in a campaign with n~59,000 users who had shown an interest in environmental topics before. ***A*** *shows percentage point differences (treatment – control) and 95% confidence intervals for probability tests. * indicates statistical significance at the 10%-level, ** at the 5%-level (compare Table A-3)* ***B*** *shows the coefficients from logit regression controlling for age and gender and 95% confidence intervals, with n=16,318 for Conservatives, n=17,833 for Moderates, and n=24,840 for Liberals*

(Progressives), note that coefficients have to be interpreted relative to the respective base category, the 'rational' setting (see Table A-4 for full results).

Only the extreme 'madmen' framing presented in a highly polarized context evokes either crowding in or out, with large differences across the political spectrum (Figure 4). Adding SRM to a framing that presents Republicans' climate policy as 'madmen' and calling SRM "Big Oil's latest excuse against climate action", for example, increases conservatives' 'likes' compared to the baseline message that shows the same image but drops "solar geoengineering" from the text and instead calls out "Big Oil" more directly as "still making excuses against climate action!" (+0.61 percentage points, n = 4,325). It also decreases liberals' support (-0.74 percentage points, n = 6,705). One reason for this divergence might be that progressive environmentalists are more motivated by the baseline message (3.21% engagement rate; Table A-3, Figure 2**B**), while conservatives are pushed away (2.30%); mentioning "solar geoengineering" in the 'madmen' framing does not influence liberals' or conservatives' level of engagement significantly compared to the 'rational' mitigation messaging. Thus, the difference is driven by the reactions to the baseline rather than the SRM treatment.

In other words, these results from Experiment 1 allow us to say with some confidence that, in the context of our large-scale social media experiment, talking about solar geoengineering does not motivate our study population to support a large US environmental NGO; it also does not turn them off relative to the baseline.

Experiments 2 and 3

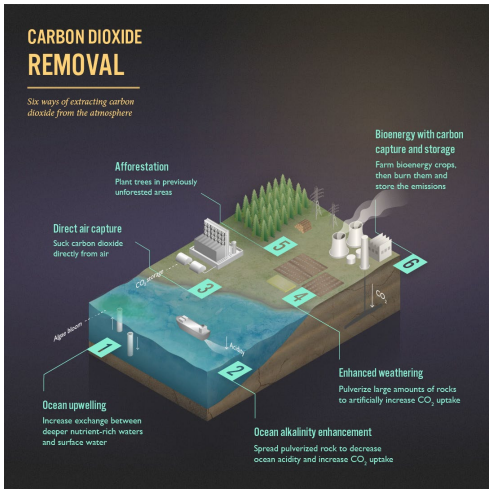
Experiment 2 focused on a newsletter-campaign testing the differences in engagement in form of newsletter sign-ups per impression. We compare engagement rates for two CDR treatments

and two SRM treatments each to one baseline mitigation treatment. We frame the approaches either as a complement to reducing emissions or as a substitute for reducing emissions. Figure 5 shows the experimental setup, including graphics and messaging.

Signing up for the NGO's newsletter shows a higher level of engagement and interest than 'liking' a post, as it takes more time to submit the email address, and it means that one will receive regular emails. However, while the step might be more costly, it is also more private, as signing up with one's email address does not appear on the NGO's public Facebook page. We, therefore, test the same framings as a 'like'-campaign in Experiment 3 to test whether the difference in public or private costs influences the results. All campaigns ran between March and June 2019.

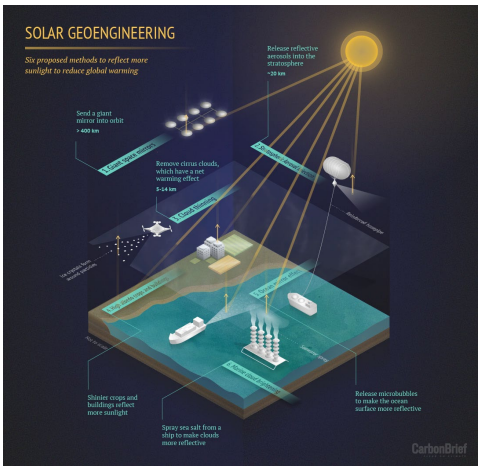
The more detailed messaging in Experiments 2 and 3 compared to 1 allowed for a direct test of 'complement' versus 'substitute' framings. If the 'moral hazard' crowding-out mechanism dominated, we would expect the CDR or SRM 'substitute' framings to lead to higher engagement rates. If instead the inverse crowding-in hypothesis dominated, we would expect the respective 'complement' framings to lead to more engagement than the standard mitigation campaign.

[A Graphics]



Mitigation

Carbon dioxide removal



Solar geoengineering

[B messaging]

Newsletter sign-up	***Like campaign***
Mitigation	
Climate change mitigation is all about addressing the root cause: greenhouse-gas emissions. We need to focus on cutting them. **Sign up to help *[NGO name]'s* work on reducing emissions.**	Climate change mitigation is all about addressing the root cause: greenhouse-gas emissions. We need to focus on cutting them. **Like *[NGO name]* to help our work on reducing emissions.**
CDR complement	
Carbon dioxide removal takes carbon out of the atmosphere and stores it in the ocean or ground. It limits climate changes without addressing the root cause: greenhouse-gas emissions. We need to focus on cutting them. Don't be distracted by carbon dioxide removal. **Sign up to help *[NGO name]'s* work on reducing emissions.**	Carbon dioxide removal takes carbon out of the atmosphere and stores it in the ocean or ground. It limits climate changes without addressing the root cause: greenhouse-gas emissions. We need to focus on cutting them. Don't be distracted by carbon dioxide removal. **Like *[NGO name]* to help our work on reducing emissions.**
CDR substitute	
Carbon dioxide removal takes carbon out of the atmosphere and stores it in the ocean or ground. It helps limit climate changes without needing to cut greenhouse-gas emissions. We need to focus on looking into these methods. **Sign up to help *[NGO name]'s* work exploring carbon dioxide removal.**	Carbon dioxide removal takes carbon out of the atmosphere and stores it in the ocean or ground. It helps limit climate changes without needing to cut greenhouse-gas emissions. We need to focus on looking into these methods. **Like *[NGO name]* to help our work exploring carbon dioxide removal.**
SRM complement	
Solar geoengineering could partially block sunlight and lower global temperatures. It limits climate changes without addressing the root cause: greenhouse-gas emissions. We need to focus on cutting them. Don't be distracted by solar geoengineering. **Sign up to help *[NGO name]'s* work on reducing emissions.**	Solar geoengineering could partially block sunlight and lower global temperatures. It limits climate changes without addressing the root cause: greenhouse-gas emissions. We need to focus on cutting them. Don't be distracted by solar geoengineering. **Like *[NGO name]* to help our work on reducing emissions.**
SRM substitute	
Solar geoengineering could partially block sunlight and lower global temperatures. It helps limit climate changes without needing to cut greenhouse-gas emissions. We need to focus on looking into these methods. **Sign up to help *[NGO name]'s* work on exploring solar geoengineering.**	Solar geoengineering could partially block sunlight and lower global temperatures. It helps limit climate changes without needing to cut greenhouse-gas emissions. We need to focus on looking into these methods. **Like *[NGO name]* to help our work on exploring solar geoengineering.**

Figure 5: Experiments 2 and 3 – Newsletter sign-up and Like campaign, graphics [A] and messaging [B].

The target group for Experiments 2 and 3 were akin to the environmentalists in the *Limited optimization* in Experiment 1: Facebook users who have shown prior interest in environmental topics, excluding users who have shown an interest in chemtrails, geoengineering or climate engineering. Again as in experiment 1, political leanings ('liberal', 'moderate', and 'conservative') were targeted separately to avoid Facebook's ad targeting algorithm focusing ads to more liberal users, who have a higher likelihood to engage with the content and the NGO.

The newsletter campaign appeared on the timeline of ~91,000 users, the like campaign on ~82,000, with average engagement rates of 0.96% and 2.64%, respectively (Table 3). As anticipated, engagement rates were substantially lower in the newsletter campaign than in the like campaign, indicating higher (private) costs of the former.

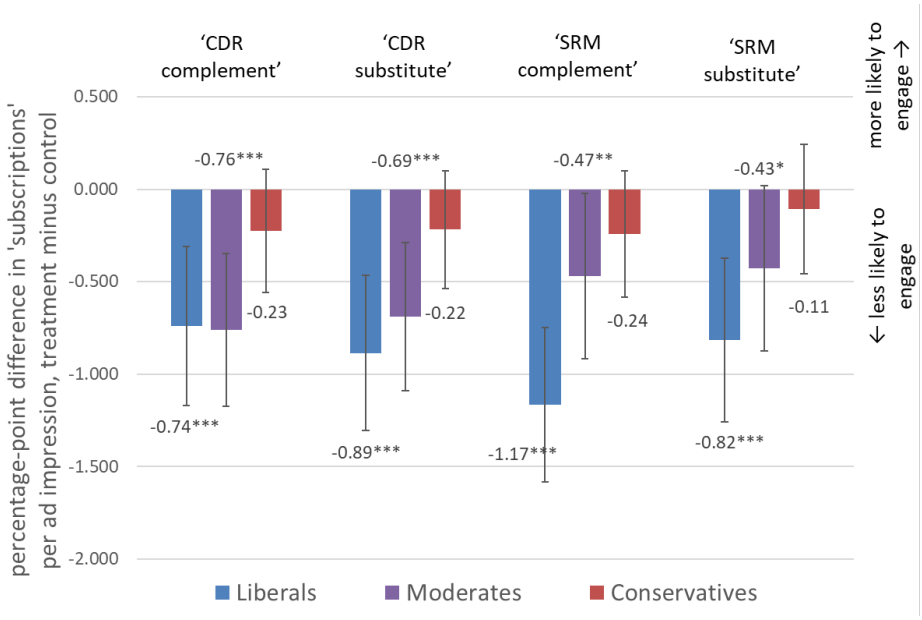
	Liberals			Moderates			Conservatives		
		T- C			T- C			T- C	
Newsletter	*n=38,369*			*n=27,455*			*n=25,131*		
Mitigation [C]	*2.06%*			*1.34%*			*0.75%*		
CDR complement [T]	1.32%	-0.74	***	0.57%	-0.77	***	0.53%	-0.22	
CDR substitute [T]	1.17%	-0.89	***	0.64%	-0.70	***	0.53%	-0.22	
SRM complement [T]	0.89%	-1.17	***	0.86%	-0.48	**	0.51%	-0.24	
SRM substitute [T]	1.25%	-0.81	***	0.90%	-0.44	*	0.65%	-0.10	
Like	*n=38,854*			*n=24,793*			*n=18,268*		
Mitigation [C]	*2.70%*			*2.55%*			*3.32%*		
CDR complement [T]	2.60%	-0.09		2.76%	0.22		2.69%	-0.64	*
CDR substitute [T]	2.13%	-0.57	**	2.22%	-0.33		2.43%	-0.90	**
SRM complement [T]	3.07%	0.38		3.56%	1.01	**	2.86%	-0.46	
SRM substitute [T]	2.74%	0.04		2.40%	-0.15		2.80%	-0.53	

*Table 3: Engagement rates in % by treatment groups and political leaning and difference between treatment groups [T] and control group [C] in percentage points; * indicates statistical significance at the 10%-level, ** at the 5%-level, *** at the 1%-level. See also Figure 6.*

In Experiment 2, the newsletter campaign, engagement is either not significantly different compared to traditional mitigation messaging – for conservatives in all framings and for moderates in the SRM framings ($p>0.01$) – or it is lower – for liberals in all framings ($p<0.01$; Figures 6**A** and 7**A**). This means messaging about technologies to cut emissions attracts more attention compared to any messaging about CDR or SRM; i.e. the engagement with climate action is crowded out.

In the like campaign, the results are mixed (Figures 6**B** and 7**B**). The 'complement' framing shows significantly higher engagement rates compared to the 'substitute' framing for Liberals/CDR ($p=0.028$), Moderates/CDR ($p=0.071$) and Moderates/SRM ($p=0.003$, Table 4). That result might support the 'inverse moral hazard' (crowding-in) hypothesis, albeit weakly so. There is no such significant result for conservatives, further supporting the conclusion that 'reasonable' CDR or SRM messages do not lead to either crowding out nor in of the desire to mitigate.

A [Newsletter sign-ups]



B ['like' campaign]

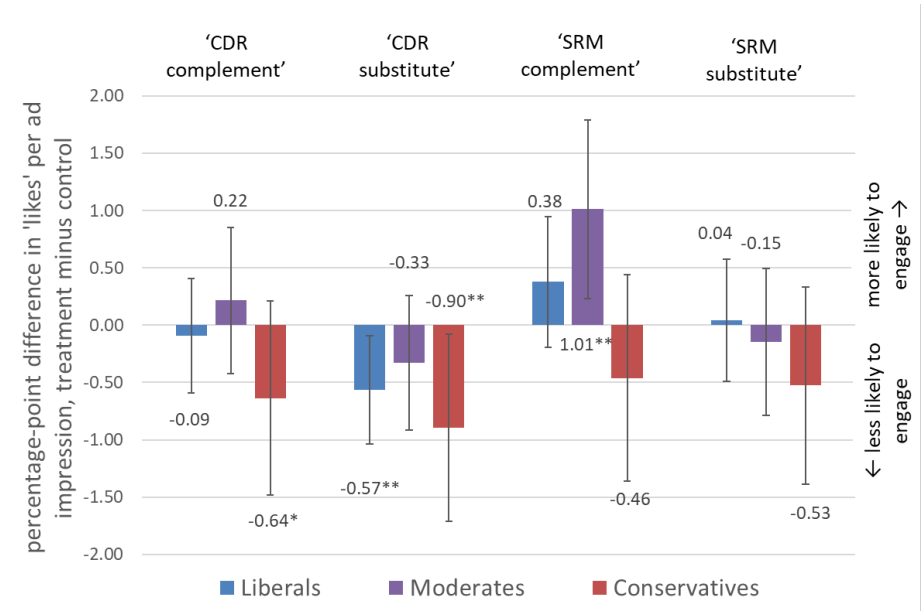
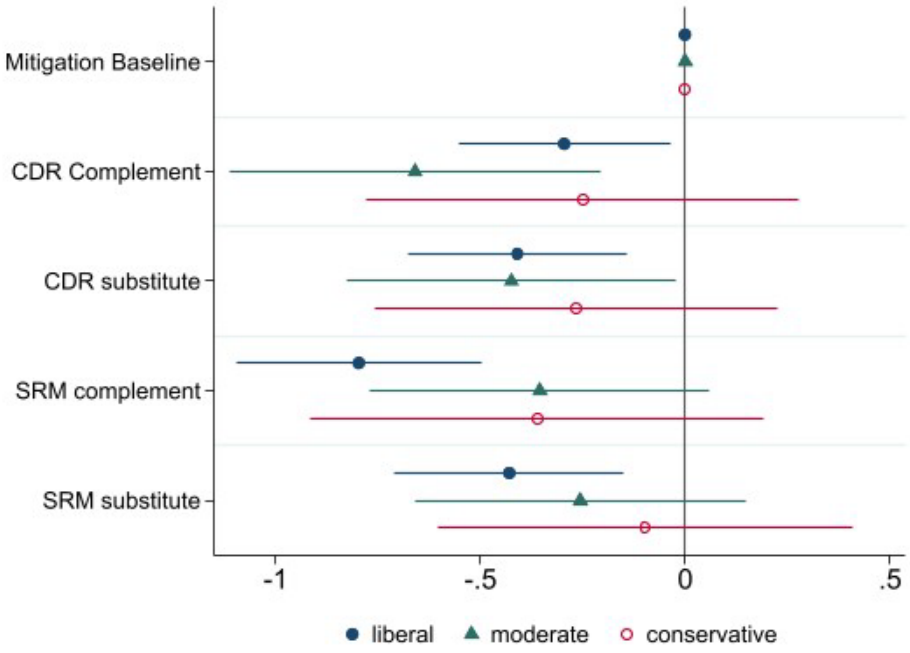


Figure 6 – Treatment effect by framing and political leaning of Facebook 'newsletter sign-up' campaign (panel A, n=90,955) and 'like' campaign (panel B, n=81,915) testing 'CDR Complement', 'CDR substitute', 'SRM complement' and 'SRM substitute' against the control framing 'mitigation' (Figure A-*). Figures show percentage point differences (treatment – control) and 95% confidence intervals for probability tests. * indicates statistical significance at the 10%-level, ** at the 5%-level, *** at the 1%-level. (See Table 3 for detailed results.)*

A [Newsletter sign-up campaign]



B ['like' campaign]

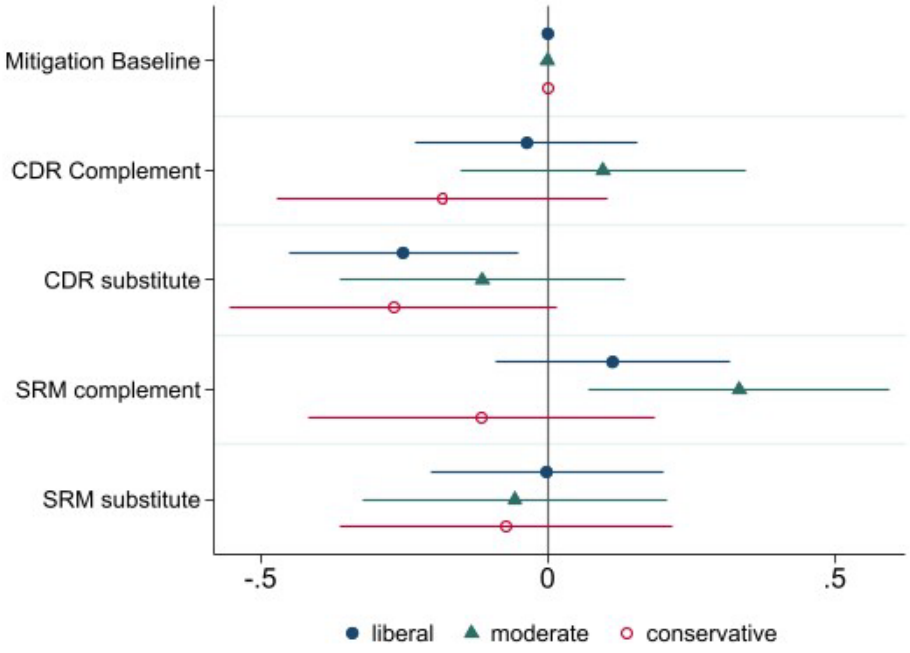


Figure 7 – Coefficient plots and 95% confidence intervals by political leaning for the newsletter campaign [A] and the like-campaign [B] testing the materials and messages in experiment 2 and 3 (see Figure 5), coefficients not shown: female, age, campaign round (only for newsletter), full results see Table A-5.

We further test the difference in complementarity versus substitutability framings by directly comparing coefficients from the logit regressions (Figure 7). Table 4 presents the results, showing statistically significant differences for SRM among liberals in the newsletter campaign (-0.367; p = 0.025), and for CDR among liberals in the 'like' campaign (0.215; p = 0.028), as well as for moderates in the 'like' campaigns for both CDR (0.210; p = 0.071) and SRM (0.391; p = 0.003). The sign for the SRM newsletter campaign among liberals is negative, pointing to how liberals in this case might be swayed more by the substitutability argument, whereas the positive signs in the 'like' campaigns would point to the opposite. We would, however, caution against over-interpreting these results, precisely because there appears to be little agreement across campaigns. In any case, the majority of comparisons here, too, supports the overall null finding of there not being a significant difference across framings.

	Liberals			Moderates			Conservatives		
	comp - subst	SE	p	comp - subst	SE	p	comp - subst	SE	p
Newsletter									
CDR	0.115	0.136	0.397	-0.235	0.228	0.303	0.016	0.254	0.951
SRM	-0.367 **	0.164	0.025	-0.099	0.216	0.648	-0.263	0.280	0.347
Like									
CDR	0.215 **	0.098	0.028	0.210 *	0.117	0.071	0.085	0.137	0.536
SRM	0.114	0.104	0.270	0.391 **	0.133	0.003	-0.043	0.146	0.768

*Table 4: Hypotheses tests of difference between the logit coefficients CDR complement [compl] – CDR substitute [subst] = 0 and SRM complement [compl] – SRM substitute [subst] = 0 from regression in Table A-5, standard errors and p-values; * p<0.1, ** p<0.05, *** p<0.01; See also Figure 7.*

Conclusion

Our results add to a large and growing 'moral hazard' literature on geoengineering. While some studies find weak support for crowding out, depending on the framing (e.g. Raimi et al 2019),

others find crowding in both in surveys (Cherry et al 2021) and revealed-preference experiments (Merk et al 2016, Andrews et al 2022, Cherry et al 2022). Using a large-scale Facebook experiment allows for a significantly larger sample size (a combined n~340,000), with ample room for experimentation about which messages raise attention among which user groups. At the same time, it reveals some novel challenges driven by overall low engagement rates. Moreover, any effects observed on Facebook may not extend to changes in broader beliefs and opinions (Guess et al. 2023). In short, a large-scale Facebook experiment most directly tests behavior exhibited on Facebook.

This null finding of neither consistent experimental support for 'moral hazard' nor its inverse may, thus, not be surprising. In the end, our study participants appear to be more swayed by framing and other external factors than by the characteristics of SRM or CDR per se. They are not alone. Framing matters (Raimi et al 2019), and even experts exhibit biases: The worse climate damages are, the less inclined they are to support SRM; that conclusion changes as they expect worse climate damages in their home country (Dannenberg and Zitzelsberger 2019).[3] Arguably, none of these findings, including ours, present a good guide for whether crowding in or out will indeed occur in the presence of SRM or CDR as part of public climate policy discourse. If anything, such effects might well depend more on policymakers' perceptions of public opinions (Andrews et al 2022) and second-order opinions more broadly (Mildenberger and Tingley 2019), as well as on vested and institutional interests (Buck 2019).

[3] Merk et al (2019), in a stated-preference survey, shows that laypeople exhibit moral hazard behavior, while experts do not.

References

Andrews, Talbot M., Andrew W. Delton, and Reuben Kline. "Anticipating moral hazard undermines climate mitigation in an experimental geoengineering game." *Ecological Economics* 196 (2022): 107421.

Barberá, Pablo. "Social media, echo chambers, and political polarization." *Social media and democracy: The state of the field, prospects for reform* 34 (2020).

Buck, Holly Jean. After geoengineering: Climate tragedy, repair, and restoration. *Verso Books*, 2019.

Burns, Elizabeth T., Jane A. Flegal, David W. Keith, Aseem Mahajan, Dustin Tingley, and Gernot Wagner. "What do people think when they think about solar geoengineering? A review of empirical social science literature, and prospects for future research." *Earth's Future* 4, no. 11 (2016): 536-542.

Cherry, Todd L., Steffen Kallbekken, Stephan Kroll, and David M. McEvoy. "Does solar geoengineering crowd out climate change mitigation efforts? Evidence from a stated preference referendum on a carbon tax." *Climatic Change* 165, no. 1 (2021): 1-8.

Cherry, Todd L., Stephan Kroll, David M. McEvoy, David Campoverde, and Juan Moreno-Cruz. "Climate cooperation in the shadow of solar geoengineering: an experimental investigation of the moral hazard conjecture." *Environmental Politics* (2022): 1-9.

Corner, Adam, and Nick Pidgeon. "Geoengineering, climate change scepticism and the 'moral hazard'argument: an experimental study of UK public perceptions." *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 372, no. 2031 (2014): 20140063.

Crutzen, Paul J. "Albedo enhancement by stratospheric sulfur injections: a contribution to resolve a policy dilemma?." *Climatic change* 77, no. 3-4 (2006): 211.

Dannenberg, Astrid, and Sonja Zitzelsberger. "Climate experts' views on geoengineering depend on their beliefs about climate change impacts." *Nature climate change* 9, no. 10 (2019): 769-775.

Guess, Andrew M., Neil Malhotra, Jennifer Pan, Pablo Barberá, Hunt Allcott, Taylor Brown, Adriana Crespo-Tenorio et al. "Reshares on social media amplify political news but do not detectably affect beliefs or opinions." *Science* 381, no. 6656 (2023): 404-408.

Hart, P. Sol, Victoria Campbell-Arvai, Kimberly S. Wolske, and Kaitlin T. Raimi. "Moral hazard or not? The effects of learning about carbon dioxide removal on perceptions of climate mitigation in the United States." *Energy Research & Social Science* 89 (2022): 102656.

IPCC (2022). Summary for Policymakers. In P. R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum,… J. Malley (Eds.), Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK, New York, NY, USA: *Cambridge University Press*. doi: 10.1017/9781009157926.001

Jebari, Joseph, Olúfémi O. Táíwò, Talbot M. Andrews, Valentina Aquila, Brian Beckage, Mariia Belaia, Maggie Clifford et al. "From moral hazard to risk-response feedback." *Climate Risk Management* 33 (2021): 100324.

Keith, David W. "Geoengineering the climate: History and prospect." *Annual review of energy and the environment* 25, no. 1 (2000): 245-284.

Lawrence, Mark G. "The geoengineering dilemma: To speak or not to speak." *Climatic Change* 77, no. 3-4 (2006): 245.

Lawrence, Mark G., and Paul J. Crutzen. "Was breaking the taboo on research on climate engineering via albedo modification a moral hazard, or a moral imperative?" *Earth's Future* 5, no. 2 (2017): 136-143.

Lin, Albert C. "Does geoengineering present a moral hazard." *Ecology LQ* 40 (2013): 673.

Mahajan, Aseem, Dustin Tingley, and Gernot Wagner. "Fast, cheap, and imperfect? US public opinion about solar geoengineering." *Environmental Politics* 28, no. 3 (2019): 523-543.

Marshall, John M. "Moral hazard." *The American Economic Review* 66, no. 5 (1976): 880-890.

McLaren, Duncan. "Mitigation deterrence and the “moral hazard” of solar radiation management." *Earth's Future* 4, no. 12 (2016): 596-602.

Mercer, Ashley M., David W. Keith, and Jacqueline D. Sharp. "Public understanding of solar radiation management." *Environmental Research Letters* 6, no. 4 (2011): 044006.

Merk, Christine, Gert Pönitzsch, and Katrin Rehdanz. "Knowledge about aerosol injection does not reduce individual mitigation efforts." *Environmental Research Letters* 11, no. 5 (2016): 054009.

Merk, Christine, Gert Pönitzsch, and Katrin Rehdanz. "Do climate engineering experts display moral-hazard behaviour?." *Climate Policy* 19, no. 2 (2019): 231-243.

Mildenberger, Matto, and Dustin Tingley. "Beliefs about climate beliefs: the importance of second-order opinions for climate politics." *British Journal of Political Science* 49, no. 4 (2019): 1279-1307.

Morrow, David R. "Ethical aspects of the mitigation obstruction argument against climate engineering research." *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 372, no. 2031 (2014): 20140062.

Pidgeon, Nick, Adam Corner, Karen Parkhill, Alexa Spence, Catherine Butler, and Wouter Poortinga. "Exploring early public responses to geoengineering." *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 370, no. 1974 (2012): 4176-4196.

Raimi, Kaitlin T., Alexander Maki, David Dana, and Michael P. Vandenbergh. "Framing of geoengineering affects support for climate change mitigation." *Environmental Communication* 13, no. 3 (2019): 300-319.

Reynolds, Jesse. "A critical examination of the climate engineering moral hazard and risk compensation concern." *The Anthropocene Review* 2, no. 2 (2015): 174-191.

Tingley, Dustin, and Gernot Wagner. "Solar geoengineering and the chemtrails conspiracy on social media." *Palgrave Communications* 3, no. 1 (2017): 1-7.

Tsipiras, Katelyn, and Will J. Grant. "What do we mean when we talk about the moral hazard of geoengineering?." *Environmental Law Review* 24, no. 1 (2022): 27-44.

Wagner, Gernot, and Martin L. Weitzman. *Climate shock: the economic consequences of a hotter planet*. Princeton University Press, 2015.

Wagner, Gernot, and Daniel Zizzamia. "Green moral hazards." *Ethics, Policy & Environment* (2021): 1-17.

Supplementary Material

	NGO optimization		Facebook optimzation		Chemtrailers	
	Treatment	Control	Treatment	Control	Treatment	Control
Framing, baselevel: rational						
sensible	0.103	-0.164	0.087	0.154	-0.447	1.034
	(0.207)	(0.185)	(0.209)	(0.203)	(0.735)	(0.872)
technofix	-0.062	-0.271	-0.117	0.155	0.609	0.662
	(0.216)	(0.190)	(0.219)	(0.205)	(0.564)	(0.845)
madmen	0.199	-0.070	0.185	0.300	0.920 *	1.095
	(0.200)	(0.169)	(0.202)	(0.193)	(0.528)	(0.808)
Female	0.265 *	0.247 *	0.152	0.238	0.460	0.452
	(0.160)	(0.148)	(0.149)	(0.145)	(0.368)	(0.483)
Age, baselevel: 18-24						
25-44	-0.037	-0.916	-0.146	-0.030	-0.700	-1.194 *
	(0.271)	(0.792)	(0.316)	(0.355)	(0.494)	(0.622)
45-64	-0.270 *	-0.100	-0.207	0.435	-0.371	-0.643
	(0.158)	(0.728)	(0.310)	(0.340)	(0.479)	(0.566)
65+	0.000	0.275	-0.098	0.560 *	0.000	0.000
	(.)	(0.723)	(0.309)	(0.339)	(.)	(.)
Constant	-3.774 ***	-3.596 ***	-3.547 ***	-4.270 ***	-4.161 ***	-4.667 ***
	(0.208)	(0.729)	(0.321)	(0.351)	(0.607)	(0.840)
N	7,702	8,394	7,155	8,751	1,628	1,458
Pseudo R^2	0.004	0.012	0.002	0.010	0.035	0.041
df	6	7	7.000	7	6	6
Log likelihood	-927.089	-1135.481	-910.469	-1060.119	-148.080	-93.010

Table A-1: Logit regression on likes (experiment 1) for treatment and control groups; Reported are logit coefficients and standard errors in parentheses.

*Note: * p<0.1, ** p<0.05, *** p<0.01*; results *see also Figure 3. 65+ is reference category in the Chemtrailers group because 18-24 group empty.*

	Limited optimization			
	Treatment		Control	
Framing, baselevel: rational				
sensible	-0.073		-0.065	
	(0.089)		(0.085)	
technofix	-0.049		-0.080	
	(0.090)		(0.085)	
madmen	0.049		0.031	
	(0.062)		(0.081)	
Female	0.113	*	0.193	***
	(0.086)		(0.058)	
Age, baselevel: 18-24				
25-44	0.342	***	0.253	***
	(0.089)		(0.084)	
45-64	0.616	***	0.656	***
	(0.091)		(0.085)	
65+	0.850	***	0.850	***
	(0.089)		(0.083)	
Political leaning, baselevel: conservative				
Moderate	0.108		0.226	***
	(0.078)		(0.076)	
Liberal	-0.113		-0.009	
	(0.078)		(0.075)	
Environmental interest	0.818	***	0.756	***
	(0.064)		(0.060)	
Constant	-4.996	***	-4.966	***
	(0.109)		(0.106)	
N	66,936		69,288	
Pseudo R^2	0.027		0.027	
df	10		10	
Log likelihood	-5349.905		-5956.954	

Table A-2: Logit regression on likes (experiment 1) for treatment and control group, limited optimization setup; Reported are logit coefficients and standard errors in parentheses.

*Note: * p<0.1, ** p<0.05, *** p<0.01; results see also Figure 3.*

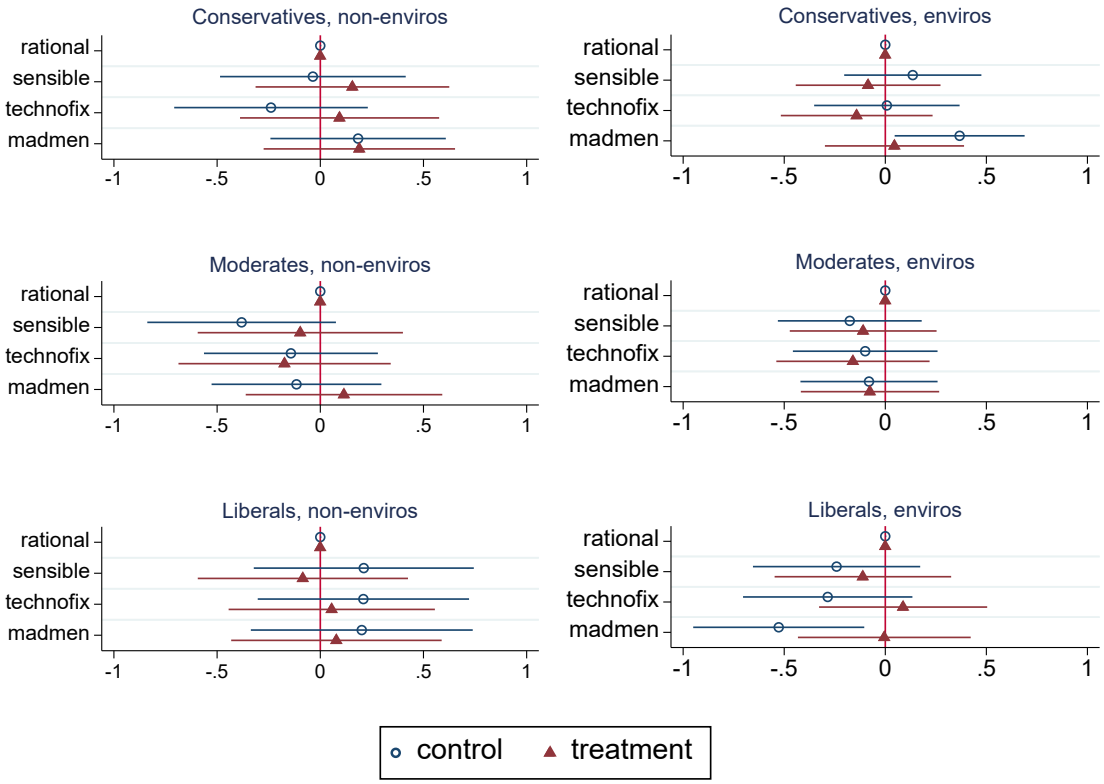


Figure A-1: Coefficients from logit regression on likes (experiment 1) with 95%-confidence intervals for treatment and control groups by non-enviros, i.e. users who have not shown an interest in environmental topics on Facebook before, and enviros, i.e. users who have shown an interest in environmental topics on Facebook before in the `Limited optimization´ group. Full results for enviros see also Table A-4

Note: Models include gender and age as control variables (not shown here). The plots for enviros are shown for comparison and are the same as in Figure 2B. Non-enviros: Liberals n=30,347; Moderates n=24,708; Conservatives n=22,178. Enviros: Liberals n=24,840; Moderates n=17,833; Conservatives n=16,318.

	Liberals			Moderates			Conservatives		
	T	C	T - C	T	C	T - C	T	C	T - C
Rational	2.18%	2.08%	0.1	3.21%	3.29%	0.08	2.15%	2.70%	-0.54
Sensible	1.98%	2.29%	-0.31	2.79%	2.72%	-0.07	1.89%	2.11%	-0.22
Technofix	1.88%	1.99%	-0.11	2.63%	2.91%	0.29	2.42%	2.22%	0.20
Madmen	2.29%	3.03%	-0.74	2.97%	3.21%	0.24	2.30%	1.70%	0.61

Table A-3: Engagement rates treatment group, control group, and treatment (T) – control (C) (see also Figure 2, Panel A) by political leaning only users interested in environmental topics for `Limited optimization´.

	Liberals				Moderates				Conservatives			
	Treatment		Control		Treatment		Control		Treatment		Control	
Framing, baselevel: rational												
sensible	-0.085		0.136		-0.109		-0.176		-0.111		-0.241	
	(0.183)		(0.173)		(0.185)		(0.182)		(0.223)		(0.211)	
technofix	-0.141		0.008		-0.160		-0.099		0.088		-0.285	
	(0.191)		(0.184)		(0.193)		(0.183)		(0.212)		(0.216)	
madmen	0.045		0.368	**	-0.076		-0.081		-0.005		-0.527	**
	(0.176)		(0.164)		(0.175)		(0.173)		(0.218)		(0.216)	
Female	0.027		0.152		0.346	***	0.366	***	-0.004		0.126	
	(0.131)		(0.116)		(0.130)		(0.125)		(0.156)		(0.153)	
Age, baselevel: 18-24												
25-44	0.237		0.239		0.281		0.023		0.470	**	0.444	*
	(0.190)		(0.167)		(0.182)		(0.171)		(0.232)		(0.228)	
45-64	0.427	**	0.507	***	0.350	*	0.346	*	1.029	***	0.896	***
	(0.192)		(0.170)		(0.192)		(0.173)		(0.223)		(0.234)	
65+	0.832	***	0.812	***	0.435	**	0.386	**	1.302	***	1.332	***
	(0.182)		(0.165)		(0.189)		(0.173)		(0.221)		(0.255)	
Constant	-4.182	***	-4.300	***	-3.841	***	-3.734	***	-4.438	***	-4.235	***
	(0.190)		(0.182)		(0.195)		(0.168)		(0.226)		(0.224)	
N	11785		13055		8728		9105		8050		8268	
Pseudo R^2	0.010		0.013		0.006		0.007		0.026		0.027	
df	7		7		7		7		7		7	
Log likelihood	-1183.194		-1446.701		-1138.537		-1225.172		-824.563		-832.441	

*Table A-4: Logit regression on likes (experiment 1) for treatment and control groups in the `limited optimization' target group by political leaning; only users who are interested in environmental topics. Reported are logit coefficients and standard errors in parentheses. * p<0.1, ** p<0.05, *** p<0.01*

	Newsletter			Like		
	Liberals	Moderates	Conservatives	Liberals	Moderates	Conservatives
Treatment, baseline: Mitigation						
CDR Complement	-0.295 **	-0.660 ***	-0.251	-0.036	0.097	-0.183
	(0.132)	(0.231)	(0.269)	(0.099)	(0.127)	(0.147)
CDR Substitute	-0.410 ***	-0.425 **	-0.267	-0.251 **	-0.114	-0.268 *
	(0.136)	(0.205)	(0.252)	(0.102)	(0.127)	(0.146)
SRM Complement	-0.798 ***	-0.355 *	-0.361	0.113	0.334 **	-0.115
	(0.153)	(0.212)	(0.282)	(0.104)	(0.134)	(0.154)
SRM Substitute	-0.430 ***	-0.256	-0.098	-0.001	-0.057	-0.072
	(0.142)	(0.206)	(0.259)	(0.104)	(0.136)	(0.148)
Female	0.091	0.246	0.568 ***	0.106	-0.214 ***	0.163
	(0.094)	(0.155)	(0.187)	(0.065)	(0.081)	(0.095)
Age, *baseline: 18-24*						
25-34	-0.266	0.736 *	-0.013	0.206 *	-0.091	-0.076
	(0.325)	(0.431)	(0.629)	(0.114)	(0.129)	(0.209)
35-44	-0.260	0.180	0.255	0.193	0.059	-0.245
	(0.318)	(0.477)	(0.579)	(0.123)	(0.140)	(0.220)
45-54	-0.162	1.039 **	-0.201	0.159	-0.022	-0.141
	(0.297)	(0.418)	(0.562)	(0.137)	(0.166)	(0.218)
55-64	0.232	1.246 ***	0.037	0.484 ***	0.279 *	0.428 **
	(0.269)	(0.404)	(0.529)	(0.130)	(0.165)	(0.201)
65+	0.488 *	1.402 ***	0.515	0.550 ***	0.851 ***	0.548 ***
	(0.262)	(0.402)	(0.520)	(0.130)	(0.154)	(0.199)
June/July 2019	0.226 **	0.091	0.386 **			
	(0.091)	(0.136)	(0.171)			
Constant	-4.362 ***	-5.706 ***	-5.734 ***	-3.888 ***	-3.624 ***	-3.657 ***
	(0.283)	(0.425)	(0.556)	(0.122)	(0.145)	(0.206)
n	38369	27455	25131	38854	24793	18268
Pseudo R^2	0.015	0.023	0.018	0.005	0.012	0.014
df	11.000	11.000	11.000	10.000	10.000	10.000
Log likelihood	-2631.45	-1260.65	-886.37	-4667.31	-2969.89	-2278.74

*Table A-5: Results from logit regression, coefficients and standard errors in parentheses for Newsletter (experiment 2) and Like campaign (experiment 3) for Conservatives, Moderates, and Liberals * p<0.1, ** p<0.05, *** p<0.01; see also coefficient plots in Figure 7.*