Q:1,2,3,4,5,6,7,8

Solar geoengineering may lead to excessive cooling and high strategic uncertainty

Anna Lou Abatayo[a], **Valentina Bosetti**[a,b], **Marco Casari**[c,d,1], **Riccardo Ghidoni**[e,f,g], **and Massimo Tavoni**[b,h]

[a]Bocconi University, Milan 20136, Italy; [b]~~Resources for the Future-CMCC~~ European Institute on Economics and the Environment, Milan 20144, Italy; [c]Bologna University, Bologna 40126, Italy; [d]Center for Advanced Study in the Behavioral Sciences, Stanford University, Stanford, CA 94305; [e]University of Milano-Bicocca, Milan 20126, Italy; [f]~~Center for European Studies, Milan 20126, Italy;~~ [g]Tilburg University, 5037AB Tilburg, Netherlands; and [h]Politecnico di Milano, Milan 20156, Italy

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Climate engineering—the deliberate large-scale manipulation of the Earth's climate system—is a set of technologies for reducing climate-change impacts and risks. It is controversial and raises novel governance challenges [T. C. Schelling, *Climatic Change*, 33, 303–307 (1996); J. Virgoe, *Climatic Change*, 95, 103–119 (2008)]. We focus on the strategic implications of solar geoengineering. When countries engineer the climate, conflict can arise because different countries might prefer different temperatures. This would result in too much geoengineering: ~~The~~ country with the highest preference for geoengineering cools the planet beyond what is socially optimal at the expense of the others—a theoretical possibility termed "free-driving" [M. L. Weitzman, *Scand. J. Econ.*, 117, 1049–1068 (2015)]. This study is an empirical test of this hypothesis. We carry out an economic laboratory experiment based on a public "good or bad" game. We find compelling evidence of free-driving: ~~Global~~ geoengineering exceeds the socially efficient level and leads to welfare losses. We also evaluate the possibility of counteracting the geoengineering efforts of others. Results show that countergeoengineering generates high payoff inequality as well as heavy welfare losses, resulting from both strategic and behavioral factors. Finally, we compare strategic behavior in bilateral and multilateral settings. We find that welfare deteriorates even more under multilateralism when countergeoengineering is a possibility. These results have general implications for governing global good or bad commons.

Q:9

climate governance | geoengineering | multilateralism | inequality

Unless urgent and drastic policy measures are taken, climate change will have profound consequences on human societies, national economies, and Earth's ecosystems. Despite the scientific consensus on climate change, global CO_2 emission levels in 2019 are at their historical highest (1). Agreements on effective international measures for emissions reduction have been difficult because of the challenges posed by climate governance (2–4). Meanwhile, by procrastinating action, we have consumed the largest part of the carbon budgets compatible with climate stabilization at 1.5 and 2 °C, the targets defined in the Paris Agreement, with only a few years left at the current emission rates (5, 6). Because climate change is a stock externality (7), even if effective and timely actions to curb emissions occur, we will not completely halt the temperature increase resulting from the accumulation of past emissions. These emissions have modified the CO_2 content of the atmosphere far above any level within the past hundreds of thousands of years (8). Recent literature has highlighted negative economic impacts resulting from climate change (9) and the fast-approaching tipping point to be higher than previously expected (10).

In this context, climate-engineering options are increasingly being considered as a means of deliberately intervening in Earth's climate system (11). They comprise two fundamentally different strategies (12–14). CO_2 removal, which tackles the source of anthropogenic climate change, is similar to emission reduction. Solar geoengineering (henceforth, geoengineering), on the other hand, affects the amount of incoming radiation from the sun and, thus, directly affects the planet's temperature. Geoengineering does not address the cause of anthropogenic alteration of the climate—namely, the atmospheric CO_2 concentration—and the direct damage it entails (e.g., ocean acidification). In this paper, we focus on the latter type of climate engineering.

Solar geoengineering has three notable characteristics. First, it is relatively effective. It has been shown to be able to offset temperature increase rapidly and well (15–19). Second, it is cheap. Cost estimates vary, but they are generally lower than those associated with mitigating CO_2 emissions (20, 21). Third, it is risky. The potential side effects include direct impacts on health (22–24) and agriculture (25), as well as other adverse effects that are not yet fully understood. Moreover, and most importantly for this paper, the nature of this technology sets the stage for new and serious governance challenges (26–29).

One such challenge stems from the possibility that one or more regions could deploy geoengineering to the detriment of others. Given its relatively low cost, a unilateral geoengineering effort would not have expense as a limitation, particularly in light of the potential geopolitical benefits of setting the world temperature at the ideal point for a specific region. This possibility might be particularly appealing to regions that would suffer the most from unabated global warming (30). However, uncoordinated unilateral actions could result in global geoengineering

Significance

Governing climate change and other global commons is challenging. Climate engineering has recently gained attention as a way to manage climate risks. Solar geoengineering is a technology that allows countries to unilaterally influence the world temperature. Solar geoengineering could trigger conflicting interventions by countries who prefer different temperatures; economic theory suggests that countries wanting a cooler climate impose it on others. Other countries may react through countergeoengineering interventions. We study the governance of solar geoengineering using a laboratory experiment in which participants engage in a public good-or-bad game. Results confirm that too much geoengineering can occur, leading to considerable economic losses and increased inequality. The experiment also highlights unforeseen governance risks associated with such technologies.

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[1]To whom correspondence may be addressed. Email: marco.casari@unibo.it.

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levels well above the social optimum, a phenomenon known as "free-driving" (31). Such an oversupply of geoengineering would have clear winners—the regions with a low ideal temperature—and almost everyone else would lose. The free-driving externality could lead to significant welfare losses (32), which would exacerbate the already looming free-riding problem that affects emission reductions. It could also lead to retaliatory actions, including an escalation of geoengineering efforts. Specifically, regions that are adversely affected by another region's efforts could countergeoengineer the climate by spraying particles that absorb sunlight radiation and thus cause temperature to increase (33, 34).

The general setup underlying free-driving is that of a public good or bad (GoB). The GoB game differs from the canonical public good games (35)—even those in which agents can both give or take contributions (36)—in that 1) the provision cost is so low that agents can provide the good; and 2) a conflict over the total provision is present because agents are characterized by heterogeneous, single-peaked preferences. Geoengineering is a commodity that has public consequences; that is, it affects Earth's temperature. Different parties have different ideal temperatures and, thus, potentially conflicting ideal points in terms of global geoengineering effort. Any upward or downward deviation from a region's ideal point leads to economic losses for that region. This framework aligns with the climate case, for which empirical evidence suggests a nonmonotonic relation between temperature and economic growth and the existence of an optimum temperature for productivity growth (30). Because of the heterogeneity in ideal points, different regions will most likely disagree on their ideal level of geoengineering. As a consequence, an overprovision by the country or coalition with the highest ideal level of geoengineering would result in global welfare losses and likely exacerbate inequality. A GoB game with two countries resembles a dictator game where roles are random and bargaining power asymmetric. Yet, the country with low ideal point has choices and can punish the other one.

The literature includes some experimental evaluations of climate-change cooperation (37–39), but, to the best of our knowledge, empirical evidence is lacking on the hypothesis of free-driving in climate engineering. Further, no investigations have been conducted regarding the consequences of possible technological responses, such as countergeoengineering, that could make climate governance even more challenging. Our study is intended to bridge this gap in the literature and contribute to the growing debate about climate engineering in climate negotiations. Our methodology centers on a controlled laboratory experiment to analyze behavior in a GoB game that is carried out in a simple bilateral world with just two decision makers and in a complex multilateral world with six decision makers. In the experiment, decision makers with different ideal points choose a level of geoengineering through a decentralized effort decision with global consequences.

In our experiment, the basic decision-making unit is a team of two persons. We did this because teams are generally considered more rational than individuals making decisions in isolation (see ref. 40 for a review) and because the design minimally captures the collective process behind national choices generated by countries. The experiment is unframed, and climate change is never mentioned, although we refer to it in what follows.

The experiment comprises two treatments, "baseline" and "counter," that differ according to whether or not decision makers can exert effort in countergeoengineering (i.e., undo the geoengineering efforts of other decision makers). We define countergeoengineering as the use of technical means to negate the change in radiative forcing caused by geoengineering deployment (34, 41). Each session has three parts (*SI Appendix*, Fig. S1). In part 1, all participants, regardless of the treatment, play the baseline GoB game for five rounds under economies of two decision makers ($N=2$) that are characterized by distinct ideal points. In part 2, participants remain in the same economies of part 1 and play their treatment-specific game (baseline or counter) for five rounds. In part 3, the treatment-specific game is played for 15 rounds, but in economies of six decision makers ($N=6$), with each decision maker characterized by one of three possible ideal points.

For tractability, we introduce some simplifying assumptions. First, the outcomes of geoengineering policies are deterministic. We abstract from unknown effects of geoengineering, such as its effect on rainfall patterns, ozone levels, and the political cost of conflict over the level of geoengineering. Second, we consider a repeated but static interaction: Geoengineering in a round does not affect temperature in subsequent rounds. Third, apart from their ideal points, we assume that all decision makers are identical: They have the same size, action space, geoengineering costs, and losses incurred from deviations from their ideal points.

Geoengineering Game. In each round t, each decision maker i chooses how much of their endowment, $E=150$, they want to invest in geoengineering effort, g_i. Participant earnings are expressed in E$ (2 E$ = 0.01 euro [EUR]). These earnings are converted to EURs at the end of the session, and participants are paid in cash. In baseline, $g_i \in [0, 15]$, while in counter, $g_i \in [-15, 15]$. Every unit of geoengineering effort, $|g_i|$, costs $\alpha = 4$. We leave out other climate strategies such as mitigation and adaptation. We assume that the world has continued to excessively produce greenhouse-gas emissions and that extensive climate-related damage—in the form of rising sea levels, altered ocean and atmospheric circulation patterns, and harmful regional weather changes—are imminent unless we are able to deliberately geoengineer the temperature. The global provision of geoengineering, $\sum_i g_i = G$, affects the payoffs of each decision maker i:

$$\pi_i = E - \alpha|g_i| - \lambda|G - G_i^*|. \qquad [1]$$

The decision makers are heterogeneous in their desired level of global geoengineering, G, reflecting different geographical locations. In the experiment, ideal points G_i^* could be either two, six, or 10 (henceforth, IP2, IP6, and IP10, respectively). Both underprovision or overprovision of G results in loss. More specifically, any deviation of the global geoengineering effort G from the decision maker's ideal point, G_i^*, entails a loss, symmetric on both sides, amounting to $\lambda = 10$ per unit. All parameter values are public information. After each round, decision makers observe the global geoengineering level, as well as efforts of others.

An economy of six always includes two each of IP2, IP6, and IP10. Decision makers with IP10 will have a unilateral incentive to geoengineer because $\alpha < \lambda$. Hence, theory predicts baseline to be inefficient with global geoengineering equal to the highest ideal point in the economy ($G=10$) and social surplus at 86% of the socially optimal level (Fig. 1, *Materials and Methods*, and *SI Appendix*, *Proofs*). Theory predicts that IP2 and IP6 decision makers will not produce anything, and IP10 decision makers will divide a total production of 10 among themselves. The social optimum is at $G=6$, corresponding to the median ideal point in the economy. Countergeoengineering is predicted to bring the global effort down to the socially optimal level. However, a "geoengineering war" would ensue as a result of the escalation of efforts (33) and is expected to generate greater inefficiencies than baseline (Fig. 1; see also *Materials and Methods*). The reasoning is similar for economies of two in parts 1 and 2, with the caveat that there are three different types of economies of two: 1) IP2 facing IP6, 2) IP2 facing IP10, and 3) IP6 facing IP10 (*Materials and Methods* and *SI Appendix*, Table S1). Under baseline

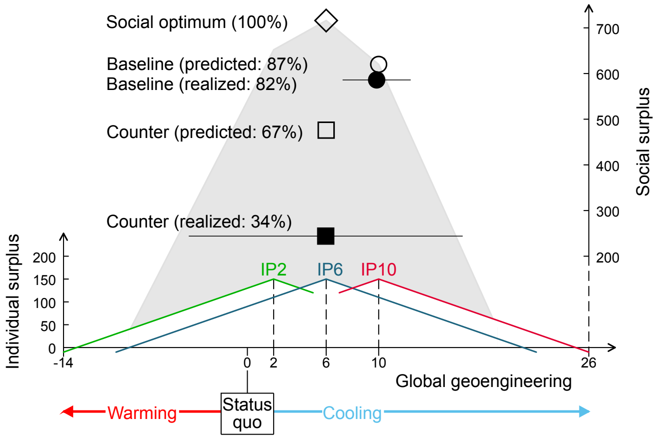

Fig. 1. Geoengineering in a multilateral world ($n = 6$). Global geoengineering is the sum of all effort levels. Relative to the status quo, geoengineering efforts reduce temperature, while countergeoengineering efforts increase it. Individual surplus refers to individual profits, while social surplus is the sum of individual profits in an economy. The lower part of the figure shows that individual payoffs from global geoengineering peak at a decision maker's ideal point. Losses, due to excessive cooling or warming, are symmetric. The shaded area in the upper part of the figure refers to the efficiency frontier in terms of social surplus. The diamond, circle, and square open symbols indicate the social surplus under social optimum, baseline prediction, and counter prediction, respectively, while their filled counterparts refer to the realized outcomes in the experiment. The horizontal lines on the filled symbols represent the average within-economy 95% CI for global geoengineering. Percentages in parentheses refer to the fraction of efficiency achieved. The unit of observation is an economy in a round (i.e., for each treatment $n = 90$).

economies of two, the predicted effort equals the higher ideal point, while the social optimum equals the lower ideal point. Additional details on the experimental design can be found in *Materials and Methods* and *SI Appendix*.

Results

Free-Driving Confirmed. The experimental evidence* strongly supports the hypothesis of free-driving behavior when each decision maker chooses its geoengineering effort. In a multilateral scenario ($N = 6$), global geoengineering is near the predicted level (average 9.8 vs. predicted 10 in baseline: WSR test, $P > 0.10$, $n = 6$). This level brings excessive cooling and lowers social surplus, which is computed as the sum of the earnings of all decision makers in an economy in a round. The realized total surplus is significantly below the socially optimal level (82%; Fig. 1; total surplus actual vs. social optimum: WSR test, $P < 0.05$, $n = 6$), but very close to the predicted value of 87%. The social optimum prescribes a level of geoengineering that yields the median of all ideal points in the economy, not the highest one. Also in line with the predictions, the geoengineering effort in baseline is overwhelmingly undertaken by the decision makers with the highest ideal point (86% with $N = 6$; *SI Appendix*, Figs. S2*A* and S3). In a multilateral scenario, the two IP10 decision makers roughly split the cost of effort to reach the desired global geoengineering level—in 37% of cases, the split was exact—and the other decision makers contribute a negligible amount (*SI Appendix*, Fig. S3). Additional support for the free-driving hypothesis comes from the data generated under the economies of two scenarios ($N = 2$). At the economy level, global geoengineering was close to the preferred level of the decision maker with the highest ideal point (*SI Appendix*, Figs. S4 and S5*A*), who exerted most of the effort (91%; part 2). Prosocial behavior is lower than in many dictator games, most likely because 1) decision makers are teams rather than individuals (42); 2) initial endowments are equal and substantial (43); and 3) interaction is repeated (44).

Dramatic Effects of Countergeoengineering. Theory predicts a strategic shift when decision makers are able to countergeoengineer the climate. One effect is a geoengineering war, which occurs as those with high ideal points boost their geoengineering efforts in anticipation of those with lower ideal points counteracting them with (negative) efforts to warm temperatures. In a multilateral scenario ($N = 6$), such escalation of efforts is expected to reduce social surplus to 67% of the socially optimal surplus. In terms of effort, positive and negative efforts would counteract each other, and the predicted outcome of the experiment is a temperature at the socially optimal level. The observed average global geoengineering in counter is very close to this prediction (actual of 5.97 vs. predicted of 6.00) and is significantly lower than the level of aggregate geoengineering in baseline (WMW test, $P < 0.01$, $n = 12$; see also regressions in *SI Appendix*, Table S3). But this average hides a variability that has massive implications for welfare. Indeed, countergeoengineering induces a significant welfare loss: The realized social surplus in the multilateral scenario of counter is only 34% of the socially optimal level, half the predicted level of 67% (Fig. 1; total surplus vs. social optimum: WSR test, $P < 0.05$, $n = 6$). This outcome is not, as would be expected, the result of a geoengineering war. This is less severe than predicted (Fig. 2*A*), with a welfare loss of only 22% of the socially optimal surplus. Rather, the driver of the poor performance is the frequent undershootings and overshootings of global geoengineering levels (Fig. 2*B*). Although the average global effort was close to the predicted level of six, this level was exactly achieved in only 4.4% of the cases (*SI Appendix*, Fig. S2*B*). In about 23% of cases, global geoengineering was at or below zero, and in about 16% of the cases, it was at or above 15 (*SI Appendix*, Fig. S2*B*). The variability in global geoengineering is also evident from the 95% CI shown in Fig. 1, which spans from -4.5 to 16.4 and is four times as wide as the corresponding interval in baseline (7.3 to 12.4). In counter, oscillations of effort in an economy across rounds were present in all economies and were wider than in baseline (average [ave.] baseline deviation from prediction is 1.8 vs. ave. counter deviation from prediction is 8.3: WMW test, $P < 0.01$, $n = 12$; *SI Appendix*, Figs. S6 and S7). Thus, in counter, inefficiencies due to temperature undershooting and overshooting are greater than the inefficiencies due to the escalation of effort (44% vs. 22%; Fig. 2*B* and *SI Appendix*, Fig. S8). The first ones diminish over rounds as experience accumulates, but never vanishes.

The origin of temperature undershooting and overshooting is the strategic uncertainty characterizing the multilateral scenario of counter. The first factor generating uncertainty is the presence of many decision makers all putting nonzero effort (472 times in counter vs. 223 times in baseline; Fig. 3 and *SI Appendix*, Fig. S9). The second factor is the strategic interdependency of choices in counter, which is absent in baseline. Assume that some decision makers systematically deviate from the theoretical equilibrium behavior because of mistakes or in an attempt to restrain the escalation in efforts. In baseline, IP10 decision makers should react to small deviations of others, while the best reply of IP2 and IP6 decision makers would be unaffected. In counter, all decision makers need to adjust their effort level in response to others' deviations. In the experiment, such responses played a larger role in early rounds because IP2 and IP10 were not exerting efforts at the bounds (-15 and 15, respectively), as theory would predict (*SI Appendix*, Fig. S8). Paradoxically, the losses generated by the strategic uncertainty caused by this behavior early on

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*All nonparametric tests conducted are either Wilcoxon–Mann–Whitney (WMW) or Wilcoxon signed rank (WSR) two-tailed exact tests.

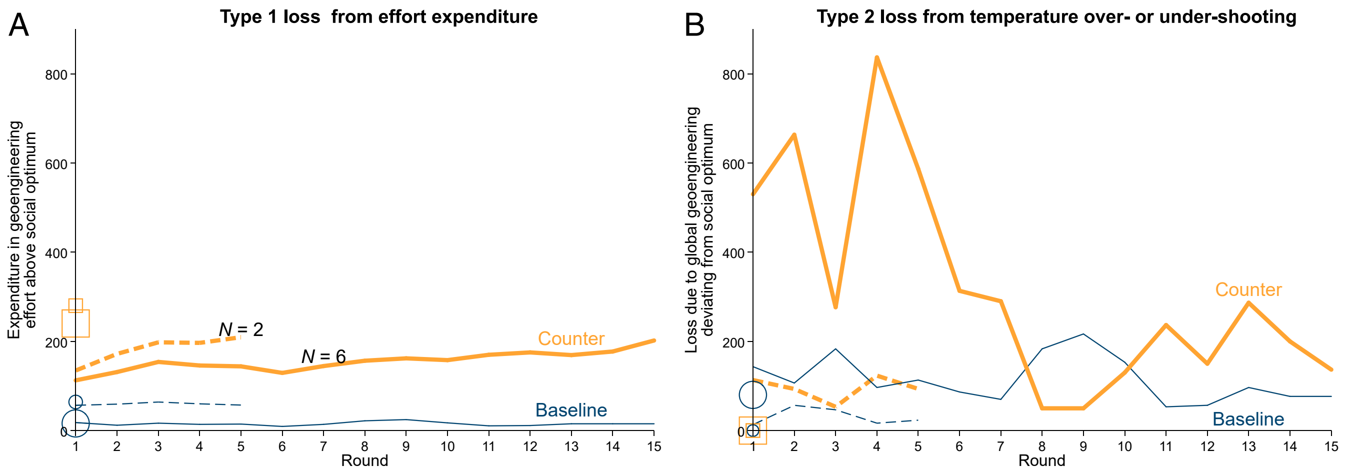

Fig. 2. Drivers of inefficiency over time. Losses to social surplus can come either from the escalation in geoengineering effort expenditures (type 1 loss; *A*) or overshooting and undershooting the social optimum level of global geoengineering (type 2 loss; *B*). In a multilateral scenario ($N = 6$), baseline shows a low type 1 loss (as predicted) and a medium type 2 loss (as predicted), while counter shows a high type 1 loss (as predicted) and an even higher type 2 loss (not predicted). The type 2 loss in counter heavily affected realized surplus. Open symbols on the vertical axes indicate the predicted values for $N = 2$ (small symbols) and $N = 6$ (large symbols). Circles refer to baseline and squares to counter. In both treatments, type 1 losses were higher under $N = 2$ than under $N = 6$, while type 2 losses were lower under $N = 2$ than under $N = 6$. For $N = 6$, the unit of observation is an economy in a round ($n = 90$ for each treatment). For $N = 2$, the unit of observation is the sum of three different economy types of part 2 ($n = 90$ for each treatment).

overshadow the potential losses from effort escalation that they were trying to avoid. Further support for this interpretation comes from the bilateral scenarios, which exhibit a drastically lower loss from overshooting and undershooting (8% in counter and 3% in baseline; Fig. 2*B*).

Finally, the counter condition generated a high inequality in payoffs among decision makers. The Gini index in counter was higher than in baseline (*SI Appendix*, Table S2), but also higher than predicted (actual of 0.31 vs. predicted of 0.25). As predicted, IP2 and IP10 decision makers had lower profits in counter compared to baseline (counter: 33 [IP2], 23 [IP10] vs. baseline: 70 [IP2], 115 [IP10]). Contrary to predictions, IP6 decision makers in counter also had lower profits than those in baseline (67 in counter vs. 109 in baseline).

Complexity in a Multilateral World. Our experiment also highlights the importance of studying geoengineering in a multilateral setup. Theoretical and empirical reasons exist for going beyond a bilateral setup. In theoretical models, the strategic incentives to exert effort can substantially change, depending on the number and preferences of decision makers. Going from a bilateral to a multilateral scenario has consequences for the complexity of the coordination problem and for the equilibrium structure. For instance, our GoB game has a unique equilibrium in the bilateral scenarios and multiple equilibria in the multilateral scenario.

Experimental evidence shows that decision makers understood the change in game incentives well (Fig. 3 and *SI Appendix*, Tables S4–S7). First, consider baseline. In a bilateral setting, the IP10 decision maker is expected to provide the entire global geoengineering effort, while in a multilateral setting, two decision makers coordinate efforts to reach the same global geoengineering level of 10. In the experiment, the average effort of IP10 decision makers was 8.4 under $N = 2$ and 4.2 under $N = 6$ (significantly different at $P < 0.001$ according to Tobit regressions in *SI Appendix*, Table S6*A*; Fig. 3*A*). Next, consider counter. In a bilateral setting, the IP6 decision maker is predicted to provide an effort level of 15 if paired with IP2 or −9 if paired with IP10, while in a multilateral setting, two decision makers coordinate efforts to provide a global geoengineering level of six. In the experiment, the average effort of IP6 was 9.5 and −4.7, respectively, under $N = 2$, and it was 1.1 under $N = 6$ (significantly different at $P < 0.01$, according to Tobit regressions in *SI Appendix*, Table S6*B*; Fig. 3*B*). Experimental evidence also shows that moving from a bilateral to a multilateral setting in counter resulted in unexpectedly large losses stemming from the frequency of temperatures overshooting and undershooting with respect to the socially optimum level, as discussed above.

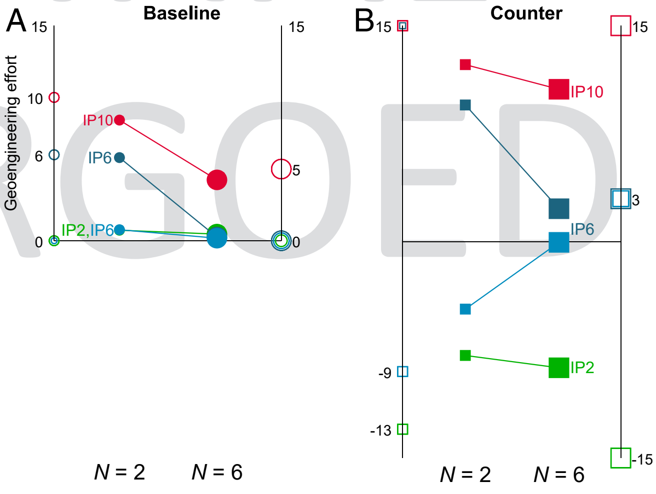

Fig. 3. Strategic behavior in a bilateral (N = 2) vs. multilateral (N = 6) scenario. (*A*) Baseline. (*B*) Counter. All decision makers were initially placed in a bilateral setting ($N = 2$) and then in a multilateral setting ($N = 6$). If decision makers were together in economies of two, they remained together in economies of six. A decision maker's ideal point remained the same within the session. In the experiment, decision makers were able to adjust their effort level in the predicted direction. Open symbols on the vertical axes represent the predictions for each ideal point under $N = 2$ (left axis) and $N = 6$ (right axis). Filled symbols show the average geoengineering effort for each ideal point. The unit of observation is a decision maker in a round; that is, for each treatment and economy type, $n = 540$ for $N = 6$ and $n = 60$ for $N = 2$. More about bilateral scenarios is in *SI Appendix*, Fig. S10, part 1 vs. part 2).

In other words, the shift in complexity affected treatments differently. In baseline, the difference in aggregate variability between the bilateral and the multilateral setups was minimal: The number of times that global geoengineering fell outside the ideal points' range was similar in the two setups (16% vs. 22%, probit regression: $P = 0.11$, $n = n_{pt2} + n_{pt3} = 720$ with $n_{pt1} = 180$, $n_{pt1} = 540$). For counter, the multilateral scenario exhibited a much higher variability in outcomes, although experience progressively reduced variability (26% vs. 52%, probit regression: $P < 0.01$, $n = n_{pt2} + n_{pt3} = 720$ with $n_{pt1} = 180$, $n_{pt1} = 540$).

Discussion

Geoengineering is a potential additional strategy for combating the detrimental effects of climate change that is increasingly being considered in scientific and policy discourses (45). While it may be inexpensive and effective in immediately reducing temperature levels, it may also generate risks that outweigh those it is intended to reverse. In particular, we focus on risks and challenges associated with its governance. Countries whose optimal level of geoengineering is highest, such as those that will suffer the most from climate change, can free-drive and thereby propel geoengineering efforts beyond what is socially optimal. In an experimental assessment, we confirm the theoretical predictions of free-driving: Under baseline, the total surplus of economies of six is 82% of what would be the social optimum, slightly worse than theoretically predicted (86%). The lion's share of geoengineering efforts is borne by those with the highest desire to cool the planet, at the expense of the others. Countries with the highest ideal level of geoengineering earn, on average, 65% more than those with the lowest ideal level of geoengineering.

We also study a technology that can place the global temperature at the socially optimal level by counterbalancing excessive efforts in geoengineering. While countergeoengineering can theoretically offset global cooling, neutralizing the free-driving inefficiency, one can also expect retaliatory efforts that increase inequality and generate deadweight losses. The empirical results are even higher than theoretically predicted and confirm the onset of a geoengineering war, but not to the extent predicted by theory. However, the experiment reveals that the greatest inefficiency of countergeoengineering does not come from effort escalation, but rather from the instability in global effort, which theory did not predict. Many rounds are needed before the variability in outcomes is smoothed out. A plausible explanation is that decision makers at lower and higher ideal points do not exert extreme efforts, as theory predicts, in an attempt to avoid escalation. This behavior, however, creates high strategic uncertainty. The resulting variability in outcomes ends up being more detrimental to the economy in terms of economic surplus than the losses that would be incurred from effort escalation.

These results hold regardless of economy size ($N = 2$ or $N = 6$). However, multilateralism complicates coordination. This complication is particularly relevant for countergeoengineering, especially in the field, where policing investments in geoengineering efforts is difficult, and group sizes and compositions are uncertain and possibly change in each round. This possibility has implications for the governance of geoengineering, which is likely to take place in a context of multiple countries. Communication may likely improve outcomes, and this could certainly also be studied experimentally.

The setup used in this paper makes a series of simplifying assumptions, such as assuming geoengineering is the only strategy and abstracting from the indirect effects of geoengineering. The presence of costly side effects from geoengineering would further weaken the attractiveness of a world with countergeoengineering. The possibility of further retaliatory actions, such as military intervention, might also limit free-driving. On the other hand, inequality in decision makers' endowments, which is a proxy for variable welfare of countries, might exacerbate free-driving, given that the regions that will suffer the most from global warming are also the poorest.

Regardless of these shortcomings, which we hope to address in future work, our paper provides a serious warning of the consequences of strategic as well as behavioral factors for geoengineering. Both contribute to lowering welfare and increasing inequalities. The set-up, and the experimental results we derived, apply more generally to the class of public GoB games, which are relevant for the management of economic and natural resources.

Materials and Methods

A total of six sessions were conducted on the campus of Bologna University, with exactly 24 participants per session (*SI Appendix*, Table S8), who were recruited from the undergraduate student population by using ORSEE (46). Each session was randomly assigned to be either a baseline treatment or a counter treatment, and it comprised 25 rounds of interaction. Each participant participated in only one session. Average earnings were about 20 EUR, inclusive of the 6 EUR of the show-up, for sessions that lasted for 2 h on average.

At the beginning of the experiment, individuals were randomly matched in teams of two members, and a team was assigned an ideal point that they kept for the entire experiment. In each round, a team could have a 1- or 2-min discussion and had to reach a unanimous decision. Decisions were made individually, but had to be identical within a team. In cases of disagreement, individuals were asked to re-enter their decisions. Unresolved disagreements occurred in between 2% and 4% of all choices, depending on the session, affecting on average 10% of economies (*SI Appendix*, Fig. S11). In part 3, though, the impact was larger on counter than baseline economies (16% vs. 3%, WMW test, $P < 0.05$, $n = 12$).

Before the first round, teams were randomly matched in economies of two and remained in a fixed matching for 10 rounds under a bilateral setting. After round 10, three economies of two with different ideal point combinations were merged to form an economy of six under a multilateral setting. This matching remained fixed for 15 rounds. Each participant was assigned a computer station with partitions blocking their view of all other stations. Participants were not allowed to communicate with one another for the duration of the experiment, except when the chat window opened for communicating with their team member. The experiment was conducted by using z-Tree (47). An experimenter read the instructions aloud, after which the participants answered a quiz to ensure that they understood them. At the end of the session, participants were asked to complete an unpaid survey questionnaire, which included socio-demographic questions as well as questions on individual preferences following ref. 48. Copies of the full experimental instructions and the questionnaire are provided in *SI Appendix*, *Instructions*.

In the same experiment, we collected data on two additional treatments, treaty and transfers. We will report about these treatments in a separate paper.

The experiment was neutrally framed and involved no deception. We never mentioned climate change, and decision makers were referred to as "teams," economies were referred to as "groups," and geoengineering was referred to as "production." The experiment was granted ethics (Institutional Review Board) approval by Bocconi University on December 4, 2013. Informed consent was obtained from all participants.

Theoretical Considerations. For both baseline and counter treatments, the optimal level of global geoengineering in $N = 2$ was equal to the lowest ideal point and in $N = 6$, to the median ideal point. Under $N = 2$, this yielded a total surplus of 252 (IP2 and IP6), 212 (IP2 and IP10), and 236 (IP6 and IP10), and, under $N = 6$, a total surplus of 716 (IP2, IP6, and IP10). Under $N = 6$, the predicted Gini index of inequality reaches a minimum of 0.07 if effort is equally split by the two IP6 decision makers.

In baseline, all types of economies admit a unique subgame perfect Nash equilibrium outcome: Global geoengineering equals the highest ideal point in the economy. Under $N = 2$, the decision maker with the highest ideal point contributes all of the effort, and the other decision maker puts in zero. Under $N = 6$, the two IP10 decision makers put in a total effort equal to 10. The predicted outcome is suboptimal relative to the total surplus from the social optimum: 94% for economy (IP2 and IP6), 85% for economy (IP2 and IP10), 93% for economy (IP6 and IP10), and 87% for economy of six. Inequality, as measured by the Gini index, is 0.03 for economy (IP2 and IP6), 0.11 for economy (IP2 and IP10), 0 for economy (IP6 and

IP10), and 0.13 for the economy of six (when IP10 decision makers produce five each).

In counter, global geoengineering equals the lowest ideal point of the decision makers in $N = 2$ and the median ideal point of the decision makers in $N = 6$. In $N = 2$, the decision maker with the higher ideal point contributes the maximum amount of effort, while the decision maker with the lower ideal point counteracts this effort and brings it down to its own ideal level. In $N = 6$, IP10 decision makers put in 15, IP2 decision makers put in −15, and IP6 decision makers put in a total of six. Counter leads to a level of global geoengineering equivalent to the socially optimal one, but the resulting total surplus is not the same; that is, countries' efforts are wasted, as $\sum_{j \neq i} |g_{j,i}| \gg G$. In $N = 2$, this sum is 26 for economies (IP2 and IP6) and (IP2 and IP10) and 24 for (IP6 and IP10). In $N = 6$, this sum is 66, resulting in a total surplus of just 66% of the socially optimal surplus and an inequality of 0.25 (when IP6 decision makers produce three each).

A summary of these theoretical predictions is available in *SI Appendix*, Table S1. The formal proofs for a general N is available in *SI Appendix*, *Proof of Theoretical Predictions*. We also report theoretical analyses of two model extensions in *SI Appendix*, *Robustness of Theoretical Results to Variations of the Model Assumptions*): allowing quadratic instead of linear damages and taking away the upper bound of effort. Predictions are qualitatively similar.

Data Availability. All relevant data and code are included in the manuscript, *SI Appendix*, and Datasets S1–S4. Q:15

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1. Future Earth, Global carbon budget (2020) https://futureearth.org/initiatives/other-initiatives/global-carbon-budget/. Accessed ■■■. Q:17
2. S. Barrett, Self-enforcing international environmental agreements. *Oxf. Econ. Pap.* **46**, 878–894 (1994).
3. C. Carraro, D. Siniscalco, Strategies for the international protection of the environment. *J. Publ. Econ.* **52**, 309–328 (1993).
4. W. Nordhaus, Climate clubs: Overcoming free-riding in international climate policy. *Am. Econ. Rev.* **105**, 1339–1370 (2015).
5. T. Stocker *et al.*, *Climate Change 2013: The Physical Science Basis. Contribution for Working Group 1 to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press, Cambridge, UK, 2013).
6. J. Rogelj *et al.*, Scenarios towards limiting global mean temperature increase below 1.5 °C. *Nat. Clim. Change* **8**, 325–332 (2018).
7. G. Calzolari, M. Casari, R. Ghidoni, Carbon is forever: A climate change experiment on cooperation. *J. Environ. Econ. Manag.* **92**, 169–184 (2018).
8. J. Hansen *et al.*, Global temperature change. *Proc. Natl. Acad. Sci. U.S.A.* **103**, 14288–14293 (2006).
9. T. A. Carleton, S. M. Hsiang, Social and economic impacts of climate. *Science* **353**, aad9837 (2016).
10. W. Steffen *et al.*, Trajectories of the Earth system in the Anthropocene. *Proc. Natl. Acad. Sci. U.S.A.* **115**, 8252–8259 (2018).
11. J. Tollefson, Geoengineering debate revives. *Nature* **567**, 156 (2019).
12. J. C. Minx *et al.*, Negative emissions—Part 1: Research landscape and synthesis. *Environ. Res. Lett.* **13**, 063001 (2018).
13. S. Fuss *et al.*, Negative emissions—Part 2: Costs, potentials and side effects. *Environ. Res. Lett.* **13**, 063002 (2018).
14. G. F. Nemet *et al.*, Negative emissions—Part 3: Innovation and upscaling. *Environ. Res. Lett.* **13**, 063003 (2018).
15. B. Kravitz *et al.*, The geoengineering model intercomparison project (GeoMIP). *Atmos. Sci. Lett.* **12**, 162–167 (2011).
16. H. D. Matthews, K. Caldeira, Transient climate-carbon simulations of planetary geoengineering. *Proc. Natl. Acad. Sci. U.S.A.* **104**, 9949–9954 (2007).
17. G. A. Ban-Weiss, K. Caldeira, Geoengineering as an optimization problem. *Environ. Res. Lett.* **5**, 034009 (2010).
18. D. G. MacMartin, K. L. Ricke, D. W. Keith, Solar geoengineering as part of an overall strategy for meeting the 1.5 °C Paris target. *Phil. Trans. Math. Phys. Eng. Sci. A* **376**, 20160454 (2018).
19. S. Tilmes, A. Jahn, J. E. Kay, M. Holland, J. F. Lamarque, Can regional climate engineering save the summer Arctic Sea ice? *Geophys. Res. Lett.* **41**, 880–885 (2014).
20. S. Barrett, The incredible economics of geoengineering. *Environ. Resour. Econ.* **39**, 45–54 (2008).
21. R. Moriyama *et al.*, The cost of stratospheric climate engineering revisited. *Mitig. Adapt. Strategies Glob. Change* **22**, 1207–1228 (2017).
22. P. J. Irvine *et al.*, Towards a comprehensive climate impacts assessment of solar geoengineering. *Earth's Future* **5**, 93–106 (2017).
23. P. Heckendorn *et al.*, The impact of geoengineering aerosols on stratospheric temperature and ozone. *Environ. Res. Lett.* **4**, 045108 (2009).
24. A. Robock, A. Marquardt, B. Kravitz, G. Stenchikov, Benefits, risks, and costs of stratospheric geoengineering. *Geophys. Res. Lett.* **36**, L19703 (2009).
25. J. Proctor, S. Hsiang, J. Burney, M. Burke, W. Schlenker, Estimating global agricultural effects of geoengineering using volcanic eruptions. *Nature* **560**, 480–483 (2018).
26. F. Rabitz, Governing the termination problem in solar radiation management. *Environ. Polit.* **28**, 502–522 (2019).
27. A. Millard-Ball, The Tuvalu syndrome. *Climatic Change* **110**, 1047–1066 (2012).
28. D. G. Victor, M. G. Morgan, F. Apt, J. Steinbruner, The geoengineering option—a last resort against global warming. *Foreign Aff.* **88**, 64 (2009).
29. T. C. Schelling, The economic diplomacy of geoengineering. *Climatic Change* **33**, 303–307 (1996).
30. M. Burke *et al.*, Opportunities for advances in climate change economics. *Science* **352**, 292–293 (2016).
31. M. L. Weitzman, A voting architecture for the governance of free-driver externalities, with application to geoengineering. *Scand. J. Econ.* **117**, 1049–1068 (2015).
32. J. Emmerling, M. Tavoni, Exploration of the interactions between mitigation and solar radiation management in cooperative and non-cooperative international governance settings. *Global Environ. Change* **53**, 244–251 (2018).
33. D. Heyen, J. Horton, J. Moreno-Cruz, Strategic implications of counter-geoengineering: Clash or cooperation?. *J. Environ. Econ. Manag.* **95**, 153–177 (2019).
34. A. Parker, J. B. Horton, D. W. Keith, Stopping solar geoengineering through technical means: A preliminary assessment of counter-geoengineering. *Earth's Future* **6**, 1058–1065 (2018).
35. J. Ledyard, "Public goods: A survey of experimental research" in *Handbook of Experimental Economics*, J. Kagel, A. Roth, Eds. (Princeton University Press, Princeton, NJ, 1995), 111–194. Q:18
36. J. Andreoni, Warm-glow versus cold-prickle: The effects of positive and negative framing on cooperation in experiments. *Q. J. Econ.* **110**, 1–21 (1995).
37. A. Tavoni, A. Dannenberg, G. Kallis, A. Löschel, Inequality, communication, and the avoidance of disastrous climate change in a public goods game. *Proc. Natl. Acad. Sci. U.S.A.* **108**, 11825–11829 (2011).
38. S. Barrett, A. Dannenberg, Climate negotiations under scientific uncertainty. *Proc. Natl. Acad. Sci. U.S.A.* **109**, 17372–17376 (2012).
39. S. Barrett, A. Dannenberg, Tipping versus cooperating to supply a public good. *J. Eur. Econ. Assoc.* **15**, 910–941 (2017).
40. G. Charness, M. Sutter, Groups make better self-interested decisions. *J. Econ. Perspect.* **26**, 157–176 (2012).
41. G. Feingold, W. R. Cotton, S. M. Kreidenweis, J. T. Davis, The impact of giant cloud condensation nuclei on drizzle formation in stratocumulus: Implications for cloud radiative properties. *J. Atmos. Sci.* **56**, 4100–4117 (1999).
42. W. J. Luhan, M. G. Kocher, M. Sutter, Group polarization in the team dictator game reconsidered. *Exp. Econ.* **12**, 26–41 (2009).
43. O. Korenok, E. L. Millner, L. Razzolini, Are dictators averse to inequality? *J. Econ. Behav. Organ.* **82**, 543–547 (2012).
44. C. Engel, Dictator games: A meta study. *Exp. Econ.* **14**, 583–610 (2011).
45. The National Academies of Sciences, Engineering, and Medicine, National Academies launching new study on sunlight-reflection research (2018). http://www8.nationalacademies.org/onpinews/newsitem.aspx?RecordID=10162018. Accessed ■■■. Q:19
46. B. Greiner, Subject pool recruitment procedures: Organizing experiments with ORSEE. *J. Eco. Sci. Assoc.* **1**, 114–125 (2015).
47. U. Fischbacher, z-Tree: Zurich toolbox for ready-made economic experiments. *Exp. Econ.* **10**, 171–178 (2007).
48. A. Falk *et al.*, Global evidence on economic preferences. *Q. J. Econ.* **133**, 1645–1692 (2018).

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