RESOURCES
for the FUTURE

A Unifying Theory of Foreign Intervention in Domestic Climate Policy

Juan Moreno-Cruz and Anthony Harding

Working Paper 23-24
May 2023

About the Authors

Juan Moreno-Cruz is an associate professor at the School of Environment, Enterprise and Development and the Canada research chair in energy transitions at the University of Waterloo. He is also a CESifo research affiliate. Moreno-Cruz has a PhD (2010) from the University of Calgary and a BA and MS in electrical engineering from the Universidad de Los Andes. Prior to his current position, Moreno-Cruz was an associate professor in the School of Economics at the Georgia Institute of Technology (2011-2017), were he remains an adjunct professor. He has also been a visiting researcher in the Department of Global Ecology of the Carnegie Institution for Science at Stanford University (since 2015), an advisor for Carnegie Energy Innovation (since 2017), and a research associate of Harvard University's Solar Geoengineering Research Program.

Moreno-Cruz's research focuses on the interaction of energy systems, technological change, and climate policy. His most influential work examines how solar and carbon geoengineering technologies affect climate policy. His most recent work provides novel insights into the process of energy transitions by demonstrating how energy access shapes the organization of the economy in cities and how energy consumption in cities in turn pollutes the local and global environment.

Anthony Harding is a postdoctoral fellow researching the intersection of innovative technologies and climate policy. He received his PhD in economics from Georgia Institute of Technology, where his research focused on climate and energy economics, and earned a BS from Rensselaer Polytechnic Institute in math and physics. Harding's research applies both econometrics and economic modelling to evaluate climate policy and climate impacts. His most recent work estimates the distribution of economic impacts of solar geoengineering across countries and compares it to the impacts of climate change. His current interests include the design of effective international climate governance structures and the measurement of the value of scientific learning.

Acknowledgements

We acknowledge support from the LAD Climate Fund and useful comments and feedback from Jonathan Weiner and other participants in workshops at Resources for the Future, the Latin American Association of Environmental and Resource Economists, and the Canadian Economics Association. Moreno-Cruz acknowledges additional support from the Canada Research Chair program and National Science Foundation grant NSF #1948154.

About RFF

Resources for the Future (RFF) is an independent, nonprofit research institution in Washington, DC. Its mission is to improve environmental, energy, and natural resource decisions through impartial economic research and policy engagement. RFF is committed to being the most widely trusted source of research insights and policy solutions leading to a healthy environment and a thriving economy.

Working papers are research materials circulated by their authors for purposes of information and discussion. They have not necessarily undergone formal peer review. The views expressed here are those of the individual authors and may differ from those of other RFF experts, its officers, or its directors.

About the Project

The Resources for the Future Solar Geoengineering research project applies tools from multiple social science research disciplines to better understand the risks, potential benefits, and societal implications of solar geoengineering as a possible approach to help reduce climate risk alongside aggressive and necessary mitigation and adaptation efforts. The project began in 2020 with a series of expert workshops convened under the SRM Trans-Atlantic Dialogue. These meetings resulted in a 2021 article in *Science* that lays out a set of key social science research questions associated with solar geoengineering research and potential deployment. The Project followed this with additional sponsored research, including a competitive solicitation designed to address research areas highlighted in the *Science* article. This paper is one of eight research papers resulting from that competition and supported by two author workshops. A key goal of the solicitation and the overall project is to engage with a broader set of researchers from around the globe, a growing number of interested stakeholders, and the public.

Sharing Our Work

Abstract

Strategic interventions among nations are likely to differ across the portfolio of possible climate change policies, including mitigation, adaptation, and solar geoengineering. With this in mind, we propose a theory of climate policy-motivated foreign intervention to study different forms of international climate governance in the presence of power imbalance. Foreign countries have at least three options to intervene in another country's domestic climate policy: a) agreements with extraction, b) agreements with transfers, and c) agreements with sanctions. We distill the fundamental properties of different climate-policy options into a simple parameterization and examine the incentives and preferences for each type of foreign intervention. We find that the preference for the type of intervention depends critically on the policy externality of different domestic climate policies.

Contents

Free-riding occurs when a party receives the benefits of a public good without contributing to the costs. In the case of the international climate-change policy, countries have an incentive to rely on the emissions reductions of others without taking proportionate domestic abatement.

Nordhaus (2015)

[Free driving] A second less-familiar externality shows up in the scary form of geo-engineering the stratosphere …The challenge with this second global externality also appears to be enormous, because here too so much is at stake, and because it also seems difficult to reach an international governing agreement.

Weitzman (2015)

1. Introduction

In a warming world, the fates of all countries are intertwined. Given the globalized nature of the economic system and Earth's climate system, global cooperation is needed to reduce the impacts of climate change. Cooperation on reducing greenhouse gas emissions has been insufficient. Emissions reductions are a global public good, which results in the suboptimal allocation of effort to limit the harmful impacts of climate change. This lackluster progress on emissions reductions, including negative emissions, has opened the door to other forms of climate-policy options that deal with impacts rather than the root cause of the problem: adaptation and solar geoengineering (SG). Against this background of multiple possible climate strategies, there is an international political economy literature that treats mitigation, adaptation, and SG as intrinsically different.[1] Countries also have multiple options to influence the climate-policy decisions of other countries, such as a) voluntary international environmental agreements, b) agreements with transfers, and c) agreements with sanctions. While there could be good reasons to maintain these strategies as separate (Jinnah et al. 2021), we hypothesize that by embedding mitigation, adaptation, and SG into a more extensive set of international governance mechanisms, we can learn new insights that could help break the deadlock in international climate negotiations.[2]

[1] Some recent entries have considered an optimal portfolio approach to climate policy (Aldy and Zeckhauser, 2020; Moreno-Cruz et al., 2018; Ricke and Moreno-Cruz 2020; Belaia et al., 2021; Harding et al., 2022), but the international political economics literature continues to place the different approaches to managing climate change into silos.

[2] The Climate Overshoot Commission was recently convened to look at the governance of accelerated adaptation, CO_2 removal, and solar geoengineering (SG). Our paper speaks directly to that effort.

Our research question is under which political, economic, and technological circumstances countries decide to intervene and what form of foreign intervention they choose. To answer this question, we propose a unifying framework that considers diverse forms of domestic climate policy and multiple international governance mechanisms.

We consider an environment where a powerful country, the Hegemon, can threaten a weak country, the Target, to induce the behavior desired by the Hegemon. Intervention can be costly, and the Hegemon can alter the Target's decision to the extent that is possible short of direct military intervention.[3] We develop a game-theoretical framework to capture this strategic environment. The game has two stages. In the first stage, the Target chooses the domestic climate policy, considering the possibility of foreign intervention. In the second stage, the Hegemon decides whether to intervene and the type of intervention. The solution concept is that of subgame-perfect equilibrium.

We show that the Hegemon's selected form of foreign intervention chosen by the Hegemon depends mainly on the **magnitude** and **nature** of the policy externality that the Target imposes on the Hegemon; that magnitude depends on **exposure** and **preference asymmetry**. Exposure is the degree of influence of any domestic policy on foreign nations. Preference asymmetry is the difference in the preferred policy outcome between countries. The nature of the externality can take the form of underprovision due to **free riding** or overprovision due to **free driving**. When countries have equal power, the possibility of reaching an agreement is limited and occurs when either country wants to curtail the other's excessive use of a given climate management portfolio. When we introduce power, we find that the Hegemon can increase participation by imposing an agreement that is in principle costly, but it can extract all the gains from the move to the optimal allocation. When there are no rents to extract, the Hegemon pursues either transfers or sanctions.

Our paper contributes to the literature on international environmental agreements that started with the work of Scott Barrett (1993, 2003). Since then, several other publications expanded on this seminal contribution. Some authors have introduced heterogeneity (e.g., McGinty 2007), uncertainty (e.g., Finus and Pintassilgo 2013), and other complications into the analysis of climate-change coalitions. Overall, the lesson learned from this literature is that stable self-enforced coalitions are not large enough (see Finus and McGinty [2019] for an exception). For this reason, alternatives to self-enforced climate agreements have been introduced in academic and policy circles, including transfers (Carraro et al. 2006; Bosetti et al. 2013) and trade sanctions (Barrett 1997; Nordhaus 2015). We consider all of these forms of agreement simultaneously in our unifying framework.

[3] We limit our foreign intervention options to diplomatic channels. The possibility of direct conflict is not often discussed in the international political economy of climate change, but it is in the context of SG (Schelling, 1996). We leave this tantalizing possibility for future research.

Adaptation was mostly left to the fringes of climate-change research for almost a decade, with some notable exceptions (e.g., Mendelsohn 2000). As a result, entries in the literature that consider it as part of an international environmental agreement are limited (Lazkano et al. 2016; Li and Rus 2019). Our paper expands this literature by presenting adaptation as another form of climate management that is subject to international governance or that affects the governance of other climate-policy options by altering the exposure to foreign policy or countries' preference asymmetries.

Adaptation measures are often constrained to national or regional plans, so they are assumed to be mostly private goods and less likely to suffer from underprovision. Insufficient international finance and aid, however, jeopardizes the deployment of successful adaptation strategies. Adaptation measures are also likely to become transboundary issues as vulnerable populations look for ways to preserve their livelihoods (Black et al. 2011; see also Waldinger 2022 for a historical perspective). Another clear example of this possibility is China damming the Mekong River, altering the flow to Myanmar, Laos, Thailand, Cambodia, and Vietnam (Eyler 2020). Thus, through financing, migration and large infrastructure projects, adaptation becomes subject to international governance (Khan and Munira 2021) and should be considered with other, more global, forms of climate management.

More recently, SG has entered the conversation to address the urgency of delayed action on climate change and limit the impacts of unmitigated emissions (Aldy et al. 2021; Field et al. 2021). SG brings with it novel risks and governance challenges. The recent interest in the international political economy of SG started with Barret (2008) and has since explored other issues (Heyen et al. 2019; Moreno-Cruz 2015; Ricke et al. 2013; Rickels et al. 2020; Sayegh et al. 2021; Millar-Ball 2012; Urpelainen 2012; Heyen and Lehtomaa 2021), with a focus on voluntary international environmental agreements. Of particular interest for us is the free-driving externality that results from the low-cost, high-leverage nature of SG techniques; tackling that is, from an international governance perspective, the most complex issue (Parson and Reynolds 2012; Reynolds 2021). We show it is not uniquely related to SG and that the policy repertoire already has options to govern the free rider.

This paper also contributes to the international political economy literature (Aidt et al. 2021). Much of the international political economy literature on climate change compartmentalizes the study of different interventions and focuses on each possibility in isolation. In the framework we propose here, we consider multiple channels of foreign intervention, thus placing the likelihood of voluntary cooperation and economic transfers or sanctions in the same context. We demonstrate that the type of foreign intervention is a strategic choice and a function of the technical and political characteristics of the source of the negative externalities (Eguia 2021).

The rest of the paper proceeds as follows. In Section 2, we discuss how different climate management strategies, although diverse in terms of costs, benefits, and technological pathways, can be represented in international governance as simply as the degree of asymmetry between countries' preferred outcomes and the degree of exposure of one country to the other's climate strategy. In Section 3, we introduce the model, define policy externality, and highlight the assumptions governing our modeling approach. In Section 4, we analyze the equilibria that exist when power is balanced between countries. In Section 5, we introduce the foreign intervention options available when a country holds substantial power over others. We characterize the space where different interventions are preferred depending on the characteristics of the climate policy externality.

2. Technological Landscape

Policymakers and the academic community often consider mitigation, adaptation, and SG as intrinsically different and subject to independent international governance mechanisms and regulations. For mitigation, the goal is to increase provision; the goal for solar geoengineering is to limit provision; and the goal for adaptation is to fill the provision gap in the other two. Yet, these are not neatly disjoint sets in international governance.

For example, consider emissions reduction strategies. Think of these as low-emissions technologies. They are becoming increasingly cheaper yet require a system-level transition that makes them overall costly, although moderate private benefits do arise, such as the co-benefits from improved air quality (Gallagher and Holloway 2020). However, policy externalities are limited because the global effects of domestic emissions reductions are small and only a concerted effort influences the climate. Direct Air Capture (DAC) is a form of negative emissions that satisfies the same role as emissions reductions, at least until zero emissions are achieved. DAC is high cost but can substantially reduce the burden of emissions reductions across countries. One single country, with enough effort, can reduce the negative effects of the most marginalized countries. This implies DAC has high policy externalities. Domestic climate policies can affect other policies. For example, consider the case of rare materials and the need for battery storage. If a country deems its materials an object of national security, it could implement a policy that bans their export, thus increasing the costs of acquiring them for the rest of the world. There are no direct externalities for such a policy, but it will still affect the costs of foreign climate policy, including energy systems transitions to near-zero emissions technologies.

Climate policies traditionally understood as adaptation are also quite diverse in terms of underlying characteristics, at least in dimensions relevant for foreign intervention in domestic climate policy. For example, if countries defend their coasts by building sea walls or dikes, the policy externalities are very low. The costs are high, as are the private benefits. Another form of adaptation is to switch to more heat-resistant or less water-intensive crops. These changes are highly decentralized, although they can be coordinated via national policies. In either case, this change in crop composition could affect the balance of trade in global markets. This represents moderate policy impacts in other countries. A third option could be damming a river to increase irrigation or for hydroelectric power. The cost could be high, and the private benefits are high. In principle, this policy would not have foreign implications, except for a transboundary river, such as the Mekong (where upstream decisions impose direct externalities on downstream countries).

This leads us to the final category: SG. Two characteristics make solar geoengineering a different object of global governance relative to mitigation and adaptation. First, its effects and impacts are not uniformly distributed worldwide. Countries have different preferences regarding their climate and SG. Second, implementation can be unilateral and done without the need for global consensus. Low costs of global deployment make it high leverage. The literature discusses many forms of SG. The two most prominent are marine cloud brightening and stratospheric aerosol injection. Marine cloud brightening consists of spraying microscopic droplets of sea salt in the lower atmosphere, seeding clouds that, are on balance more reflective of solar radiation than they are absorptive of heat radiating energy (Field et al. 2020). These techniques have predominantly local effects and could be designed to affect regional climates, but they can also affect the climate in other regions, such as through teleconnections (Ricke et al. 2021), or even the whole planet. Stratospheric aerosol injection is a high-leverage, low-cost technique that has limited or no isolated local effects but can alter the climate at a global scale at a very low–cost absorptive.

While our assessment is somewhat subjective, there is enough variation across possible interventions to merit a more general, unified approach to the question of international governance that is not restricted to narrow technical classifications and highlights the needs of a framework to think about these interventions in a more comprehensive setting.

3. Model

We consider a two-country world with a Hegemon (H) and a Target (R). Each country has a domestic climate policy lever with no positivity constraints, g_i for $i \in \{H, R\}$, that it uses to minimize the damages from climate change. We think of domestic climate policy as policy portfolios implemented by a country. We are interested in these policies' combined effect on the climate. Countries can have policy portfolios with negative effects on the climate, such as by subsidizing fossil fuel production more than near-zero emissions technology. In the context of SG, we can think of negative policies as countergeoengineering.[4]

[4] Imagine a set of policy options indexed by $k = 1, \dots, K$. The net effect of policies on the climate is given by $g_i = g(g_{i1}, \dots, g_{ik}, \dots, g_{iK})$. The cost of a given portfolio is $c_i(g_i) = c(g_{i1}, \dots, g_{ik}, \dots, g_{iK})$. We assume each country implements a portfolio that minimizes the cost of the policy portfolio for any given g_i chosen in the international stage.

Countries minimize total costs of climate change, $TC_i(g_i, g_j)$, taken as the sum of the damages from climate change, $D_i(g_i, \gamma_{ji} g_j; \Delta_i)$, and the private costs of implementing climate policy, $c_i(g_i)$. That is,

$$TC_i(g_i, g_j) = D_i(g_i, \gamma_{ji} g_j; \Delta_i) + c_i(g_i) \qquad \text{Eq. 1}$$

Each country has a preferred amount of policy intervention that reduces its damages to zero, captured by $\Delta_i > 0$.[5] Damages from climate change in each country increase in deviations from its preferred climate. Policy g_i can reduce climate damages in country i by shifting either the realized climate closer to its preferred state (mitigation and SG) or the preferred climate closer to the realized climate (adaptation). Importantly, the policy of country j can also have a direct effect on country i's damages. We measure the strength of the exposure of country j to country i's policy by $\gamma_{ji} \in \mathbb{R}^+$.

We assume simple quadratic forms for each component of the total costs:

$$D_i(g_i, \gamma_{ji} g_j; T_i) = \frac{1}{2}\delta\left(\Delta_i - g_i - \gamma_{ji} g_j\right)^2 \qquad \text{Eq. 2}$$

$$c_i(g_i) = \frac{1}{2}\tau {g_i}^2 \qquad \text{Eq. 3}$$

Definition 1. We define $\Delta = \Delta_{\mathrm{R}} - \Delta_H$ as the **preference asymmetry** between countries and $\gamma = \gamma_{HR} - \gamma_{RH}$ and the *exposure divergence* between countries.

Definition 2. We define **Policy Externality** as a function $F_i(\gamma, \Delta)$ for $i \in \{H, R\}$ that jointly captures differences in exposure and differences in preferred climate policies.

While there are many technology parameters that affect the outcomes, such as private implementation costs and benefits, we assume that the only differences between countries' climate policies are due to strength of the **policy externality**.

Assumption 1a. Global average temperature is too high for the two countries, $\Delta > -\Delta_H$.

Assumption 1b. The own effect of a policy is always larger than the indirect effect from the other country's policy, $\gamma_{HR}\gamma_{RH} < \left(\frac{\delta}{\delta+\tau}\right)^2$.

Assumption 1a ensures that countries have an incentive to implement some amount of combined policy that reduces the temperature. That is, this setting has no winners from climate change. Assumption 1b ensures the Subgame Perfect Nash Equilibrium (SPNE) equilibrium is stable.

[5] That is, when the combined policy implemented by two countries, $g_i + \gamma_{ji} g_j = \Delta_i$, damages for country i are zero.

4. No-Intervention Benchmarks

To begin, we assume that countries are symmetric, $\Delta = 0$ and $\gamma = 0$. This does not imply that the policy externality is zero, just that it is equal across countries: $F(\gamma = 0, \Delta = 0) \geq 0$. Later, we show how the Hegemon's policy changes as preferences and exposure diverge, when $\Delta \neq 0$ and $\gamma \neq 0$.

We begin by analyzing the solution for an uncoordinated equilibrium, U , with no foreign intervention. The Hegemon, in its position of power, moves in anticipation of the response it will elicit from the Target. The solution concept is that of SPNE. Define the SPNE policy as g_i^U for $i \in \{H, R\}$ and the corresponding total costs associated with these policies as $TC_i\left(g_i^U, g_j^U\right) \equiv TC_i^U$ for $i \in \{H, R\}$.

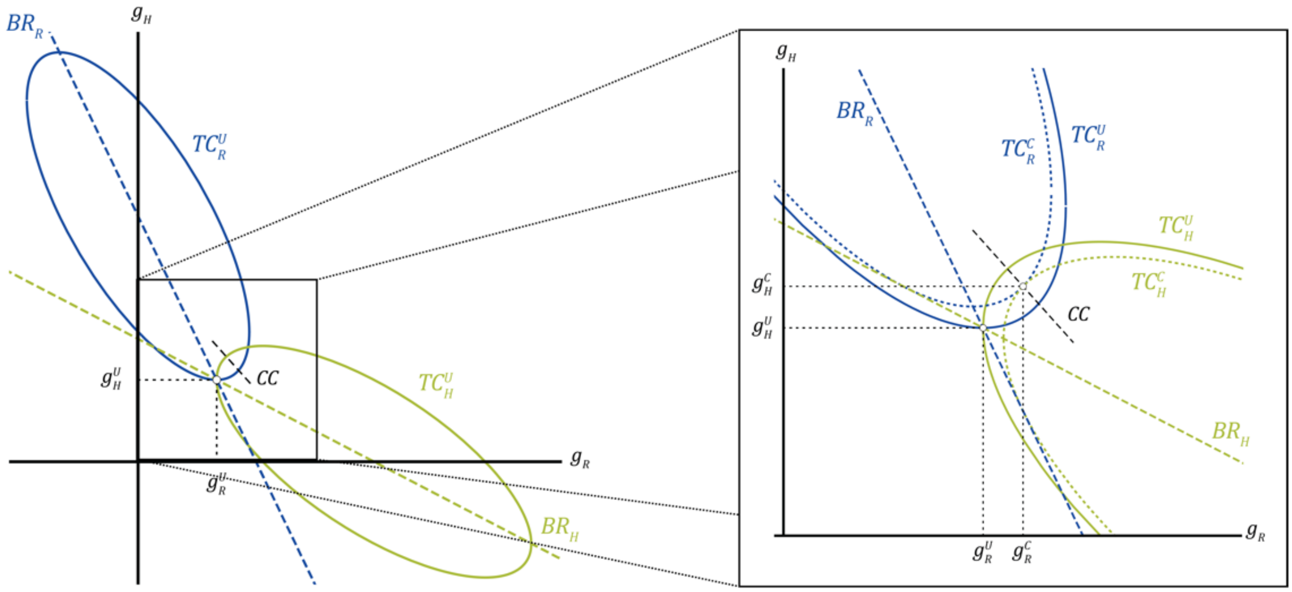
Figure 1 displays the strategic decision space for the game. We represent the countries' equilibrium policy decisions in terms of their best responses.[6] The Target's policy, g_R, is on the horizontal axis, and the Hegemon's policy, g_H, is on the vertical axis. These policy portfolios can have a net positive or negative effect on the climate depending on a country's energy and climate policies.

The best response function of the Hegemon is given by $g_H = BR_H(g_R)$ and the Target's best response is given by $g_R = BR_R(g_H)$. The SPNE lies at the intersection of both functions, (g_R^U, g_H^U). The resulting total costs of climate and policy faced by the Hegemon are given by $TC_H(g_H^U, g_R^U\ ) \equiv TC_H^U$. The total costs of the Target are $TC_R(g_R^U, g_H^U\ ) \equiv TC_R^U$. Iso-cost curves are depicted as ellipses, which follows directly from our choice of quadratic functional forms. These ellipses are centered where the $g_j = BR_j(g_i) = 0$, so that $TC_j^U = 0$. Higher total costs are captured by expanding concentric ellipses.

---

[6] Our presentation of the results was inspired by two classic papers by Brander and Spencer (1985, 1987) on the role of R&D in industrial competition. We also borrowed from Aidt et al. (2021) to depict our solutions in the policy space. While our context and analysis are substantially different, we are intellectually indebted to them as we worked on developing the intuition for our own work.

Figure 1. SPNE for Symmetric Countries



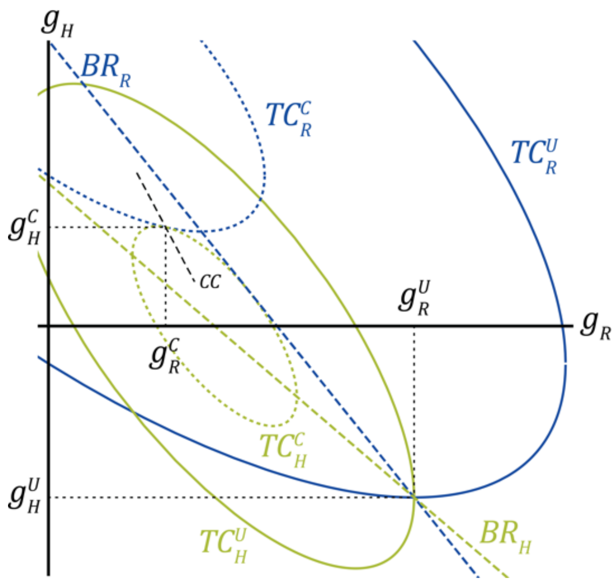
Continuing with the symmetric case, we analyze a coordinated equilibrium without intervention, C. Countries minimize the joint total cost, leading to the optimal equilibrium allocation. The resulting policies are denoted as $\{g_R^C,\ g_H^C\}$. The resulting total costs are given by $TC_H(g_H^C, g_R^C) \equiv TC_H^C$ and $TC_R(g_R^C, g_H^C) \equiv TC_R^C$. These costs are represented by smaller concentric ellipses relative to the SPNE costs in the expanded panel on the right side of Figure 1.

4.1. Free Driving vs. Free Riding

In the symmetric case, the coordinated equilibrium is interior to the uncoordinated equilibrium iso-cost curves for the Hegemon, $TC_H^U > TC_H^C$, and the Target, $TC_R^U > TC_R^C$. That is, the coordinated equilibrium lies inside the Pareto set and is therefore a Pareto improvement. When both countries do more to address climate change, their total costs decrease. When decisions are uncoordinated, countries do not consider the externalities of their policy. Given the negative slope of the best response functions, the two policies are strategic substitutes. Thus, each country has an incentive to reduce its contribution to the public good, inducing a higher amount of policy on the other country. Of course, as is well known in these situations, the other country has incentive to behave the same way. This captures the **free-riding externality** that results in too little of the public good contributed in equilibrium, which is often discussed in the context of emissions reductions.

Free-riding equilibria are the only possibility when countries are symmetric. If we introduce asymmetry, the coordinated equilibrium may be outside the Pareto set. In fact, for large enough asymmetries, one country may implement too much of a given policy, forcing the other to choose countervailing actions (see Figure 2). The amount of policy implemented by the Target is too high, and the Hegemon policy is then negative. Although this idea of countervailing policies is not typically encountered in discussions of emissions cuts or adaptation, it has been raised as an issue in the context of SG,[7] where it has been described as the "free-driver externality" because, in equilibrium, a country overprovides policy to the detriment of others.

Figure 2. Example of Asymmetric Countries with Free-Driving SPNE



When an equilibrium is a free-riding equilibrium, countries are better off increasing total policy provision. When an equilibrium is a free-driving equilibrium, countries are better off reducing the net amount of their policy provision.

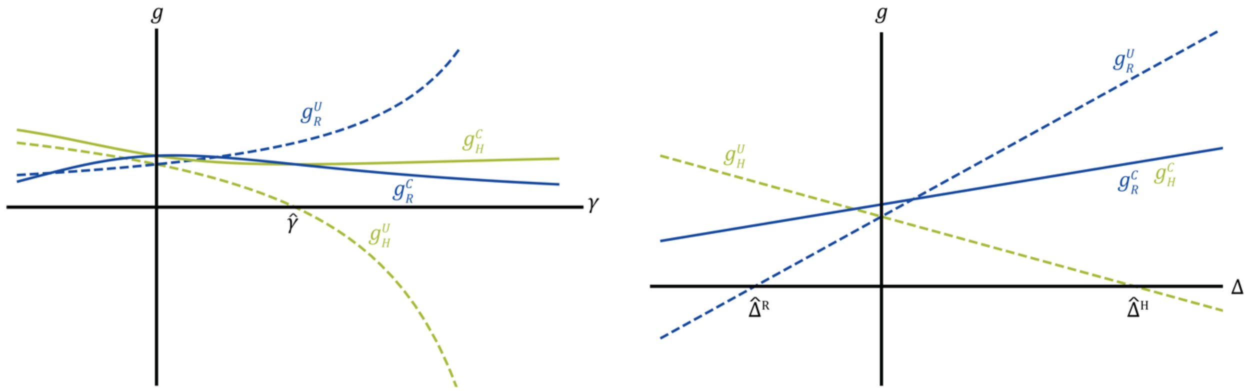
The only source of asymmetry in our context is the policy externality $F(\gamma, \Delta)$ and equilibria can be fully characterized as a function of preference divergence Δ and exposure divergence γ. Figure 3 illustrates how changes in the exposure γ or preference asymmetry Δ can affect policy outcomes in both the uncoordinated and coordinated equilibria. In Figure 3A, we fix preference asymmetry and show how the equilibrium policy choices change with the exposure of the Hegemon to the Target's policy, starting from the symmetric case, where $\gamma = 0$, as γ increases g_H decreases. The Hegemon is free riding as spillovers from the Target's policy grow. The Target's policy increases with γ to compensate for the free riding. When $\gamma > \hat{\gamma}$, the free-riding equilibrium becomes a free-driving equilibrium. The Target country implements policy in excess of the amount preferred by the Hegemon, so the Hegemon begins to implement a net negative amount of policy to compensate for the excess.

---

[7] These equilibria with countervailing policies are examples of the climate clash discussed in Heyen et al. (2019).

Figure 3. Asymmetric SPNE under Increased Policy Externalities

A. Exposure Divergence **B. Climate Preference Divergence**



In Figure 3B, we fix policy exposure asymmetry and show how equilibrium policy choices change with the Target's preferred policy. Starting from the symmetric case, as Δ increases, the Target prefers a cooler world relative to the Hegemon. The Target implements more policy, and the Hegemon free rides on the Target's efforts. Eventually, for $\Delta > \widehat{\Delta}^H$, the amount of policy implemented by the Target becomes excessive for the Hegemon, so the Hegemon implements countervailing policies to compensate. The free riding becomes free driving. This result is reversed when Δ decreases, starting from the symmetric case. As the Target prefers a warmer climate, it implements less policy, free riding on the efforts of the Hegemon. Eventually, for $\Delta < \widehat{\Delta}^R$, the Hegemon's policy becomes too much for the Target, so it implements countervailing policy. The free riding becomes free driving.

Drawing from these comparisons, whether an equilibrium is free driving or free riding depends critically on both preference asymmetry and policy exposure asymmetry. We can generalize our findings to the two-dimensional policy externality space $F(\Delta, \gamma)$.

Proposition 1. (equilibrium policy outcomes). Some $\widehat{\Delta}^R(\gamma)$ and $\widehat{\Delta}^H(\gamma)$ exist such that

> **Target free driver**: if $\Delta = \widehat{\Delta}^H(\gamma)$, then $g_H = 0$, and if $\Delta < \widehat{\Delta}^H(\gamma)$, then $g_R > 0$ and $g_H < 0$.
>
> **Hegemon free driver**: if $\Delta = \widehat{\Delta}^R(\gamma)$, then $g_R = 0$, and if $\Delta < \widehat{\Delta}^R(\gamma)$, then $g_R < 0$ and $g_H > 0$.
>
> **Free rider**: if $\widehat{\Delta^R}(\gamma) < \Delta < \widehat{\Delta^H}(\gamma)$, then $g_R > 0$ and $g_H > 0$.

Proof. See the Appendix.

Figure 4. Policy Outcomes in the Policy Externality Space

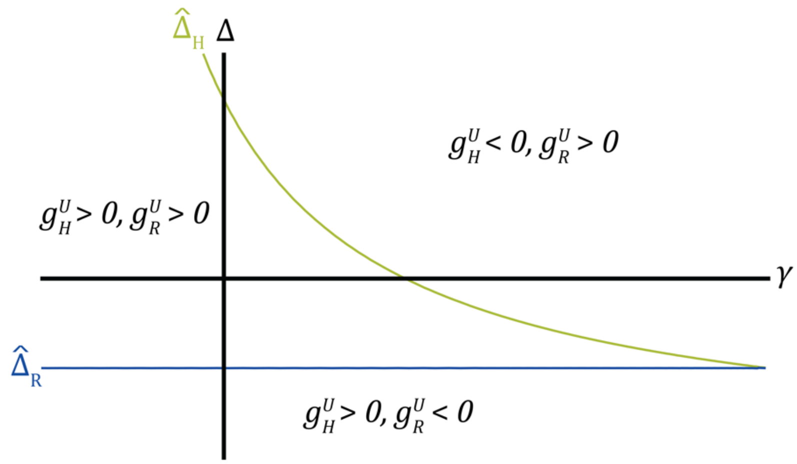


Figure 4 shows that the nature of the equilibrium is a function of the policy externality, $F(\Delta,\ \gamma)$. The horizontal axis captures asymmetry in policy exposure, γ. The vertical axis captures asymmetry in preferences, Δ. We are interested in how the Hegemon responds to changes in the nature and magnitude of the Target's policy externality. We fix the policy externality γ_{HR} so that changes in γ capture changes in γ_{RH}. We similarly fix Δ_H so that changes in Δ capture changes in Δ_R.

Using Figure 4, we can explain the intuition behind Proposition 1, starting at the origin, with the symmetric case ($\gamma = 0, \Delta = 0$). The Hegemon and Target both implement net positive policies to reduce climate damages in both countries. However, as explained above, equilibrium has too little policy contribution. Free riding continues to occur with small deviations from the symmetric case. When $\Delta = \widehat{\Delta}^R(\gamma)$, the Hegemon provides cooling exactly equal to that preferred by the Target, with no contribution or cost to the Target. $\widehat{\Delta}^R$ is independent of the exposure of the Hegemon to the Target and thus is a horizontal line. Similarly, when $\Delta = \widehat{\Delta}^H(\gamma)$, the Target provides cooling exactly equal to that preferred by the Hegemon, with no contribution or cost to the Hegemon. $\widehat{\Delta}^H(\gamma)$ is decreasing in exposure of the Hegemon to the Target because as exposure increases, a given amount of cooling by the Target has a larger effect on the Hegemon. We label the region between these two curves, $\widehat{\Delta}^R(\gamma) < \Delta < \widehat{\Delta}^H(\gamma)$, the free-rider space because at least one of the countries is underproviding to limit climate change in equilibrium.

If Δ decreases below $\widehat{\Delta}^R$, the Hegemon's policy becomes too much for the Target, and the Target begins to engage in countervailing policy. Thus, we label the region such that $\Delta < \widehat{\Delta}^R(\gamma)$ the Hegemon the free-driver space. Alternatively, as Δ increases above $\widehat{\Delta}^H(\gamma)$, policy provision by the Target becomes too much for the Hegemon and the Hegemon begins to engage in countervailing policy. Thus, we label the region $\Delta > \widehat{\Delta}^H(\gamma)$ the Target free-driver space.

4.2. Preferences between Coordinated vs. Uncoordinated Equilibria

Countries enter an agreement that implements the coordinated equilibrium with the expectation of improving on their uncoordinated equilibrium. These agreements are commonly known in the climate-change literature as a "Self-Enforcing International Environmental Agreement," introduced in Barrett (1994). An agreement is stable if it is incentive compatible for both players, for which self-enforcing agreements get their name. We define incentive compatibility as lower total cost in the coordinated relative to the uncoordinated equilibrium,

$$TC_i^C \leq TC_i^U \text{ for } i \in \{R, H\}.$$

As with most international environmental agreement models, we assume equal power between countries. In the next section, we relax this assumption to explore the role of power imbalances.

In the symmetric case, both countries prefer the coordinated equilibrium, so an agreement is incentive compatible and stable. But whether an agreement is stable depends on the policy externality, $F(\Delta, \gamma)$.

Proposition 2. (coordinated (C) versus uncoordinated (U) equilibrium outcomes). Some $\overline{\Delta}_H^{CU}(\gamma)$, $\underline{\Delta}_H^{CU}(\gamma)$, $\overline{\Delta}_R^{CU}(\gamma)$, $\underline{\Delta}_R^{CU}(\gamma)$, and $\overline{\overline{\Delta}}_H^{CU}(\gamma)$ exist such that

- If $\underline{\Delta}_H^{CU}(\gamma) < \Delta < \overline{\Delta}_H^{CU}(\gamma)$, then $U \succ C$
- If $\Delta < \overline{\overline{\Delta}}_H^{CU}(\gamma)$, then $U \succ C$
- If $\underline{\Delta}_R^{CU}(\gamma) < \Delta < \overline{\Delta}_R^{CU}(\gamma)$, then $C \succ U$, but C is not a stable equilibrium
- Else, $C \succ U$.

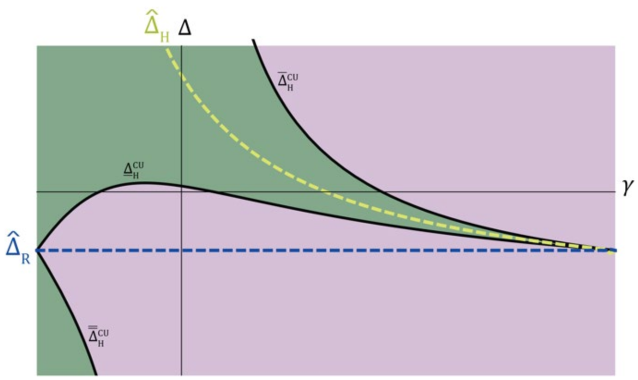
Proof. See the Appendix.

Figure 5 illuminates the intuition behind Proposition 2 through a decomposition of each countries' incentive to cooperate. Figure 5A shows the incentives of the Hegemon. Consider the space above the curve $\widehat{\Delta}_H$, which demarks $g_H^U = 0$. From Proposition 1, this is the Target free-driver space. Along the curve $\widehat{\Delta}_H$ the Hegemon's total costs are zero in the uncoordinated equilibrium. The Target provides the Hegemon with its preferred climate at no cost to the Hegemon. Thus, it prefers this to the coordinated equilibrium, where it must provide policy to share costs with the Target. Increasing Δ from this curve into the Target free-driver space, clashing with the Target eventually becomes too costly and the Hegemon prefers to cooperate. For $\Delta > \overline{\Delta}_{\mathrm{H}}^{\mathrm{CU}}(\gamma)$, the Hegemon is willing to concede a small positive policy provision in exchange for reining in the Target.

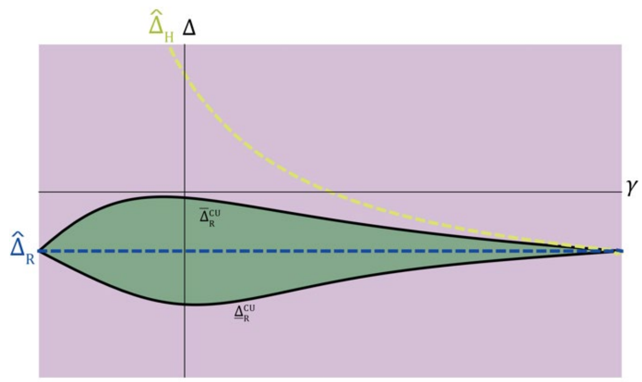
Figure 5 illuminates the intuition behind Proposition 2 through a decomposition of each countries' incentive to cooperate. Figure 5A shows the incentives of the Hegemon. Consider the space above the curve $\widehat{\Delta}_H$, which demarks $g_H^U = 0$. From Proposition 1, this is the Target free-driver space. Along the curve $\widehat{\Delta}_H$ the Hegemon's total costs are zero in the uncoordinated equilibrium. The Target provides the Hegemon with its preferred climate at no cost to the Hegemon. Thus, it prefers this to the coordinated equilibrium, where it must provide policy to share costs with the Target. Increasing Δ from this curve into the Target free-driver space, clashing with the Target eventually becomes too costly and the Hegemon prefers to cooperate. For $\Delta > \overline{\Delta}_{\mathrm{H}}^{\mathrm{CU}}(\gamma)$, the Hegemon is willing to concede a small positive policy provision in exchange for reining in the Target.

Figure 5. Coordinated vs. Uncoordinated Preference in the Policy Externality Space

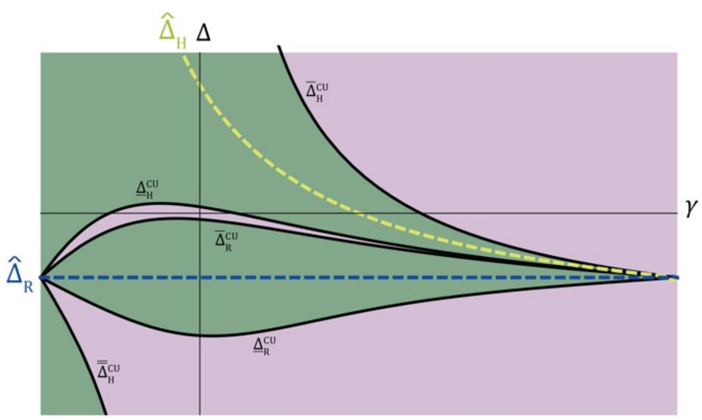
A. Hegemon preference



B. Target preference



C. Stable coordinated vs. uncoordinated equilibria



Next, consider when Δ decreases from the curve $\widehat{\Delta}_H$. Policy provision by the Hegemon increases. Eventually, when $\Delta < \underline{\Delta}_H^{CU}(\gamma)$, the Hegemon prefers cooperation, to encourage the Target to contribute more to the joint policy effort. The exception is when the Hegemon's exposure to the Target is low ($\Delta < \overline{\overline{\Delta}}_H^{CU}$), so it has no desire to cooperate and increase its policy provision when it receives little benefit for its cooperation efforts. The Hegemon prefers cooperation for $\overline{\overline{\Delta}}_H^{CU} < \Delta < \underline{\Delta}_H^{CU}(\gamma)$, but this is not always the case for the Target, and for an agreement to be stable, both countries must have incentive to cooperate.

Now consider the incentives of the Target, Figure 5B. Along the curve $\widehat{\Delta}_F$, where $g_R^U = 0$, the Target's total costs are minimized in the uncoordinated equilibrium. The Hegemon provides the Target with its preferred climate at no cost to the Target. For deviations of Δ from this curve, either positively or negatively, costs for the Target increase. As Δ increases, the Target prefers a cooler climate and increases policy provision. Once $\Delta > \overline{\Delta}_R^{CU}(\gamma)$ the preferred cooling is sufficient that the Target is willing to engage in the coordinated equilibrium to encourage more policy provision by the Hegemon. Alternatively, as Δ decreases, the Target engages in countervailing policy. Once $\Delta < \underline{\Delta}_R^{CU}(\gamma)$ the Target's costs of countervailing policy become sufficient that it prefers the coordinated equilibrium to discourage policy provision by the Hegemon. Between these curves, $\underline{\Delta}_R^{CU}(\gamma) < \Delta < \overline{\Delta}_R^{CU}(\gamma)$, the Target does not have incentive to cooperate, even though the Hegemon does. In this range, the Target requires additional incentive from the Hegemon, opening the door for foreign intervention.

5. Strategic Intervention Strategies

In this section, we introduce power asymmetries by allowing the Hegemon to intervene in the domestic policy set by the Target. When there are power asymmetries, the options of the Hegemon go beyond the uncoordinated and coordinated equilibria.

Most previous work on international environmental agreements assumes countries have equal power, and an agreement is successful only if all countries prefer to participate. The negotiation takes the form, either implicitly or explicitly, of a Nash bargain where final allocation depends on the outside option. Here, we make power asymmetry explicit. The Hegemon can induce more activity if the Target is free riding in the uncoordinated equilibrium or restrain the Target's activity if it is free driving.

We consider three options for possible interventions available to the Hegemon to impose its will on the Target. First, the Hegemon uses its power to propose a take-it-or-leave-it offer and extracts all the gains from entering the agreement. We refer to this sort of intervention as **agreement with extraction**. Second, given no rents to extract from the Target, the Hegemon needs to shift its strategy to convincing the Target to participate. Hence, the Hegemon promises a reward in exchange for an action taken by the Target. We refer to this type of intervention as **agreements with**

transfers, such as the Climate Investment Fund. Third, the Hegemon imposes a penalty on the Target if its actions do not align with the Hegemon's interest. These penalties can take many forms, but trade tariffs or financial constraints are the most discussed so far in the literature, such as those envisioned in climate clubs (Nordhaus 2015) We refer to this type of intervention as **agreements with sanctions**. We use our framework to analyze these three types of policy intervention in turn and show how the Hegemon's choice depends on the nature and magnitude of the policy externality.

5.1. Agreement Interventions with Extraction

The Hegemon proposes a take-it-or-leave-it set of policy outcomes that minimizes its costs net of the gains from the agreement that it extracts from the Target. The Hegemon's objective function with extraction is defined as

$$TC_H\big(g_R, g_H(g_R)\big) - M\big(g_R, g_H(g_R)\big)$$

where $M\big(g_R, g_H(g_R)\big)$ are the rents extracted from the Target by the Hegemon. To maintain stability of the equilibrium, the Hegemon can only extract as much value as to leave the Target indifferent between the proposed agreement and the uncoordinated equilibrium:

$$TC_R\big(g_R, g_H(g_R)\big) + M\big(g_R, g_H(g_R)\big) \leq TC_R^U.$$

We assume the Target takes the offer when it is indifferent. If the gains of an agreement are positive, the Hegemon extracts value $M > 0$. Otherwise, it cannot extract value from the Target and maintain a stable outcome, so $M = 0$. Thus, the gains extracted can be expressed as

$$M\big(g_R, g_H(g_R)\big) = \min\{0, TC_R(g_R, g_H) - TC_R^U\}.$$

The Hegemon's objective when considering an agreement with extraction is given by

$$\{g_H^E, g_R^E\} = \arg\min\{TC_H(g_R, g_H) + TC_R(g_R, g_H) - TC_R(g_R^U, g_H^U)\} \qquad \text{Eq. 5}$$

It follows from Equation 5 that the Hegemon ends up proposing a solution that implements the same globally optimal allocation of the coordinated equilibrium, but it appropriates all the gains from moving toward the coordinated outcome. By extracting the gains under coordinate policy outcomes, the Hegemon always weakly prefers an agreement with extraction to the coordinated equilibrium. When extraction is positive, this is a strong preference.

As an initial benchmark, we can compare the Hegemon's preference for an agreement with extraction to the uncoordinated equilibrium.

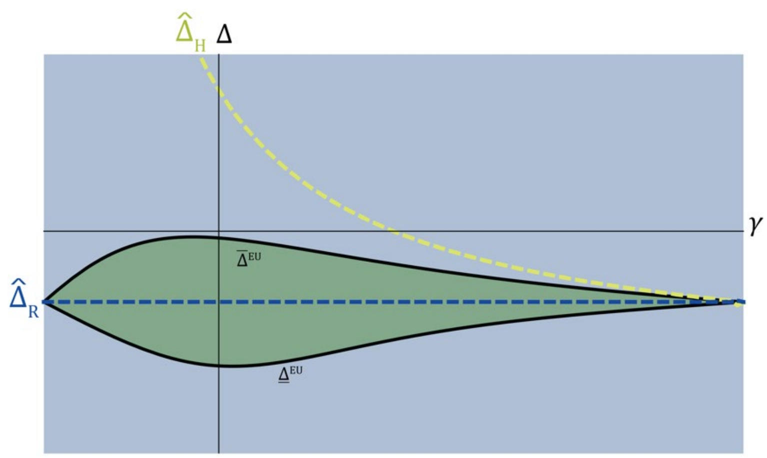
Proposition 3. (agreement with extractions (E) versus uncoordinated (U) equilibrium outcomes). Some $\overline{\Delta}^{EU}(\gamma)$ and $\underline{\Delta}^{EU}(\gamma)$ exist such that

- If $\underline{\Delta}^{EU}(\gamma) < \Delta < \overline{\Delta}^{EU}(\gamma)$, then $U \succ E$
- Else, $E \succ U$.

Proof. See the Appendix.

Figure 6 illustrates Proposition 3 in the policy exposure space. First, consider the region between $\underline{\Delta}^{EU}(\gamma)$ and $\overline{\Delta}^{EU}(\gamma)$. It is identical to the space between $\underline{\Delta}^{CU}(\gamma)$ and $\overline{\Delta}^{CU}(\gamma)$ in Figure 5. In this range, the Target does not have incentive to participate in the coordinated equilibrium. It would rather free ride on the Hegemon's efforts or engage in a small amount of countervailing policy. This is still true here. With extraction, the Hegemon can take more from the Target, but it cannot provide additional incentive to the Target to participate.

Figure 6. Agreement with Extraction vs. Uncoordinated Equilibria Outcomes



Outside of this range, the Hegemon chooses the value extracted to leave the Target indifferent between an agreement with extraction and the uncoordinated equilibrium. When the Hegemon preferred the coordinated equilibrium, it similarly prefers the agreement with extraction to the uncoordinated equilibrium, as extraction can only improve its outcome. In addition, in the range that the Hegemon previously did not prefer the coordinated equilibrium, the gains from extraction are sufficient to make the agreement with extraction preferable to the uncoordinated equilibrium. Thus, an agreement with extraction is the Hegemon's preferred intervention when possible.

5.2. Policy Interventions with Transfers

In an agreement with transfers, the Hegemon can offer a reward, W, in exchange for a policy that aligns more with the Hegemon's interests. The simplest way to think about this is the Hegemon transferring cash to the Target in exchange for cooperation in an agreement. Of course, this takes many other forms: global investment funds, technological transfers, and investment deals, such as the Clean Development Mechanism. The Hegemon will only offer a reward when it prefers cooperation in an agreement and the Target is unwilling to participate without additional incentives. The objective function of the Target includes a transfer of the following form:

$$TC_R(g_R, g_H(g_R)) - W\big(g_R, g_H(g_R)\big) \qquad \text{Eq. 6}$$

where $W(g_R, g_H(g_R))$ is the reward the Hegemon offers as a function of the policy choice of the Target and $g_H(g_R)$ is the Hegemon's best response to that choice. The transfer associated with the reward needs to be incentive compatible, so that the Target is not worse off with the transfer relative to the uncoordinated outcome. This implies

$$TC_R(g_R, g_H(g_R)) - W\big(g_R, g_H(g_R)\big) \leq TC_R^U$$

If it is a positive amount, the Hegemon transfers the exact amount that makes this equation binding. This leaves the Target indifferent between accepting and rejecting the transfer. We assume it accepts in the case of indifference. The transfer is then given by

$$W\big(g_R, g_H(g_R)\big) = \max\{0, TC_R(g_R, g_H(g_R)) - TC_R^U\} \qquad \text{Eq. 7}$$

The problem of the Hegemon is now equivalent to minimizing the joint total cost so that

$$\{g_H^T, g_R^T\} = \arg\min\{TC_H(g_H, g_R) + TC_R(g_R, g_H\ ) - TC_R(g_R^U, g_H^U)\} \qquad \text{Eq. 8}$$

This is the same objective function as in the agreement with extraction. The difference is who captures the rents from the coordinated allocation: the Hegemon in extractions and the Target in transfers. Since the Hegemon has power, they it sets rewards just to make the Target indifferent between joining the agreement and the uncoordinated equilibrium. In the absence of power, Nash bargaining would set the value of rewards.'

Figure 7. Policy—Outcomes—Transfers

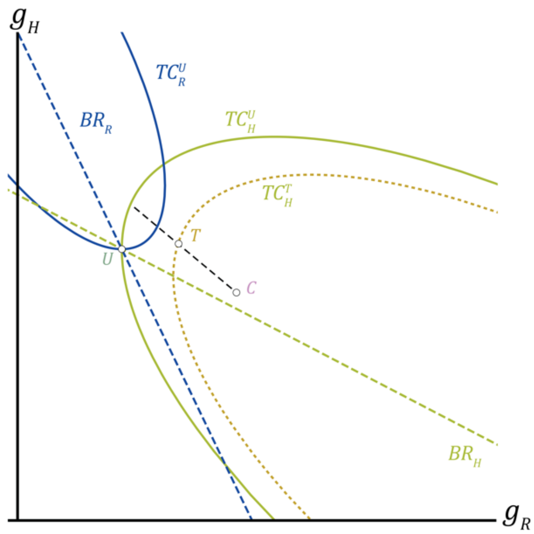
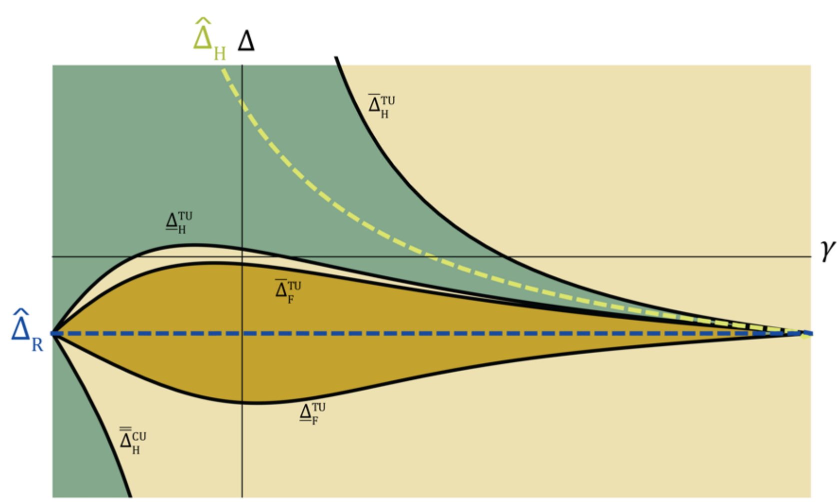


Figure 7 illustrates an example of an agreement with positive transfers. The Hegemon prefers the coordinated equilibrium, C, to the uncoordinated equilibrium, U, but the Target does not. The Hegemon can move closer to their its provision under the global optimum, along the contract curve, with the transfer of a reward, shown as the equilibrium T.

We now return to our question of the Hegemon's foreign intervention preference by comparing its preference for an agreement, now with transfers, to the uncoordinated equilibrium and analyzing how this depends on preference asymmetry and policy exposure.

Figure 8. Agreement with Transfers vs. Uncoordinated Equilibria Outcomes



Proposition 4. (Agreement with transfers (T) versus uncoordinated (U) equilibrium outcomes). Some $\overline{\Delta}_H^{TU}(\gamma)$, $\underline{\Delta}_H^{TU}(\gamma)$, $\overline{\Delta}_R^{TU}(\gamma)$, $\underline{\Delta}_R^{TU}(\gamma)$, and $\overline{\overline{\Delta}}_H^{TU}(\gamma)$ exist such that

- If $\underline{\Delta}_H^{TU}(\gamma) < \Delta < \overline{\Delta}_H^{TU}(\gamma)$, then $U \succ T$
- If $\Delta < \overline{\overline{\Delta}}_H^{TU}(\gamma)$, then $U \succ T$
- If $\underline{\Delta}_R^{TU}(\gamma) < \Delta < \overline{\Delta}_R^{TU}(\gamma)$, then $T \succ U$ and $W > 0$
- Else, $T \succ U$ and $W = 0$.

Proof. See the Appendix.

Figure 8 illustrates Proposition 4. To understand the intuition of the proposition, first note that when transfers are zero, the equilibrium for agreement with transfers is identical to the coordinated equilibrium. Thus, for this area of the policy exposure space, the Hegemon's preference for an agreement with transfers is identical to its preference for the coordinated equilibrium and how this compares to the uncoordinated equilibrium, as described in Proposition 2. We focus on what happens when transfers are nonzero: the Target requires additional incentive to participate in the coordinated equilibrium (Figure 5b). This is the region described by Propositions 2(iii) and 4(iii), which is shaded darker yellow in Figure 6. The original agreement is unstable, but the Hegemon offers rewards to make the Target indifferent with the coordinated option. Given the cost of these transfers, the Hegemon still prefers this intervention to the uncoordinated equilibrium.

5.3. Policy Interventions with Sanctions

The Hegemon could threaten the Target with a sanction if its policy does not align with the Hegemon's preferences. Sanctions take many forms, but as mentioned, trade tariffs are preferred in our interconnected world.[8] The Target's objective function includes a sanction:

$$C_R\big(g_R, g_H(g_R)\big) + \sigma L\big(g_R, g_H(g_R)\big) \qquad \text{Eq. 10}$$

where $L\big(g_R, g_H(g_R)\big)$ is the sanction that the Hegemon imposes as a function of the policy choice of the Target and, as before, $g_H(g_R)$ is the Hegemon's best response. We introduce the parameter $\sigma \in [0,1]$ to capture the capacity of the Hegemon to inflict damages in the Target via sanctions. For example, if the Target can divert trade flows via other trade partners, then the effects of the sanction are diluted but the costs of imposing the sanction remain the same.

[8] Perhaps the closest to an energy-related sanction has been those imposed on Iran to deter it from developing a nuclear program. Russia's threats to curtail natural gas sales to Europe is another recent example, although it is not motivated by energy or climate issues.

The sanction needs to be incentive compatible, so that the Target is at least as well off as under Nash by behaving as the Hegemon demands. This implies

$$C_R\left(g_R^S, g_H\left(g_R^S\right)\right) + \sigma L\left(g_R^S, g_H^S\right) \leq C_R\left(g_R,\ g_H(g_R)\right) + \sigma L\left(g_R,\ g_H(g_R)\right)$$

If the Hegemon's threat of a sanction is credible, the Target should respond by behaving as the Hegemon demands, and $L\left(g_R^S, g_H^S\right) = 0$. The sanction is then given by

$$L(g_R, g_H) = \max\left\{0, (1/\sigma)\left[C_R\left(g_R,\ g_H(g_R)\right) - C_R\left(g_R^U, g_H^U\right)\right]\right\} \quad \text{Eq. 11}$$

The problem of the Hegemon is now

$$\left\{g_H^S, g_R^S\right\} = \arg\min \left\{C_H(g_H, g_R) + (1/\sigma)\left[C_R(g_R,\ g_H) - C_R\left(g_R^U, g_H^U\right)\right]\right\} \quad \text{Eq. 12}$$

The Hegemon will only threaten sanctions when it prefers cooperation in an agreement and the Target is unwilling to participate without additional incentive. This is the space described in Proposition 2 and shown in Figure 5. When $\sigma = 1$, the equilibrium outcome is the same allocation as under the coordinated equilibrium. As the effectiveness of the sanctions declines, $\sigma < 1$, equilibrium policies move along the contract curve away from the Hegemon's preferred outcome. How far along the curve they shift ultimately depends on the value of σ.

Figure 9. Policy—Outcomes—Sanctions

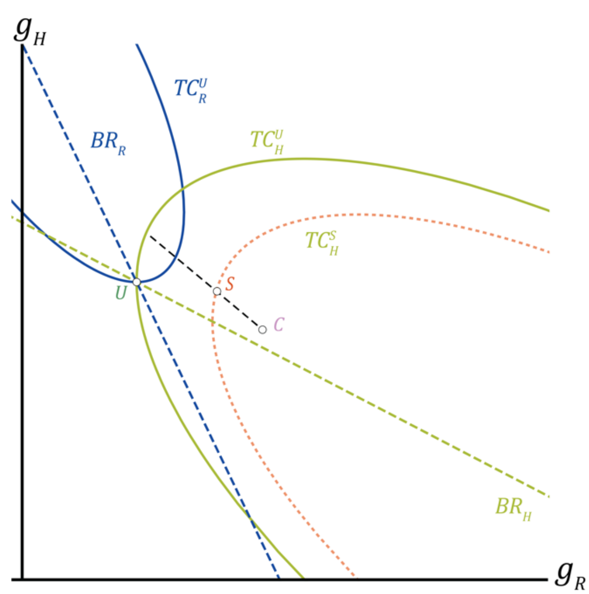


Figure 9 provides an example of an equilibrium with sanctions when the Hegemon prefers the coordinated equilibrium C but the Target needs additional incentives. With the threat of sanctions, the Hegemon can move the equilibrium S closer to the coordinated equilibrium along the contract curve. We consider costly sanctions, $\sigma < 1$, so the Hegemon cannot move S all the way to the coordinated equilibrium.

We return to our question of when the Hegemon prefers and agreement, now with sanctions, to the uncoordinated equilibrium and how this depends on preference asymmetry and policy exposure.

Proposition 5. (agreement with sanctions (S) versus uncoordinated (U) equilibrium outcomes). Some $\overline{\Delta}_H^{SU}(\gamma;\sigma)$, $\underline{\Delta}_H^{TU}(\gamma;\sigma)$, $\overline{\Delta}_R^{SU}(\gamma;\sigma)$, $\underline{\Delta}_R^{SU}(\gamma;\sigma)$, and $\overline{\overline{\Delta}}_H^{SU}(\gamma;\sigma)$ exist such that

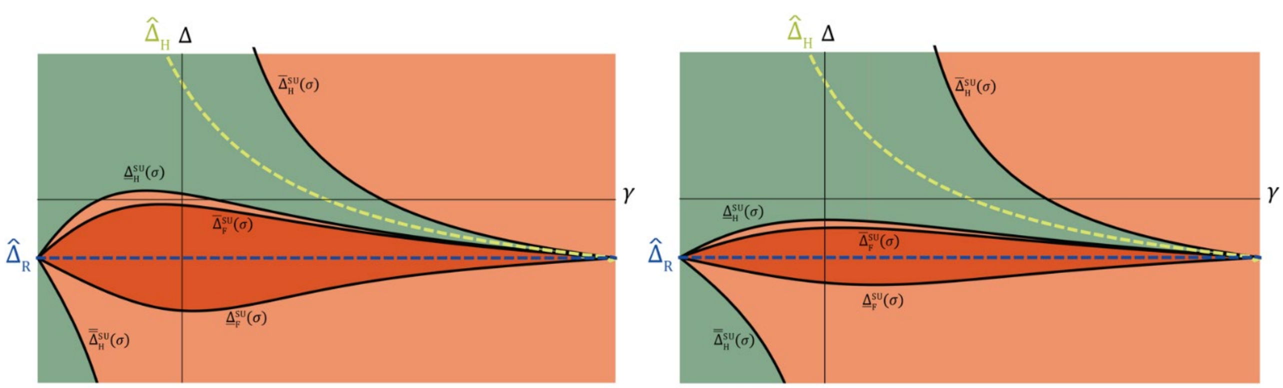
- If $\underline{\Delta}_H^{SU}(\gamma;\sigma) < \Delta < \overline{\Delta}_H^{SU}(\gamma;\sigma)$, then $U \succ S$
- If $\Delta < \overline{\overline{\Delta}}_H^{SU}(\gamma;\sigma)$, then $U \succ S$
- If $\underline{\Delta}_R^{SU}(\gamma;\sigma) < \Delta < \overline{\Delta}_R^{SU}(\gamma;\sigma)$, then $S \succ U$ and $S > 0$
- Else, $S \succ U$ and $S = 0$.

Proof. See the Appendix.

Figure 10 illustrates the results given by Proposition 5. Let's first consider costless sanctions (Panel A) and then how outcomes change when sanctions become costly (Panel B). For $\sigma = 1$, outcomes are the same as the coordinated equilibrium when the Target prefers that. Thus, $\overline{\Delta}_H^{SU}(\gamma, 1) = \overline{\Delta}_H^{CU}(\gamma)$, $\underline{\Delta}_H^{SU}(\gamma, 1) = \underline{\Delta}_H^{CU}(\gamma)$, and $\overline{\overline{\Delta}}_H^{SU}(\gamma, 1) = \overline{\overline{\Delta}}_H^{CU}(\gamma)$. But, unlike in the coordinated equilibrium, in the range $\underline{\Delta}_F^{SU}(\gamma, 1) < \Delta < \overline{\Delta}_F^{SU}(\gamma)$, the threat of sanction from the Hegemon is sufficient to incentivize the Target to provide optimal policy effort when it would not be incentive compatible in the absence of sanctions. This makes sanctions stable in this region.

Figure 10. Agreement with sanctions vs. uncoordinated equilibria outcomes

A. Costless sanctions $(\sigma = 1)$ **B. Costly sanctions** $(0 < \sigma < 1)$



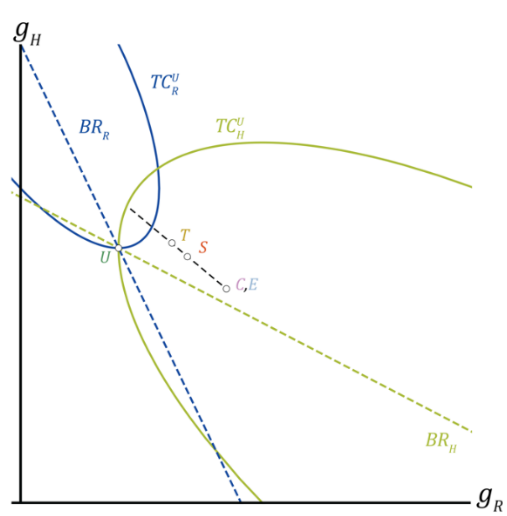
As σ increases, sanctions become costly, so the threat carries less power. As a result, the equilibrium policy outcome moves along the contract curve toward the Target's total cost–minimizing policy provision and, typically, further from that for the Hegemon. It follows that the Hegemon's preference for an agreement with sanctions weakens as sanctions become more costly. For example, in the extreme case of infinitely costly sanctions, $\sigma = 0$, the Hegemon will always prefer the uncoordinated equilibrium regardless of policy externality. Figure 10b shows how moderately costly sanctions change the Hegemon's preference for an agreement with sanctions relative to the uncoordinated equilibrium.

5.4. Ranking of Interventions Under Different Policy Externalities

We can now compare how the Hegemon would rank each policy intervention depending on the policy externality. To grasp the intuition, let's first start with an example. Figure 11 combines the agreement with transfers and agreement with sanctions equilibria from Figures 7 and 9. From the Hegemon's perspective, the ranking of preference is $C \sim E \succ S \succ T \succ U$, but C and E are not incentive compatible for the Target, so the preferred intervention is sanctions. By offering transfers, the Hegemon incentivizes the Target to increase policy provision, but this comes at the cost of the transfers. With sanctions, the Hegemon makes no actual transfer of resources. Thus, it can do better by threatening sanctions, even if sanctions do not reach the optimal policy provision.

This raises the question of whether this ordering of policy preference is always the same. A quick glance at the symmetric case proves this is not the case, as the Hegemon prefers the agreement intervention without sanctions or rewards under symmetry. Proposition 6 illustrates how preference asymmetry and policy exposure jointly determine the ordering of policy preference.

Figure 11. Policy Outcomes



Proposition 6. (ordering of policy intervention preference)

$$\text{If } \Delta > \overline{\Delta}^{\mathrm{TE}}(\gamma) \text{ or } \Delta < \underline{\Delta}^{\mathrm{TE}}(\gamma), \text{ then } E \succ T \succcurlyeq S$$

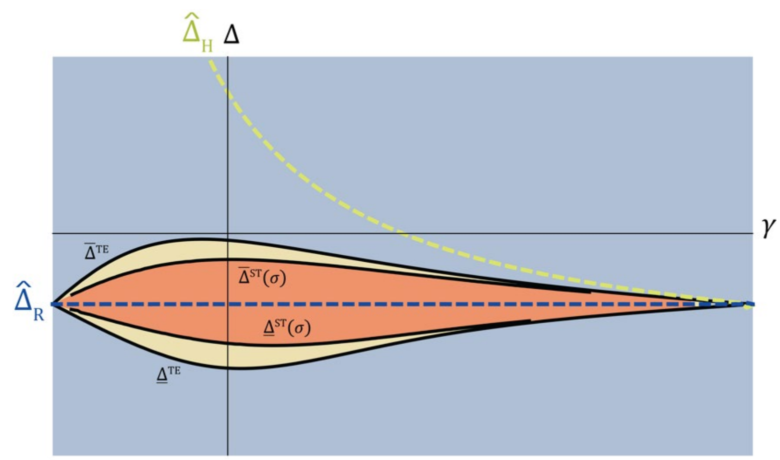
$$\text{If } \overline{\Delta}^{ST}(\gamma;\sigma) < \Delta < \overline{\Delta}^{TE}(\gamma) \text{ or } \underline{\Delta}^{ST}(\gamma;\sigma) > \Delta > \underline{\Delta}^{TE}(\gamma), \text{ then } T \succ S$$

$$\text{If } \underline{\Delta}^{ST}(\gamma;\sigma) < \Delta < \overline{\Delta}^{ST}(\gamma;\sigma), \text{ then } S \succ T.$$

Proof. See the Appendix.

Figure 12 illustrates the results given by Proposition 6. First consider the regions where the Target prefers coordination. From Proposition 3, the Hegemon always prefers an agreement with extraction to the uncoordinated equilibrium. In regions where the Target also prefers the coordinated equilibrium, agreements with transfers or costless sanctions are equivalent to it. In an agreement with extraction, the Hegemon can do even better than coordination by extracting the Target's gains and therefore also prefers the agreement with extraction to either transfers or sanctions in these regions.

Figure 12. Comparing Sanctions and Rewards



Now consider the region where the Target requires additional incentive to participate, $\underline{\Delta}^{TE}(\gamma, 1) < \Delta < \overline{\Delta}^{TE}(\gamma)$. In this region, the coordinated equilibrium and the agreement with extraction equilibrium are unstable. Thus, the Hegemon must choose between an agreement with transfers, agreement with sanctions, or uncoordinated equilibrium. An agreement with transfers is always preferred to the uncoordinated equilibrium in this region, per Proposition 4. The additional cost of transfers is less than the gains of coordination for the Hegemon. When sanctions are costless, the Hegemon always prefers sanctions to transfers because equilibrium policy outcomes are identical but the Hegemon does not have to transfer anything of value. It relies only on the threat of sanctions to provide incentive. However, as sanctions become costly, the Hegemon must trade off the cost of transfers and the cost of sanctions.

With moderately costly sanctions, as illustrated in Figure 12, the Hegemon will prefer transfers over sanctions when the value of transfers is small and prefer sanctions over transfers when the value of transfers is large.

Taken together, we can see how power influences preferences for foreign intervention in domestic climate policy. When incentives for coordination are aligned, the Hegemon will use its power to extract as much as it can from the Target. When the Target requires additional incentive to cooperate, the Hegemon will choose the intervention that provides that incentive at the least cost.

6. Conclusion

Global governance is needed to reduce the impacts of climate change, and the type depends on characteristics of the climate policy. For policies such as emissions mitigation, cooperation is needed to overcome the free-riding problem and increase policy provision. For policies such as SG, coordination is needed to overcome the free-driving problem and rein in policy provision.

We develop a unified theory of foreign intervention on domestic climate policy and analyze how preferences for different forms of intervention depend on the policy externality. By characterizing policy externality as a function of the exposure to climate interventions and preference asymmetry regarding desired objective, we remove the artificial silos around foreign climate intervention options and climate change policy options.

Within our unified framework, we specifically compare preference for alternative foreign intervention strategies for two classes of policy, those with a free-riding equilibrium and those with a free-driving equilibrium. In the absence of power asymmetries, we find countries join an agreement when one of them is free driving too much more than the preferred optimal outcome. This result occurs when exposure to a domestic policy is high or preferences diverge substantively. When we introduce power asymmetries, we find that the powerful country can induce more cooperation from the weak country by either offering transfers or threatening sanctions. When the powerful country cannot directly influence domestic policy, such as by intervening militarily, its options need to provide enough incentives for the weak country to join. This implies that any equilibrium with intervention leads to allocations that are closer to the optimal allocation and thus reduces overall climate costs. Of course, this leaves out important questions regarding justice and distributional issues that are outside of the scope of our paper.

We are at a crossroads on climate policy: how do we move forward with seemingly risky technologies, such as SG and accelerated adaptation? At the same time, we have hit a roadblock: climate negotiations have been stalling, with little meaningful progress from the international community. In this paper we find a general ranking of preferred foreign intervention options that is a function of policy characteristics that are not linked to specific technological possibilities but only characterized by the overall impacts on the climate and how they affect other countries. This framework offers an alternative to the traditional siloed approach to international governance of climate policy. Our results, although perhaps contrary to the current wisdom, offer an alternative way to look at international governance and we hope are intriguing enough to engender further exploration.

7. References

Aidt, T.S., F. Albornoz, and E. Hauk. 2021. Foreign Influence and Domestic Policy. *Journal of Economic Literature* 59(2): 426–87.

Aldy, J.E., T. Felgenhauer, W.A. Pizer, M. Tavoni, et al. 2021. Social Science Research to Inform Solar Geoengineering. *Science* 374(6569): 815–8.

Aldy, J.E., and R. Zeckhauser. 2020. Three Prongs for Prudent Climate Policy. *Southern Economic Journal* 87(1): 3–29.

Barrett, S. 1993. Strategic Environmental Policy and International Competitiveness. In *Environmental Policies and Industrial Competitiveness*. Paris: OECD. 158-167.

Barrett, S. 1994. Self-Enforcing International Environmental Agreements. *Oxford Economic Papers* 1: 878–94.

Barrett, S. 1997. The Strategy of Trade Sanctions in International Environmental Agreements. *Resource and Energy Economics* 19(4): 345–61.

Barrett, S. 2003. *Environment and Statecraft: The Strategy of Environmental Treaty-Making*. Oxford University Press.

Barrett, S. 2008. The Incredible Economics of Geoengineering. *Environmental and Resource Economics* 39(1): 45–54.

Belaia, M., J.B. Moreno-Cruz, and D.W. Keith. 2021. Optimal Climate Policy in 3D: Mitigation, Carbon Removal, and Solar Geoengineering. *Climate Change Economics* 12(03): 2150008.

Black, R., S.R. Bennett, S.M. Thomas, and J.R. Beddington. 2011. Migration as Adaptation. *Nature* 478(7370): 447–9.

Burke, M., S.M. Hsiang, and E. Miguel. 2015. Climate and Conflict. *Annual Review of Economics* 7(1): 577–617.

Bollinger, B., and K. Gillingham. 2019. Learning-by-Doing in Solar Photovoltaic Installations. SSRN 2342406.

Bosetti, V., C. Carraro, E. De Cian, E. Massetti, and M. Tavoni. 2013. Incentives and Stability of International Climate Coalitions: An Integrated Assessment. *Energy Policy* 55: 44–56.

Brander, J. and B. Spencer. 1985. Export Subsidies and International Market Share Rivalry. *Journal of International Economics* 18(1–2): 83–100.

Brander, J. and B. Spencer. 1987. Foreign Direct Investment with Unemployment and Endogenous Taxes and Tariffs. *Journal of International Economics* 22(3–4): 257–279.

Carraro, C., J. Eyckmans, and M. Finus. 2006. Optimal Transfers and Participation Decisions in International Environmental Agreements. *The Review of International Organizations* (4): 379–96.

Eguia, Jon X. and D. Xefteris. 2021. Implementation by Vote-buying Mechanisms. *American Economic Review* 111(9): 2811-28.

Eyler, B. 2020. Science Shows Chinese Dams Are Devastating the Mekong. Foreign Policy (accessed January 15, 2022). **https://foreignpolicy.com/2020/04/22/science-shows-chinese-dams-devastating-mekong-river/**

Field, C., W. Cheung, L. Dilling, P. Frumhoff, H. Greely, M. Hordequin, J. Hurrell, A. Light, A. Lin, D. MacMartin, and R. McHenry. 2021. *Reflecting Sunlight: Recommendations for Solar Geoengineering Research and Research Governance*. National Academies of Sciences, Engineering, and Medicine.

Finus, M., and M. McGinty. 2019. The Anti-Paradox of Cooperation: Diversity May Pay! *Journal of Economic Behavior & Organization* 157: 541–59.

Finus, M., and P. Pintassilgo. 2013. The Role of Uncertainty and Learning for the Success of International Climate Agreements. *Journal of Public Economics* 103: 29–43.

Gallagher, C.L., and T. Holloway. 2020. Integrating Air Quality and Public Health Benefits in US Decarbonization Strategies. *Frontiers in Public Health* 8: 563358.

Harding, A.R., M. Belaia, and David W. Keith. 2022. The Value of Information About Solar Geoengineering and the Two-Sided Cost of Bias. *Climate Policy* 1: 1–11.

Heyen, D., J. Horton, and J. Moreno-Cruz. 2019. Strategic Implications of Counter-Geoengineering: Clash or Cooperation? *Journal of Environmental Economics and Management* 95: 153–77.

Heyen, D., and J. Lehtomaa. 2021. Solar Geoengineering Governance: A Dynamic Framework of Farsighted Coalition Formation. *Oxford Open Climate Change* 1(1) :kgab010.

Horton, J.B., and J.L. Reynolds. 2016. The International Politics of Climate Engineering: A Review and Prospectus for International Relations. *International Studies Review* 18(3): 438–61.

Hsiang, S.M., M. Burke, and E. Miguel. 2013. Quantifying the Influence of Climate on Human Conflict. *Science* 341(6151).

Jinnah, S., D. Morrow, and S. Nicholson. 2021. Splitting Climate Engineering Governance: How Problem Structure Shapes Institutional Design. *Global Policy* 12: 8–19.

Khan, M.R., and S. Munira. 2021. Climate Change Adaptation as a Global Public Good: Implications for Financing. *Climatic Change* 167(3): 1–8.

Lazkano, I., W. Marrouch, and B. Nkuiya. 2016. Adaptation to Climate Change: How Does Heterogeneity in Adaptation Costs Affect Climate Coalitions? *Environment and Development Economics* 21(6): 812–38.

Li, H., and H.A. Rus. 2019. Climate Change Adaptation and International Mitigation Agreements with Heterogeneous Countries. *Journal of the Association of Environmental and Resource Economists* 6(3): 503–30.

McGinty, M. 2007. International Environmental Agreements Among Asymmetric Nations. *Oxford Economic Papers* 59(1): 45–62.

Mendelsohn, R. 2000. Efficient Adaptation to Climate Change. *Climatic Change* 45(3): 583–600.

Millard-Ball, A. 2012. The Tuvalu Syndrome. *Climatic Change* 110(3): 1047–66.

Moreno-Cruz, J.B. 2015. Mitigation and the Geoengineering Threat. *Resource and Energy Economics* 41: 248–63.

Moreno-Cruz, J., G. Wagner, and D. Keith. 2018. An Economic Anatomy of Optimal Climate Policy. CESifo Working Paper 7059.

Nordhaus, W. 2015. Climate Clubs: Overcoming Free-riding in International Climate Policy. *American Economic Review* 105(4): 1339–1370.

Parson, E.A., and J.L. Reynolds. 2012. Solar Geoengineering Governance: Insights from a Scenario Exercise. *Futures* 132:102805.

Reynolds, J.L. 2021. Linking Solar Geoengineering and Emissions Reductions: Strategically Resolving an International Climate Change Policy Dilemma. *Climate Policy*: 1–6.

Ricke, K., D. Ivanova, T. McKie, and M. Rugenstein. 2021. Reversing Sahelian Droughts. *Geophysical Research Letters* 48(14) :e2021GL093129.

Ricke, K.L., J.B. Moreno-Cruz, and K. Caldeira. 2013. Strategic Incentives for Climate Geoengineering Coalitions to Exclude Broad Participation. *Environmental Research Letters* 8(1): 014021.

Ricke, Katharine, and Moreno-Cruz, Juan. 2020. Geo-Wedges: A Portfolio Approach to Geoengineering the Climate. In *Reference Module in Earth Systems and Environmental Sciences*, vol. 531. Elsevier, p. 362.

Rickels, W., M.F. Quaas, K. Ricke, J. Quaas, J. Moreno-Cruz, and S. Smulders. 2020. Who Turns the Global Thermostat and by How Much? *Energy Economics* 91: 104852.

Schelling, T.C. 1996. The Economic Diplomacy of Geoengineering. *Climatic Change* 33: 303–307.

Sayegh, S., G. Heutel, and J. Moreno-Cruz. 20101. Regulating Geoengineering: International Competition and Cooperation. In *Climate Geoengineering: Science, Law and Governance* Springer, 229–247.

Urpelainen, J. 2012. Geoengineering and Global Warming: A Strategic Perspective. *International Environmental Agreements: Politics, Law and Economics* 12(4): 375–89.

Waldinger, M. 2022. The Economic Effects of Long-Term Climate Change: Evidence from the Little Ice Age. *Journal of Political Economy* 130(9): 2275–314.

Weitzman, M.L. 2015. A Voting Architecture for the Governance of Free-Driver Externalities, with Application to Geoengineering. *The Scandinavian Journal of Economics* 117(4): 1049–68.

A. Appendix: Proofs

A.1. Proof of Proposition 1

$g_H^U = 0$ when $\widehat{\Delta}^H(\gamma) = \Delta^H\left(\frac{2}{\gamma} - 1\right)$

$g_R^U = 0$ when $\widehat{\Delta}^R(\gamma) = -\frac{\Delta^H}{2}$

A.2. Proof of Proposition 2

Proof of each of the delimiting curves come from the conditions of incentive compatibility for the Hegemon and Target. These can be described as follows.

A.2.1. Hegemon

The Hegemon is indifferent between the coordinated and uncoordinated equilibria when

$\Delta = \Delta^H \frac{(a \pm b)}{c}$, where $a = 16 - 4\gamma + 31\gamma^2 + 26\gamma^3 - 33\gamma^4 + 21\gamma^5 - 7\gamma^6$, $b = \frac{\gamma^2(9+2\gamma^2)}{\sqrt{\frac{\gamma^2(9+2\gamma^2)}{(20-13\gamma+10\gamma^2-2\gamma^3)^2}}}$, and $c = -32 + 16\gamma - 16\gamma^2 + 24\gamma^3 + 12\gamma^4 - 6\gamma^5 + 7\gamma^6$

A.2.2. Target

The Target is indifferent between the coordinated and uncoordinated equilibria when

$\Delta = \Delta^H \frac{(a \pm b)}{c}$, where $a = 36 - 32\gamma + 52\gamma^2 + \gamma^3 - 10\gamma^4 + 9\gamma^5 - \gamma^6$, $b = \frac{\gamma^2(10+\gamma^2)}{\sqrt{\frac{\gamma^2(9+2\gamma^2)}{(20-13\gamma+10\gamma^2-2\gamma^3)^2}}}$, and $c = -72 + 32\gamma - 72\gamma^2 + 20\gamma^3 - 11\gamma^4 - 8\gamma^5 + \gamma^6$

A.3. Proof of Proposition 3

The difference in total costs for the Hegemon between the agreement with extraction and uncoordinated equilibrium can be expressed as the difference in the sum of total costs for both countries in the coordinated and uncoordinated equilibria:

$$\begin{aligned} TC_H^U - TC_H^E &= TC_H^U - \left(TC_H^C - M\right) \\ &= TC_H^U - \left(TC_H^C - \left(TC_R^U - TC_R^C\right)\right) \\ &= \left(TC_H^U + TC_R^U\right) - \left(TC_H^C + TC_R^C\right) \geq 0 \end{aligned}$$

The inequality in the final line comes from the following reasoning. By definition, both countries choose policy to minimize joint total costs in the coordinated equilibrium. Thus, these joint total costs in the uncoordinated equilibrium are always at least weakly larger than the costs in the coordinated equilibrium and the Hegemon always weakly prefers the agreement with extraction. However, stability requires incentive compatibility for both countries. Conditions for incentive compatibility stemming from the Target, $\overline{\Delta}^{EU}$ and $\underline{\Delta}^{EU}$, follow from Part ii of the proof of Proposition 2.

A.4. Proof of Proposition 4

The Hegemon sets transfers to leave the Target at least as well off as in the uncoordinated equilibrium. Thus, the only condition for stability is incentive compatibility for the Hegemon. First consider the case of positive transfers.

Transfers are positive when the Target requires additional incentive to provide policy consistent with the coordinated equilibrium. Thus, the curves $\overline{\Delta}_R^{TU}$ and $\underline{\Delta}_R^{TU}$ which distinguish the location of positive transfers in the policy exposure space are given by the indifference of the Target between the coordinated and uncoordinated equilibria. Proof of this condition is as in Part ii of the proof of Proposition 2.

Now consider stability from the Hegemon's perspective. When transfers are zero, $\Delta > \overline{\Delta}_R^{TU}$ and $\Delta < \underline{\Delta}_R^{TU}$, the equilibrium outcome is the coordinated equilibrium. Thus, proof of delimiting curves $\overline{\Delta}_H^{TU}$, $\underline{\Delta}_H^{TU}$, and $\overline{\overline{\Delta}}_H^{TU}$ follow Part i of the proof of Proposition 2. When transfers are positive, the Hegemon prefers the agreement with transfers to the uncoordinated equilibrium if the total cost with transfers is less than the total cost in the uncoordinated equilibrium:

$$\begin{aligned} TC_H^U - TC_H^T &= TC_H^U - \left(TC_H^C - W\right) \\ &= TC_H^U - \left(TC_H^C - \left(TC_R^U - TC_R^C\right)\right) \\ &= \left(TC_H^U + TC_R^U\right) - \left(TC_H^C + TC_R^C\right) \geq 0 \end{aligned}$$

The reasoning for the inequality in the final line is as in the proof of Proposition 3.

A.5. Proof of Proposition 5.

Proof of each of the delimiting curves come from the conditions of incentive compatibility for the Hegemon and the Target. These can be described as follows.

A.5.1. Hegemon

The Hegemon is indifferent between the agreement with sanctions and uncoordinated equilibrium when $\Delta = \Delta^{H} \frac{(a \pm b)}{c}$, where

$$\begin{aligned} a = \Big(4 + 6\sigma^3\gamma_{RH}^4 + 8\sigma(4 - 2\gamma_{RH} + \gamma_{RH}^2) \\ - \sigma^4\gamma_{RH}^3(-16 + 20\gamma_{RH} - 9\gamma_{RH}^2 + \gamma_{RH}^3) \\ + \sigma^2\gamma_{RH}(-16 + 44\gamma_{RH} - 15\gamma_{RH}^2 + 4\gamma_{RH}^3)\Big) \\ b = (-4 + \gamma)\gamma(1 + (4 - 2\gamma + \gamma^2)\sigma + \gamma^2\sigma^2)\sqrt{1 + 8\sigma + 2\gamma^2\sigma^2} \\ c = -32 + 16\gamma - 16\gamma^2\sigma + 2\gamma^5(1 - 4\sigma)\sigma^2 + 8\gamma^3\sigma(1 + 2\sigma) \\ + \gamma^6\sigma^2(1 + 4\sigma + 2\sigma^2) + 2\gamma^4\sigma(1 - 3\sigma + 8\sigma^2) \end{aligned}$$

A.5.2. Target

The Target is indifferent between the agreement with sanctions and uncoordinated equilibrium when $\Delta = \Delta^{H} \frac{(a \pm b)}{c}$, where

$$\begin{aligned} a = (4 + 8(4 - 2\gamma + \gamma^2)\sigma + \gamma(-16 + 44\gamma - 15\gamma^2 + 4\gamma^3)\sigma^2 + 6\gamma^4\sigma^3 \\ - \gamma^3(-16 + 20\gamma - 9\gamma^2 + \gamma^3)\sigma^4) \\ b = (-4 + \gamma)\gamma\sigma\sqrt{2 + 8\sigma + \gamma^2\sigma^2}(1 + (4 - 2\gamma + \gamma^2)\sigma + \gamma^2\sigma^2) \\ c = -8 - 16(4 - 2\gamma + \gamma^2)\sigma + \gamma^2(-56 + 20\gamma - 7\gamma^2)\sigma^2 - 12\gamma^4\sigma^3 + \gamma^4(8 \\ - 8\gamma + \gamma^2)\sigma^4 \end{aligned}$$

A.6. Proof of Proposition 6

This proof is the culmination of the proofs for the previous propositions. First consider the regions in the policy exposure space $\Delta > \overline{\Delta}_R^{TE}$ and $\Delta < \underline{\Delta}_R^{TE}$. Comparing the agreement with extractions to the agreement with transfers, the Hegemon strictly prefers the former. The equilibrium for the agreement with transfers in this region of the space is equivalent to the coordinated equilibrium. In the agreement with extractions, the Hegemon's outcome is determined by the coordinated equilibrium plus the value extracted from the gains, $M > 0$, of the Target. Thus, the Hegemon will always prefer the agreement with extractions in these regions because of the additional value from extracting gains to the Target. Additionally, comparing an agreement with sanctions, when $\sigma = 1$, the agreement with transfers and the agreement with sanctions are equivalent in these regions because there is no transfer of material in either agreement. however, when $\sigma < 1$, the Hegemon prefers an agreement with transfers because of the weakened power of costly sanctions.

Second, consider the region in the policy exposure space $\underline{\Delta}_R^{TE} < \Delta < \overline{\Delta}_R^{TE}$. Here, the agreement with exposure is unstable, as discussed in the proof of Proposition 3. From the proof of Proposition 4, transfers are always stable and preferred to the uncoordinated equilibrium. When $\sigma = 1$ sanctions are costless, so the Hegemon prefers the agreement with sanctions, where no material of value is transferred, to an agreement with transfers. As σ decreases, sanctions become costly and the Hegemon weighs the cost of sanctions against the cost of transfers. The Hegemon is indifferent between costly transfers and costly sanctions in this region when $\Delta(\sigma) = \Delta^{\mathrm{H}} \frac{(a \pm b)}{c}$, where

$$a = 84. - 56.\gamma + 36.\gamma^2 - 9.\gamma^3 + 1.\gamma^4 + (32. - 48.\gamma + 112.\gamma^2 - 78.\gamma^3 + 64.\gamma^4 - 18.\gamma^5 + 2.\gamma^6)\sigma + (64. - 128.\gamma + 216.\gamma^2 - 188.\gamma^3 + 175.\gamma^4 - 103.\gamma^5 + 50.\gamma^6 - 11.\gamma^7 + 1.\gamma^8)\sigma^2 + \gamma^2(32. + 112.\gamma - 192.\gamma^2 + 172.\gamma^3 - 78.\gamma^4 + 22.\gamma^5 - 2.\gamma^6)\sigma^3 + \gamma^4(4. + 16.\gamma - 17.\gamma^2 + 9.\gamma^3 - 1.\gamma^4)\sigma^4$$

$$\begin{aligned}
b = \gamma(&-1760. + 2224.\gamma - 1822.\gamma^2 + 892.\gamma^3 - 241.\gamma^4 + 34.\gamma^5 - 2.\gamma^6 \\
&+ (-11200. + 20960.\gamma - 23932.\gamma^2 + 17376.\gamma^3 - 8780.\gamma^4 \\
&+ 2988.\gamma^5 - 634.\gamma^6 + 76.\gamma^7 - 4.\gamma^8)\sigma \\
&+ (-4800. + 21280.\gamma - 43244.\gamma^2 + 49516.\gamma^3 - 39278.\gamma^4 \\
&+ 21790.\gamma^5 - 8569.\gamma^6 + 2322.\gamma^7 - 407.\gamma^8 + 42.\gamma^9 \\
&- 2.\gamma^{10})\sigma^2 \\
&+ (51200. - 112640.\gamma + 145024.\gamma^2 - 119296.\gamma^3 \\
&+ 67136.\gamma^4 - 24892.\gamma^5 + 4798.\gamma^6 + 232.\gamma^7 - 400.\gamma^8 \\
&+ 96.\gamma^9 - 8.\gamma^{10})\sigma^3 \\
&+ (25600. - 43520.\gamma + 86272.\gamma^2 - 99040.\gamma^3 + 85724.\gamma^4 \\
&- 50328.\gamma^5 + 19775.\gamma^6 - 3934.\gamma^7 - 507.\gamma^8 + 592.\gamma^9 \\
&- 187.\gamma^{10} + 30.\gamma^{11} - 2.\gamma^{12})\sigma^4 \\
&+ (40960. - 98304.\gamma + 164352.\gamma^2 - 177408.\gamma^3 \\
&+ 158144.\gamma^4 - 107200.\gamma^5 + 59244.\gamma^6 - 24948.\gamma^7 \\
&+ 7762.\gamma^8 - 1632.\gamma^9 + 188.\gamma^{10} - 8.\gamma^{11})\sigma^5 \\
&+ \gamma^2(25600. - 48640.\gamma + 66560.\gamma^2 - 59104.\gamma^3 + 42268.\gamma^4 \\
&- 22660.\gamma^5 + 9752.\gamma^6 - 3138.\gamma^7 + 712.\gamma^8 - 108.\gamma^9 \\
&+ 8.\gamma^{10})\sigma^6 \\
&+ 8(4. - 1.\gamma)^2\gamma^4(4. + 1.\gamma^2)(4 - 2.\gamma + 1.\gamma^2)(2.5 - 1.\gamma \\
&+ 1.\gamma^2)\sigma^7 \\
&+ 2.(4. - 1.\gamma)^2\gamma^6(4. + 1.\gamma^2)(2.5 - 1.\gamma + 1.\gamma^2)\sigma^8)^{1/2}
\end{aligned}$$

$$c = -168. + 144.\gamma - 104.\gamma^2 + 28.\gamma^3 - 3.\gamma^4 + (-64. + 32.\gamma - 160.\gamma^2 + 72.\gamma^3 - 62.\gamma^4 + 16.\gamma^5 - 2.\gamma^6)\sigma + (-128. + 128.\gamma - 240.\gamma^2 + 176.\gamma^3 - 166.\gamma^4 + 78.\gamma^5 - 45.\gamma^6 + 10.\gamma^7 - 1.\gamma^8)\sigma^2 + \gamma^2(-64. + 32.\gamma - 72.\gamma^3 + 44.\gamma^4 - 20.\gamma^5 + 2.\gamma^6)\sigma^3 + (-8.\gamma^4 + 2.\gamma^6 - 8.\gamma^7 + \gamma^8)\sigma^4$$