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Strategic dimensions of solar geoengineering: Economic theory and experiments

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ABSTRACT

Solar geoengineering denotes a set of technologies that would enable a fast and relatively cheap global temperature reduction. Besides potential physical side-effects, a major concern is the strategic dimension: Who is going to use solar geoengineering and how would it affect others? How does the presence of solar geoengineering change the strategic incentives surrounding other climate policy instruments such as mitigation? We review the existing theoretical and experimental contributions to those questions and outline promising lines of future economic research.

1. Introduction

Climate change poses global challenges with large impacts. The Paris Agreement sets the goal to limit the increase in the global average temperature to well below 2°C above pre-industrial levels, and pursue efforts to limit the temperature increase to 1.5°C. There are different climate policies available, mitigation, adaptation, and negative emissions. Even the 2°C goal, let alone the more ambitious 1.5°C goal, will be hard to reach with those climate policies alone: even under strict climate policies, at least a temporary overshoot is likely (Rogelj et al., 2018; Raiser et al., 2020; Reisinger & Geden, 2023). This has increased interest in exploring another climate policy tool, solar geoengineering (SG), also known as solar radiation modification (SRM). SG is the attempt to limit warming by increasing the amount of sunlight reflected back into space, e.g. by injecting sulfur particles into the stratosphere (sulfate aerosol injection), or increasing the albedo of marine clouds (marine cloud brightening, MCB), (National Academies of Sciences, Engineering, and Medicine 2021). So far SG is not ready for deployment yet, but technologically probably feasible.

Several features make SG an unusual tool. First, SG is fast: the cooling effects would materialize in a matter of months. Second, current estimates suggest the direct SG deployment costs would be low (in particular much lower than costs of emission reduction for the same amount of cooling). Being fast and inexpensive is what Barrett (2008) calls the "incredible economics" of SG. The fast effects and low costs make SG very attractive in global social best analyses (e.g. Harding et al., 2020). For summaries of the economic literature on SG see Klepper and Rickels (2014), Harding and Moreno-Cruz (2016) and Heutel et al. (2016).

What makes SG attractive in analyses of socially optimal policies is also the reason for concern once we understand that SG will not necessarily be deployed with social welfare in mind. In light of the fact that the SG cooling effect can hardly be locally restricted (especially for sulfate aerosol injection), and that SG deployment suffers from potential side effects such as ozone layer depletion and acid rain, the crucial question is how it will be used by self-interested actors in the absence of a social planner. In fact, many authors emphasize the governance challenges of SG and the potential for conflict over how to set the global thermostat (Bodansky, 2013; Barrett, 2014; Barrett et al., 2014; Reynolds, 2019; Gupta et al., 2020; Schelling, 1996; Victor, 2008; Victor et al., 2009; Victor et al., 2013; Rickels et al., 2020). Some have questioned the governability of SG and called for an international non-use agreement (Biermann et al., 2022). Others have called for balanced research into SG, neither advocating for a ban on deployment, nor rejecting the risky nature of SG (Wieners et al., 2023). Recently, Aldy et al. (2021) have therefore urged more social science research into understanding the ensuing issues.

As we demonstrate below, there have been a number of theoretical contributions to shed light on the strategic dimension of SG and its interplay with other climate policies such as counter-geoengineering, mitigation and research and development. At the same time, we

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should not be too confident that those findings give an accurate prediction of how SG will shape *actual* decisions. This is even more true in light of SG's unusual features. Together with the fact that any "real-world" deployment of SG will be large-scale, and all the potential risks and side-effects this might entail, there is a strong need to test the theoretical predictions. This is where economic laboratory experiments can provide one more strand of evidence, as they often prove to be indicative of actual behaviour (Snowberg & Yariv, 2021).

In this paper we review the existing theoretical and experimental economic literature on strategic problems surrounding SG and draw lessons for future research. It is important to clarify what we do *not* do in this paper. In terms of technologies, we leave out negative emissions (also known as carbon dioxide removal) and focus on solar geoengineering. In terms of climate policy instruments, we only include abatement (mitigation) and adaptation insofar as their interrelation with solar geoengineering is concerned. Furthermore, as we are interested in the strategic dimension of solar geoengineering and therefore do not include contributions on the optimal mix of technologies from a social planner's perspective (for instance excluding Rickels et al., 2020; Belaia et al., 2021). Finally, we do not review the literature on governance of geoengineering that has no primary economics angle (e.g. Reynolds, 2019). On the empirical side, we restrict ourselves to experiments and do not include surveys (Merk et al., 2015; Braun et al., 2018; Cherry et al., 2021) and scenario exercises (Parson & Reynolds, 2021).

We proceed as follows. In section 2 we summarize the economic literature on SG, both theoretical and experimental contributions. In section 3 we develop a research agenda for theory and experiments that study climate change cooperation explicitly including political economy and behavioural considerations. Section 4 wraps up with some thoughts about the outlook for future economics research that is relevant for climate change.

2. Solar geoengineering: economic theory and experiments

This section is structured as follows: we first look at contributions that focus on SG equilibria without any interaction with other climate policy options (section 2.1). We then broaden the scope to technologies to counteract SG, so-called counter-geoengineering (section 2.2). An important topic in the literature is the interaction of SG with abatement (section 2.3). Finally, we look at the interplay of SG deployment with research and development of SG technologies (section 2.4). Throughout, we contrast theoretical and experimental contributions.

2.1. Solar geoengineering equilibria (in the absence of interaction with other climate policies)

The first strand of literature looks at geoengineering without the interplay with other climate policies, aiming to understand what novel challenges SG poses to the interaction of self-interested countries and their incentives for cooperation. One of the main achievements of that strand of literature is to establish the public "GOB" structure (see below) as a central feature of the non-cooperative deployment of geoengineering.

2.1.1. Theoretical contributions

There are two papers featuring static games. Weitzman's seminal article from 2015 introduces the idea of SG as a "public GOB", where "GOB" refers to combination of "good" and "bad". SG is a public good because a global temperature reduction benefits all those who suffer from climate damages; it is a public bad because, if SG already has exceeded a country's ideal temperature, then further reducing global temperatures is detrimental. Crucially, different countries may have fairly different preferences over the ideal amount of global cooling so that there are, at the same time, winners as well as losers from reducing global temperatures. In Weitzman (2015), climate damages increase linearly as temperatures move away from the ideal level and SG is assumed to be costless. The non-cooperative equilibrium of this game is that the country with the strongest preference for cooling, the "free-driver", implements their ideal temperature, leading to over-cooling for everyone else. In terms of governance to overcome this free-driver problem, the paper presents a voting mechanism to implement the social best geoengineering deployment scheme. Weitzman points out, however, that the proposal is naïve in the sense that not enough countries will have the incentive to bind themselves to such an agreement.

Bakalova and Belaia (2023) follow Weitzman (2015) in the GOB structure (with quadratic instead of linear costs from deviating from the ideal temperature) and zero SG deployment costs. In the main part of their work (there are some extensions on mitigation and counter-geoengineering in later sections), they look at the stability of SG coalitions. There are N countries and any coalition implements the average ideal GOB level of all coalition members, due to SG being costless. Among the countries outside the coalition, some would like to do more SG ("free-drivers") and would need a compensation payment for abstaining from free-driving. The analysis in the paper is whether there exists a "bargaining zone", i.e. whether non-drivers can collect sufficient funds to pay off the free-drivers. Stability of a coalition means internal stability (no coalition member wants to leave) and external stability (no outsider wants to join the coalition). Their main finding is that the total gain to non-drivers from cooperation (measured relative to the counterfactual of the free-driver equilibrium) is sufficiently high to pay off free-drivers. This finding's robustness is checked to changes in the model structure, including asymmetric damage function, positive deployment costs, and allowing for counter-geoengineering.

There are two papers studying the dynamic interaction of countries over SG. The players in Ricke et al. (2013) are regions that want to restore temperature and precipitation to a previous baseline (here, the first decade of the 21st century). As in the contributions above, there are no deployment costs for SG. A key assumption in the paper is that SG can only be deployed by a coalition with sufficient "power" (such as population, economic, or military). This assumption has important implications for the coalition formation process: a coalition's only incentive for taking in another country is to get above the power threshold that enables them to be the winning coalition that sets the global thermostat. At the same time, the cost a coalition incurs by including another region is that it gets harder to find a compromise SG level. Within a coalition, the surplus generated from cooperation is shared according to a country's power. Ricke et al. (2013) study an open-membership game (everyone who would like to accede to the coalition can do so.) and contrast it to an exclusive membership game where the coalition can reject membership applications. Coalitions have the incentive to exclude some regions and form a "club". Everybody would like to be in the club because SG is assumed to be costless and being in the club gives access to the global thermostat. Their paper is semi-dynamic in the sense that climate change moves on, but the bargaining process starts afresh every single decade.

Heyen and Lehtomaa (2021) have two main changes relative to Ricke et al. (2013). First, as in Weitzman (2015) preferences over SG are modelled as a GOB structure, instead of the objective of restoring a previous climate as in Ricke et al. (2013). The other change is to have a fully dynamic coalition formation model. Their general framework is illustrated for three countries. Heyen and Lehtomaa (2021) assume that SG has no deployment costs, does not cause side-effects, and that side payments are not possible. An important assumption is that every country can leave any agreement. The authors then contrast different governance schemes: The first is "weak governance", where every country can deploy geoengineering as they please. Here, as predicted by Weitzman, the "free-driver" equilibrium will form where the country with the strongest preference for cooling will eventually set the global thermostat to their preferred global temperature. The second governance scheme is, similar to Ricke et al. (2013), a power threshold: a coalition requires a majority for implementing SG. The paper highlights the difference to static models of coalition formation: importantly, countries look at long-term payoffs and are therefore willing to incur short-term losses if this helps to get to long-term gains. This is an angle missing in the static literature on coalition formation. For instance, in the three-country dynamic setting, it can happen that the two countries with the lowest preference for cooling accept temporary losses in order to eventually form a coalition and, having the majority, fend off the "free-driver".

2.1.2. *Experimental contributions*

Recently, Ghidoni et al. (2023) have used a GOB game to study experimentally side-payments and their effectiveness in containing the overuse of SG. The only way in which players differ is in their ideal GOB level. Players have fixed endowment levels, choose their non-negative geoengineering level, incur a constant per-unit contribution cost, and benefits depend (linearly) on the absolute deviation from their ideal GOB level. Throughout, the paper studies the comparison of bilateral settings (two players interact) with multilateral settings (six players interact). The experiment features the repeated version of the static interaction: each round is the same and restarts anew with the same initial endowment, without spillovers from past actions. That is, SG efforts in a given period do not affect the temperature in subsequent periods. Besides a baseline treatment without side payments, there are two treatments with side payments. In the "decentralized" treatment, players can make side-payment promises that are conditional on the receiving player using SG in a certain way: "I will transfer X tokens if you produce an amount lower than/greater than/equal to Y units". The "treaty" treatment simplifies the space of promises and the players with the highest ideal GOB level can only receive promises but cannot make them. Theoretical predictions are that baseline participants are trapped in the inefficient free-driver equilibrium and that both other treatments, due to side-payment schemes, are able to implement the efficient solution. "Treaty" was overall the most effective treatment in reducing SG and increasing surplus than the "decentralized" treatment. An interesting finding is that many promises were made but turned out unattractive for recipients, leading to a failure of reaching the efficient outcome.

2.2. *Countergeoengineering*

The papers discussed so far focus exclusively on SG. We now broaden the scope and look at the interaction with counter-geoengineering (CG), i.e. the (so far theoretical) possibility of one country or agent to undo the global cooling implemented by others. This could be done in two ways. First, as "countervailing" CG, the release of substances that warm (greenhouse gases or aerosols) to undo SG's cooling effect; second, as "neutralizing" CG, i.e. removing or making ineffective the original SG particles (Parker et al., 2018).

2.2.1. *Theoretical contributions*

Parker et al. (2018) introduce the idea of counter-geoengineering and present a simple game-theoretic model with two countries that both take binary decisions: Country A can use SG or not, country B can use CG or not. In the absence of the CG option, A would be the "free-driver" and use SG to benefit from global cooling, not taking into account the large damages imposed on B. The presence of CG changes the strategic incentives. If A uses SG, B's best response is to use CG; if A abstains from SG, B's best response is not to use CG. Among the two feasible outcomes (SG, CG) and (No SG, No CG), country A prefers the latter. In this sense, the presence of CG is able to deter the free-driver.

Heyen et al. (2019) extend the basic narrative in Parker et al. (2018) by adding the following elements. At the core of their model is the GOB structure explained above, i.e. changes to the global climate affect all countries and different countries differ in their ideal GOB levels. In contrast to Parker et al. (2018), SG and CG are continuous, not binary decisions; deployment costs are taken into account (assumed to be quadratic); and countries have the possibility to cooperate by entering into treaties. The paper studies two types of treaties: a moratorium treaty, in which the countries commit themselves to neither use SG nor to counter-geoengineer; and a deployment treaty, in which countries commit themselves to using SG in a way that maximizes social welfare. Heyen et al. (2019) find two classes of non-cooperative equilibria. If the ideal GOB levels are not too different (or deployment costs are sufficiently high), the outcome is a free-rider equilibrium: both countries deploy SG, but overall too little because of free-rider incentives. In this case, CG would not be used and therefore it does not make a difference whether CG is available or not. In contrast, if ideal GOB levels are sufficiently different (or deployment costs sufficiently low), in the absence of CG the outcome is a free-driver equilibrium: the country with the stronger preference for cooling deploys more SG than the other country's ideal level and the other country cannot do anything against this. CG changes this drastically, leading to an escalating clash of large SG and CG quantities. This looming escalation can, but need not provide sufficient cooperation incentives. Under some parameter constellations the presence of CG causes a moratorium treaty to establish, but this form of cooperation need not be better than a non-cooperative free-driver outcome. Overall, therefore, the welfare effect of CG is ambiguous.

Bas and Mahajan (2020) extend the static approach by Parker et al. (2018) and Heyen et al. (2019) and study a dynamic setting. The two-country setting has a GOB structure for the effect of different global temperatures, deployment costs, and side-effects from SG by others, and the possibility of SG and CG. Another feature of their model is the possibility of military conflict. Engaging in conflict is costly, but the winning country gets exclusive access to modifying the global climate. The authors demonstrate that, irrespective of the non-cooperative equilibrium (conflict; countervailing deployment of SG and CG; free-riding) countries can sustain a cooperative deployment scheme in a tit-for-tat manner if sufficiently patient. The authors also study the aspect of imperfect monitoring of SG deployment, i.e. if it is not clear whether a country has deployed SG / CG or not. This is a realistic feature in the context of a complex climate system. An important finding of the paper is that imperfect monitoring and thus imperfect attributability may hinder cooperation.

2.2.2. *Experimental contributions*

Abatayo et al. (2020) test predictions about SG free-driving and CG experimentally. The core is a GOB game, similar to the above-mentioned Ghidoni et al. (2023). Again, players have a fixed endowment, there are constant per-unit contribution costs, and benefits depend on the absolute deviation from a player's ideal GOB level. Players only differ in their ideal GOB level. As in Ghidoni et al. (2023), each "decision-maker" consists of a "team" of two experimental subjects; within-team communication is possible and decisions need to be unanimous. There are two treatments, "baseline" (only non-negative contributions are allowed) and "counter" (in which negative contributions, representing CG, can be made). First, players play a repeated baseline GOB game in economies of two decision-makers ("bilateral"), then they play another repeated GOB game in their treatment (baseline or counter), then a repeated GOB game in economies of six decision-makers ("multilateral"). There are three possible ideal GOB levels, 2, 6 and 10. In terms of results, treatment "baseline" results in total GOB levels close to the highest ideal level, 10, confirming the hypothesis of free-driving. The most striking finding of the paper pertains to CG. The theoretical prediction is a SG-CG clash with opposing deployment levels counteracting each other. This is indeed what the authors find, however only on average. There is wide variability with over- and undershooting of total GOB levels that is not predicted by theory. Coordination is hard due to strategic uncertainty and the failure of coordination gives rise to significant welfare losses on top of the inefficiency related to the free-driver problem. Highlighting the problem of coordination with many agents, the welfare losses were more pronounced in the multilateral than in the bilateral setting.

2.3. Interaction with abatement / mitigation

A central concern about SG is that it might distract attention from emissions reduction. This is known as the "moral hazard" concern (National Academies of Sciences, Engineering, and Medicine 2021; Merk & Wagner, 2024). Unsurprisingly, the interaction of SG with abatement has received most attention in the literature. In the following we first review papers in which agents do not have the possibility to cooperate with each other and then study settings with cooperation.

2.3.1. Papers without cooperation possibilities

2.3.1.1. Theoretical contributions. Urpelainen (2012) develops a two-period model with two symmetric countries. In the first period, countries decide on mitigation by choosing a non-negative emission level. In the second period, they decide on SG by choosing a non-negative SG level. The main model assumptions are as follows. First, mitigation is costly, i.e. countries benefit from emitting more. Second, climate damages depend on total emissions and can be reduced by SG, where again the sum of countries' SG efforts matter. Third, SG is costly, and fourth, SG has side-effects on the other country. The size of this negative side-effect is an important parameter in the analysis. Urpelainen (2012) solves the model as usual via backward induction: the first step is to determine the SG equilibrium given an emission profile inherited from the first period; the second step is to determine the emission equilibrium anticipating how SG will be used in the second period. The main finding is that SG side-effects can be a reason to reduce emissions (see below for the rationale).

Similar to Urpelainen (2012), the main focus in Moreno-Cruz (2015) is a two-country model with two periods: Countries choose mitigation in period 1 and SG in period 2. Both mitigation and SG are costly and there are climate damages and side-effects from SG, and the two countries can be heterogenous in all those dimensions. As usual, the model is solved via backward induction. In the second stage, if SG damages are sufficiently asymmetric, only one country deploys SG. When countries are similar, total mitigation will be lower with SG than without the SG option, but temperatures will still be lower due to the cooling effect of SG. This is also what one would expect in a central-planner solution. Therefore, Moreno-Cruz (2015) shows that the strategic conflict between relatively similar countries is not strong enough to change the main logic of SG as substitution for mitigation. The paper's interesting finding is that for sufficiently asymmetric countries, overall mitigation can go up, even beyond the socially efficient mitigation level. The reason is the threat from SG. The country that would suffer high damages from SG may find it in their interest to increase mitigation in order to reduce the other country's incentives for using SG.

Instead of the intra-generational problem, Goeschl et al. (2013) study the inter-generational strategic effects between SG and abatement. The paper focuses on the "arming the future" argument, i.e. SG as an insurance policy for the future if climate change turns out to be very severe. Their model features two players, current generation and future generation. Current generation chooses abatement and whether to make SG available to the future. After climate sensitivity is revealed, interpreted as whether climate change is very severe or not, the future generation decides about SG. SG reduces climate damages but also involves side-effects. The interesting feature of the model is that the current generation considers the possibility that the future will assess side-effects differently and therefore use SG different from a conditional use profile (use SG if and only if the climate turns out severe) that current generation prefers. Current generation has two strategic instruments available, namely rejecting the future the SG option by not undertaking R&D as well as the level of abatement. Goeschl et al. (2013) demonstrate that depending on R&D costs and the bias between current and future generation, several equilibria are possible, including technology rejection as well as increase in abatement in order to reduce future's incentive to use SG in the wrong way. The latter finding mirrors the strategic intra-generational effect found in Moreno-Cruz (2015).

Moreno-Cruz and Smulders (2017) mostly deal with the optimal mix of adaptation and SG (and therefore fall outside the scope of this article), but in one section they study the effect of SG on the non-cooperative adaptation game of n countries. An interesting feature of their model is that, besides the usual negative temperature effects, they also take into account the positive fertilization effect that higher CO2 levels increase agricultural productivity. SG is deployed by one philanthropist that knows that countries play the abatement game non-cooperatively. One insight of Moreno-Cruz and Smulders (2017) is that the philanthropist's SG deployment cannot solve the countries' abatement coordination problem. Another insight is that, due to the presence of the fertilizer effect that gains relative importance when SG reduces temperature damages, SG "can turn the climate change problem from a coordination problem with over-provision of a public bad into one with under-provision of a public good."

Fabre and Wagner (2020) study a simple game-theoretical model of two countries. The model features mitigation and SG. Mitigation is modelled as a "weakest-link" public good, i.e. high mitigation is only possible if both countries choose high mitigation. The authors demonstrate the existence of a subgame-perfect equilibrium in which SG is a credible threat, bringing both players to choose high mitigation in the first round. This can happen if SG itself is too risky to be considered a magic bullet, both countries prefer high mitigation to low mitigation, and one country dislikes the idea of SG.

2.3.1.2. Experimental contributions. Andrews et al. (2022) study a modified "disaster game": four players ("citizens") contribute to a public account; if they collectively exceed a threshold, they keep their remaining private account; otherwise disaster strikes and all lose everything. The modification is to add a fifth player ("policy-maker") whose incentives are aligned with the citizens': also the policy-maker loses in case of a disaster, but she cannot directly contribute tokens to meet the threshold; rather, she can decide whether to use SG or not. With a certain probability between 10% and 90%, varied across treatments, SG is successful and averts disaster independent of the citizens' contributions; otherwise SG fails and it is down to the citizens' contributions whether disaster occurs or not. Crucially, citizens know whether SG was used or not, but they neither know the success probability nor whether it eventually was successful. In this sense, the natural application of the experiment is to R&D of SG, not deployment (where one could argue it becomes clear quite quickly whether it worked or not). The experiment is designed in such a way that, under a uniform belief of the citizens over the possible success probabilities and subjective expected utility preferences, it is rational for the citizens to still avoid the disaster by sufficient contributions. The authors interpret any deviation from that as "moral hazard", i.e. an unduly reduction in contributions. Interestingly, the authors do not find any evidence for "moral hazard". In addition, the authors study whether the fifth player, the policy-maker, engages in "moral hazard anticipation": If policymakers do not expect moral hazard they can simply use SG; otherwise they may decide not to use it. They should use SG only if they believe that its success probability is greater than the perceived probability that the group will be able to cooperate and avert disaster without SG. The authors find indeed evidence for such "moral hazard anticipation".

Cherry et al. (2022) set up a two-stage game with N players in which players cannot communicate. The first stage is a mitigation decision, the second stage is a SG decision. As in standard public good games, a player's payoff is determined by the private account (those endowed tokens not spent on mitigation in the first period) and the group account (tokens protected from climate change). As usual, mitigation is socially beneficial, but individually not attractive. In addition, players have the SG option that allows them to protect even more tokens. To simplify the analysis, SG is assumed to be costless and modelled as a 'best-shot' technology, i.e. the highest SG level chosen is the level realized for all group members. There is a GOB structure: players incur a cost if SG is too low or too high for their liking. Participants are assigned to groups of three, and the group assignments changes each period. The moral hazard conjecture predicts a decrease in mitigation. The interesting finding is that mitigation went up, not down, when SG is available. This is more in line with SG as a threat that induces more mitigation instead of the "moral hazard" concern. They also find evidence for free-driving as the actual SG level is significantly higher than the efficient level, in part due to the assumption of costless SG.

2.3.2. Papers with cooperation possibilities

2.3.2.1. Theoretical contributions. Millard-Ball (2012) extend a traditional coalition formation model by the option of using SG. There are N symmetric countries. In the first stage, countries decide whether or not to participate in an international environmental agreement (IEA). In the second stage, countries in the IEA choose their level of abatement in order to maximize the coalition's payoff. In the third stage, the countries outside of the coalition individually choose their level of abatement. This standard model is extended by the fourth stage in which countries decide whether to use SG; the SG decision is binary and taken by each country individually, without being bound by membership in the abatement coalition. SG brings benefits that decrease in the aggregate level of abatement chosen in previous stage and has side-effects on other countries. Due to symmetry, either no country or all countries want to use SG; in the latter case, one country is randomly selected that gets to deploy SG. The paper then presents several storylines compatible with the model, including "The Tuvalu Syndrome" in which a small island state heavily affected by climate change credibly threatens to use SG; this threat, in turn, brings other countries into the abatement coalition that reduces emissions and thus reduces the motivation to use SG in the first place.

Finus and Furini (2023) extend Millard-Ball (2012). Building on the core setting of Millard-Ball (2012), they analyse the entire parameter space and not only the few illustrative settings from Millard-Ball (2012). They also study stability of coalitions other than the grand coalition, adopting the frequently used stability criterion as internal stability (no coalition member wants to leave) and external stability (no country outside the coalition wants to join). They confirm Millard-Ball's finding that sufficiently large SG side-damages are required to make a climate agreement robust to deviations, but identify a missing assumption in Millard-Ball (2012): side-damages also cannot be too high, as otherwise the threat of SG deployment would not be credible. Finus and Furini (2023) also study a repeated game to study robustness of the static analysis: Focusing mostly on the grand coalition, cooperation is maintained until one country defects, triggering punishment by the others. They qualitatively confirm all conclusions from the static model, suggesting that the static cartel formation game is a decent representation of cooperation incentives.

Manoussi and Xepapadeas (2017) study a game of two countries in continuous time. The greenhouse gas stock follows a trajectory with decay. Countries have quadratic benefits from emissions, quadratic temperature damages and face quadratic SG deployment cost. The temperature profile is a function of greenhouse gas concentration. SG reduces temperatures (the contributions by both countries add up) and has side-effects. The model in principle allows heterogeneity in all parameters. As a benchmark, the authors first derive the cooperative and non-cooperative solution when countries are symmetric. The cooperative solution is defined as maximizing the sum of intertemporal welfare, the non-cooperative is the feedback Nash equilibrium, where, at every point in time t, the choice of emission and geoengineering follows a feedback rule. For the symmetric benchmark, the non-cooperative solution has higher emissions and more SG than the cooperative solution. The authors then study different sources of uncertainty and confirm the finding in Moreno-Cruz (2015) that asymmetric SG side-effects can lead to an increase in abatement.

Manoussi et al. (2018) follow Manoussi and Xepapadeas (2017) in their basic two-country structure in continuous time. The novel element is that the authors include uncertainty about the side-effects of SG. As in Hansen and Sargent (2001), this uncertainty is "deep" in the sense that several models are considered possible and the players are averse to that uncertainty. In terms of findings, this aversion to deep uncertainty about SG side-effects implies lower SG deployment both for the cooperative and the non-cooperative outcome. Another finding gives an interesting extension of the "free-driver" idea: if countries differ in their model confidence about the side-effects of SG, then the more confident country will deploy more SG.

Emmerling and Tavoni (2018b) have a static model with *N* countries. Each country can do abatement and SG. There are country-specific abatement costs, SG deployment costs, temperature damages and SG side-effect damages. The main part of the paper is numerical analysis with the calibrated game-theoretic integrated assessment model WITCH, featuring 13 world regions. What the analytical and numerical results of the paper show is the risk of excess SG cooling in the absence of cooperation: there is too much SG and temperature falls below the optimal value and SG's side effects outweigh the temperature reduction benefits. The regional results suggest that countries most affected by climate change would use SG at the expense of the rest of the world.

Pezzoli et al. (2023) adopt the basic setting from Ricke et al. (2013), described in section 2.1., with exclusive membership coalitions and the assumption that a coalition can only implement SG if the coalition's combined power (for instance population size, or economic or military power) exceeds a certain threshold. Similar to Ricke et al. (2013) and in difference to Heyen and Lehtomaa (2021), the coalition formation is not dynamic but only occurs once. The authors interpret stability as γ-core stability which assumes that a coalition breaks down when a member leaves (in contrast to external and internal stability that assumes that the remaining coalition persists, the authors study that stability concept in the appendix). The novelty is that coalitions not only make decisions on SG but also on mitigation, giving a more realistic view on strategic incentives about climate policies. The authors use the integrated assessment model RICE50+, an integrated assessment model able to quantify the interaction between climate and the economy for several regions; particularly relevant is that this model is not only able to determine the global best choices, but also capable of determining the Nash equilibria of the strategic interaction between regions. Pezzoli et al. (2023) find that the availability of SG tends to increase the stability of coalitions. One interesting finding is that the number of stable coalitions is non-monotonic in the side-effects of SG. Underlying this effect is different countries have different incentives to join a coalition. Cold countries want to avoid large amounts of SG; as higher SG damages reduce the SG amount, cold countries are more willing to be part of a coalition if SG damages are (relatively) high. The picture is different for big emitters such as China. They more likely reject a coalition if it involves high mitigation requests. Through a substitution effect higher SG damages increase the needed mitigation, so higher SG damages tend to crowd out high emitters. Pezzoli et al. (2023) also find that SG is effective: The stable SRM coalitions manage to stay below 2C warming in 2100.

2.3.2.2. Experimental contributions. To our knowledge there are, at this point in time, no experimental tests of the interaction between SG and mitigation.

2.4. R&D and learning

2.4.1. Theoretical contributions

We have already covered Goeschl et al. (2013) above in the context of the interaction of SG and abatement. In the model, besides abatement, the current generation also chooses whether to undertake R&D into SG and thus pass the option to modify the climate to the future generation. If concerned that the future generation may use SG prematurely, the current generation can increase abatement and thus reduce the incentives to use SG (as discussed above) or abstain from R&D altogether.

Quaas et al. (2017) study a three-period intergenerational model. The first generation decides whether to research SG; the second period generation decides on abatement; the third generation decides about SG deployment. Climate damages are uncertain and this uncertainty resolves just before the third generation makes their SG deployment decision. The probability of high climate damages is endogenous: the likelihood of severe climate damages decreases in abatement. SG can either be effective and harmless (reducing climate damages) or ineffective and with side-effects (leading to damages even higher than climate damages). This uncertainty resolves if (costly) research into SG was undertaken in period 1. The authors allow for hyperbolic discounting. They find evidence for a “slippery slope”: researching SG increases the likelihood of SG deployment; in contrast, research may or may not decrease abatement, so there is no clear statement about “moral hazard”. An important finding is that under geometric discounting (and therefore time-consistent decisions) the first generation always finds it optimal to research SG. In that sense the authors find that time-inconsistent behaviour may be an argument for not researching SG.

Heyen (2016) studies a setting with two countries and two stages. The first stage is the R&D stage, modelled as a threshold public good game: if the sum of R&D expenditures by both countries exceed a known threshold, then both will have access to the technology in stage two; if the R&D spending threshold is not met, no one can use the technology. In the second stage, if R&D was successful, both countries decide simultaneously about their non-negative technology level. Technology deployment has private (quadratic) costs and benefits depend on the total technology level with a GOB structure, as explained above: both countries have an ideal total technology level; any deviation from that ideal GOB level, no matter in which direction, is detrimental. The ideal GOB level can differ between countries. Depending on deployment costs and difference in ideal GOB levels, the equilibrium of the game is either a free-rider equilibrium (in which the total GOB level is below the ideal GOB level for both) or a free-driver equilibrium (in which only the country with the higher ideal GOB level deploys the technology and the total GOB level exceeds the other country’s ideal GOB level). The paper demonstrates that the country with the lower preference for cooling may have a negative willingness-to-pay for R&D: anticipating a detrimental free-driver equilibrium, that country may prefer the technology not to be available; it is even willing to pay for preventing the technology.

2.4.2. *Experimental contributions*

Andrews et al. (2022), discussed above, study the moral hazard concern but also the “moral hazard expectation” concern. The policy-maker’s decision whether to use SG could be re-interpreted as the decision whether to develop SG. If interpreted as such, their findings suggest that policy-makers will less often develop SG if they are concerned about moral hazard in the abatement choices. We are not aware of any other experimental work on the interplay of R&D with SG.

In summary, we see that there is a growing and already informative theoretical literature on various strategic issues of SG. The experimental literature is not as advanced, suggesting that there is ample opportunity for future research. Encouraging such research is one central goal of this article.

3. Research agenda for theory and experiments that study climate change cooperation: political economy and behavioural considerations

In section 2 we have reviewed the state of the art in the theoretical and experimental literature on strategic aspects of solar geoengineering. Building on the established ground, the literature can advance in several dimensions, including better representations of climate damages and SG side effects, especially regionally disaggregated impacts, as well as more realistic cooperation possibilities and treaties, including fully dynamic models.

In this section we take a cursory view about some additional promising avenues for enriching economic models and experiments with a view to shedding light on important behaviours that are relevant for climate change cooperation. For the sake of concreteness we will speculate about the potential effect of introducing some realistic political economy features in a simple public GOB provision environment.

Traditional economic models and economic experiments typically focus on a single decision-maker, implicitly assuming that the decision regarding the setting of a policy such as a climate change mitigation target or the choice of the public good provision level are in the hands of an individual. In theoretical economics this monolithic actor is the ubiquitous social planner, who typically maximizes social welfare in a vacuum: without interference from other actors and absent vested interests or hierarchical decision-making structures. In experimental work, the sole decision-maker is often the laboratory or online participant, again having control over the implemented choice.

While convenience and tractability may warrant this approach in some cases, we argue that many problems (including the management of local and global environmental externalities such as climate change) require unpacking of the decision-makers’ black box. A range of issues that have been tackled in the literature to capture the hierarchical interplay between domestic (political) pressure and international climate cooperation can be found in a recent review by Tavoni and Winkler (2021). For the sake of brevity, here we focus on two: electoral and strategic delegation (where principals delegate to agents who exhibit different preferences, such as diverging concern with respect to climate change), and lobbying by special interest groups, with a focus on the role of domestic political competition in affecting the effectiveness of international environmental agreements.

While summarising here the insights from the above-mentioned political economy contributions to climate change mitigation policy is beyond the scope of this article, we mention selected relevant findings from theory and experiments, beginning with studies that focus on climate change mitigation.

3.1. *Delegation papers*

Siqueira (2003) and Buchholz et al. (2005) study strategic voting in the context of cross-country externalities in a two-country setting. They find a systemic bias in voters’ selection of agents, favoring politicians who exhibit lesser concern for externalities than the median voter. Specifically, electing a more conservative politician in the home country results in a commitment to a lower tax on the externality, thereby shifting the burden of abatement to the foreign country (Siqueira, 2003; Buchholz et al., 2005). Hattori (2010) extends the model to incorporate competition on prices alongside quantities, finding that, when the policy choices are strategic substitutes (complements), a less (more) green policy maker is elected in the noncooperative equilibrium. Lastly, Loeper (2017) shows that whether cooperation between national delegates is beneficial only depends on the type of public good considered and, more specifically, on the curvature of the demand for the public good. In summary, the reviewed theoretical literature on delegation in the provision of the mitigation public good tends to find a race to the bottom. This finding stems from the strategic substitutability of emission choices.

There is a parallel, yet thin, experimental literature that tackles the question regarding to what extent delegation can foster public goods provision within and across groups. While the experimental literature is less pessimistic than the theoretical predictions, this can be explained at least in part by the fact that in linear public goods games there is no incentive to strategically delegate to exploit the strategic substitutability of public goods provision choices. In the following we review the few experiments that analyse the effect of delegation on public good provision *across* groups.

Kocher et al. (2018) and Kim et al. (2022) are the only experiments that we have encountered that analyse delegation in a linear public goods game across groups. In Kocher et al. (2018), nine players are divided into three groups, each formed by three players Each group elects a leader who mandates contributions to the public good for all members of their group. Aggregate public goods provision, however, depends on the contributions of all nine players across all three groups. within a similar vein to other experiments featuring delegation within groups, Kocher et al. (2018) find that delegation increased public goods provision compared to the case of nondelegation. They also find that most delegates refrain from exploiting their group members, and that contributions within groups decline over time, although slower than in the absence of delegation.

Kim et al. (2022) focus instead on representation by randomly appointed individuals, with twelve players divided in four groups. The two main differences with respect to Kocher et al. (2018) are that the four representatives cannot exploit their team members (group earnings are identical to all members) and the inclusion of a punishment mechanism across groups and of a domestic pressure mechanism within groups. Kim et al. (2022) confirm the established finding that punishment reverses the slide towards the zero contribution Nash Equilibrium. But they also uncover a novel interacting effect between hierarchical decision-making and punishment on public good provision. Namely, relative to the standard case of self-representation, the positive trend reversal in contributions is more modest when representatives are in charge for the entire team, especially when non-representatives cannot signal their preferred contribution amounts.

Two further experiments focus instead on delegation's impact on threshold public goods provision, which is particularly relevant in the context of abrupt climate change. Milinski et al. (2016) investigate a threshold public goods game involving six groups of three players. Delegated representatives, chosen randomly or by election, contribute on behalf of the group. If the public account falls below a threshold after ten rounds, there is a 90% probability of losing the private accounts. Comparing outcomes with and without delegation across treatments reveals no significant variation in group investments or threshold-reaching probability. However, evidence suggests that in delegation treatments, representatives contribute less than average, possibly to induce higher contributions from other groups, aligning with literature on strategic delegation in public goods provision. In a second experiment, Iriş et al. (2019) explore the interplay between delegation and public pressure in a threshold public goods game. Twelve subjects are randomly assigned to four teams, which elect a delegate through majority voting. Delegates play variants of a one-shot threshold public goods game where losses occur if contributions fall short of a threshold. The results show that when delegation is coupled with public pressure, it significantly reduces contributions, even with mild pressure on delegates. Delegates give more weight to the least cooperative contribution suggestion, focusing on the lower of the two contributions recommended by their teammates.

3.2. Lobbying and domestic political competition papers

Empirical evidence and political economy models conclusively indicate that politicians do not singularly prioritize public interest. Their motivations encompass not only the public good but also extend to their private interests, rendering them susceptible to influence emanating from the dynamics of national political competition (cf. Besley, 2006, Bombardini & Trebbi, 2020, Grossman & Helpman, 2001, Persson & Tabellini, 2000). Environmental policymaking is frequently characterized as a contest between business and environmental interest groups. Business lobby groups typically endeavour to constrain financially burdensome environmental measures, while their environmental counterparts pursue the opposite objective. We now look at studies delving into domestic lobbying dynamics, with particular emphasis on their impact on climate change policy.

Methodologically, the influence exerted by lobby groups on incumbent governments is commonly conceptualized through the common agency approach. Originally formulated by Bernheim and Whinston (1986) and subsequently expanded upon by Grossman and Helpman in seminal works (Grossman & Helpman, 1992, 1995a,b), this framework involves lobby groups simultaneously and non-cooperatively presenting contribution schedules. These schedules specify contributions that are contingent on the implementation of specific policies. In a subsequent phase, policymakers choose the policy, factoring in the lobby groups' contribution schedules. The result is typically distortionary, with respect to the policy level that maximizes social welfare.

The body of work by Bernheim and Whinston (1986) and Grossman and Helpman (1992, 1995a,b) shares the modelling assumption that countries are unitary actors. For instance, countries are often represented by benevolent governments, acting in the best interest of the country as a whole. This approach, however, overlooks the internal political structures within countries and consequently foregoes potential insights into the intricate interplay between domestic and international (environmental) policy.

In a recent article, Battaglini and Harstad (2020) show that domestic political competition may have an important impact on the design and effectiveness of international agreements. In a model in which a home country imposes an externality on a foreign country, they show that political competition for re-election between an incumbent government and a rival party may lead to weak treaties, i.e., agreements with control and sanctions mechanisms that cannot ensure that the treaty is adhered to independently of who wins the next election. While these treaties are always inefficient from a social welfare perspective, it is in the best interest of the incumbent government to negotiate a weak treaty if the payoff of re-election is sufficiently high. The reason is that the incumbent government can increase its re-election probability by a weak treaty, as this allows the incumbent government to further differentiate itself from the competing party.

Habla and Winkler (2013) analyse the formation of an international emission permit market when the governments of countries are influenced by special interest groups. Governments are lobbied in both stages: they first receive contributions when they decide to link domestic permit markets to an international market and again when they decide on the number of permits issued to the domestic firms. They find that lobbying may backfire: an increase in power of one lobby group may result in a policy change that it deems unfavourable. The reason is that an increase in a lobby group's power has both direct and indirect effects. While the direct effect induces a policy shift in the desired direction in the special interest group's home country, the indirect effect operates in the opposing direction on the government of another country (due to the strategic substitutability of emission permit choices), potentially outweighing the direct effect.

Marchiori et al. (2017) analyse the formation of a self-enforcing international environmental agreement in a framework where governmental emissions decisions are subject to the influence of both an industry and an environmental lobby group. Despite these lobby groups exerting their political sway exclusively in the second stage (concerning the countries' emission levels), their choices influence the decision-making process in the initial stage. That is, governments factor in this anticipated influence when deciding whether to partake in the international agreement. The study demonstrates that a potent industry lobby and/or a weak environmental lobby diminish the emissions abatement efforts of participating nations, potentially increasing overall participation. The net effect on participation hinges crucially upon whether the upswing in the number of participating countries outweighs the reduction in abatement effort by those countries.

Spycher and Winkler (2022) investigate the establishment of self-enforcing environmental agreements within a context where governments strategically delegate emission choices. This model is akin to that employed by Finus and Maus (2008), wherein cooperating nations may opt for less ambitious emission abatement goals rather than a complete internalization of emissions externalities across all participants. The study reveals that principals in all countries are motivated to strategically delegate to agents exhibiting lower environmental concerns than the principals themselves. Furthermore, principals in member countries have an additional incentive to prevent a modest environmental agreement by strategically delegating to agents with higher environmental concerns.

3.3. The political economy of public “GOB” (Good or Bad) provision

While domestic pressure and the forms of hierarchical policy making we consider here are generally more relevant for mitigation than for adaptation, as adaptation policies are primarily concerned with domestic issues, one can also think of adaptation decisions with important international repercussions. An interesting example is solar geoengineering, which, owing to its public “GOB” characteristics (potentially being either a good or a bad, depending on the provision level) may result not only in underprovision (free riding) but also overprovision (free driving) globally.

We thus end this section by speculating about possible ways to incorporate some of the political economy aspects discussed above into the GOB structure. In so doing we hope to demonstrate concrete theoretical and experimental applications of the public GOB game. These exercises, besides the fascinating strategic insights on a game that captures many real-world features applicable to issues as far reaching as academic seminar attendance, management of wolves’ populations and solar radiation management, illuminate nuances in the strategic interplay between different actors involved in the provision of GOBs. In keeping with the above overview, we start with delegation and then consider the possible effect of lobbying on provision. In both cases we sketch how an international environmental agreement modelled as a coalition formation game can be enriched by adding a stage, respectively featuring delegation to an agent who negotiates the terms of the GOB agreement on behalf of the policy-making principal, and lobbying by special interest groups that compete to steer the politician’s provision choice towards their preferred outcome.

A possible application of the delegated GOB agreement could be modelled in four stages as a solar geoengineering deployment game. In stage 1 (the membership stage), the principals of N countries decide whether to sign an international agreement regarding the choice of the level of solar geoengineering. In stage 2 (the delegation stage), principals of member and non-member countries simultaneously choose the delegate that will act on their behalf in the next stage of the game. In stage 3 (the policy-making stage), delegates choose simultaneously the level of geoengineering. Following a successful agreement, the delegates of the negotiating countries choose cooperatively the level that maximizes the aggregate welfare of the participating countries (from the viewpoint of the chosen delegates). Instead, countries outside the agreement choose the level by non-cooperatively maximizing only their own welfare. In the fourth and final stage of the game, the chosen policies are carried out.

We hypothesize that strategic delegation will result in potentially surprising outcomes with respect to an equivalent model without delegation. For instance, depending on parameters such as number of countries and functional forms, one could expect equilibria characterised by higher or lower levels of deployment. As argued before, since large-scale deployment of solar geoengineering is unlikely to be tested in the near future in light of the ensuing international governance issues, such theoretical investigations about the strategic incentives for deployment are particularly valuable, in our view.

Another tool that comes to the rescue when real-world data is missing, is economic experimentation, which allows for a clear comparison of counterfactual and treatment groups. While there are a handful of experiments that introduce coalition formation to capture the dynamics of international environmental agreements (e.g. McEvoy et al., 2010, Bosetti et al., 2017), we are not aware of experiments that study GOB provision with such framework. Furthermore, none explore the role of delegation or lobbying in this environment. The above suggestion for a multi-stage game could be implemented in the laboratory relatively simply.

We conclude this section by mentioning that a similar setup as the one described above for delegation could be analysed theoretically and experimentally to assess the influence of lobbying on the provision of GOBs such as solar geoengineering. A possible implementation would proceed as follows. In stage 1 (the membership stage), governments in all countries simultaneously choose whether to be signatories to a geoengineering agreement, as before. In the subsequent stage 2 (the emission policy stage), several sub-stages unfold. (a) Domestic lobby groups independently and simultaneously present their own government with contribution schedules, to which they fully commit. (b) Faced with these contribution schedules, governments (both signatories and non-signatories) simultaneously decide on their emission levels. (c) Lobby groups pay contributions contingent on policy choices. In the case of a standard public good such as the protection of the environment through mitigation efforts, such framework results in counterintuitive results. For instance, Marchiori et al. (2017) find that a powerful business lobby may increase the government’s incentives to sign an agreement, by providing it with strong bargaining power with respect to that lobby at the emission stage. It would be interesting to see if this would also be the case for a more complex GOB game.

4. Outlook

Climate change is no longer an abstract and contested concept: it is already part of our daily lives, and we are beginning to feel the impacts, notably in terms of rapidly increasing record-breaking global temperatures and severity of disruptive weather events. Economists can contribute much to fill the gap in research, policy and teaching, so that the economics tools are more useful in real-world applications, especially those aimed at mitigating or adapting to climate change.

Solar geoengineering presents strategic challenges as well as opportunities. Its “incredible economics” (potential for rapid and relatively inexpensive deployment) calls for much more research across the social sciences. Economists and behavioural economists can and should contribute their insights, given the invaluable contribution of experimental methods to study issues, such as SG, that pose challenges to real-world experimentation (Carattini et al., 2019). Economic experiments allow for clear comparisons across treatments, relative to a counterfactual that is elusive in the real world, to say the least.

But the governance of geoengineering is clearly an interdisciplinary matter, which calls for broader collaborations with sociologists, political scientists, philosophers, ethicists and natural scientists. Unfortunately, at the moment economists have a marginal role in this space, both in terms of research and teaching. We hope that this paper and special issue will contribute to increasing the prominence of climate change, and especially under-researched topics such as geoengineering, among behavioural and theoretical economists.

CRediT authorship contribution statement

Daniel Heyen: Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Conceptualization. **Alessandro Tavoni:** Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Conceptualization.

Data availability

No data was used for the research described in the article.

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