2010

Mitigation and the Geoengineering Threat

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November 9, 2010

Abstract

Recent scientific advances have introduced the possibility of engineering the climate system to lower ambient temperatures without lowering greenhouse gas concentrations. This possibility has created an intense debate given the ethical, moral and scientific questions it raises. This paper examines the economic issues introduced when geoengineering becomes available in a standard two-period two-country model where strategic interaction leads to suboptimal mitigation. Geoengineering introduces the possibility of technical substitution away from mitigation, but it also affects the strategic interaction across countries: mitigation decisions directly affect the geoengineering decisions made in the second stage. With similar countries, I find these strategic effects create greater incentives for free-riding on mitigation, but with asymmetric countries, the prospect of geoengineering can induce inefficiently high mitigation levels in equilibrium.

Keywords: Geoengineering, Mitigation, Climate Change.

JEL Classification: Q54, Q55, C72

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1 Introduction

Climate change is the result of the accumulation of greenhouse gases (GHG) in the atmosphere. Until now, the international community has relied on mitigation strategies to deal with the warming caused by climate change. It is well understood, however, that mitigation suffers from under-provision due to free-riding. In addition to the inability of nations to cooperate effectively on the climate change problem, there is also a great deal of uncertainty associated with the response of the climate system. As a result, scientists are exploring new technologies designed to quickly lower temperatures without lowering GHG concentrations.[1] These technologies fall under the category of *geoengineering*.

In this paper, I examine the economic issues introduced when geoengineering is made available in a world where strategic interaction leads to under-provision of mitigation due to free-riding. Specifically, I ask two questions: 1) does the presence of geoengineering increase the free-riding effect on mitigation? and 2) could the costs associated with this increase in free-riding outweigh the benefit gained from introducing geoengineering?

To answer these questions I use a conventional two-country partial equilibrium model. The model has three key features. First, the two countries interact in a two-stage strategic environment where each country minimizes its own costs of managing climate change. Each country chooses mitigation levels in the first stage and geoengineering levels in the second stage. Second, the effects of both mitigation and geoengineering are global. Third, the costs arising from the potential side-effects of geoengineering and climate change may differ across countries.

The costs of climate change are the sum of the costs of mitigation and geoengineering activities plus the economic damages. The costs of mitigation and geoengineering are quadratic

[1] A quick reduction in temperatures may be needed in the case of rapid or catastrophic climate change. For more on this topic see for example Taylor (2009)

functions of their arguments, economic damages are the sum of the damages arising from temperature changes and those arising from the side-effects of geoengineering. The damages from temperature are a quadratic function of the change in global surface temperature; which, in turn, is proportional to *radiative forcing*. Radiative forcing describes how human activity alters the balance between incoming shortwave radiation (energy coming from the sun) and outgoing long wave radiation (energy leaving the earth's atmosphere in the form of heat). The damages arising from the side-effects of geoengineering are assumed to be a quadratic function of the total level of geoengineering implemented by the two countries. Units of mitigation and geoengineering are chosen so that their radiative forcing potentials are proportional to the levels chosen.

Using this framework, I decompose each country's best response to a change in the other country's level of mitigation into a *technical substitution effect* and a *strategic effect*. Considering this decomposition I find two important results: First, when the two countries are similar regarding the damages from climate change and from geoengineering, I find that the technical substitution effect dominates the strategic effect. As a result, although there is a reduction in the levels of mitigation in both countries when geoengineering is introduced, the total cost of climate change is also lower.

Second, when countries differ in their underlying characteristics, they also differ greatly in their chosen solution to the climate change problem. When countries differ the levels of mitigation in equilibrium can increase, rather than decrease, due to the introduction of geoengineering. In particular, the possibility of having higher levels of mitigation arises if the relative losers from climate change and geoengineering differ. In this case the strategic effect dominates the technical substitution effect, mitigation rises, but the total cost of climate change is also higher.

In this paper I draw on a variety of tools from economics to answer a question most often considered in physics and other natural sciences. The cost minimizing set up with increasing and convex costs and damages is standard for the analysis of climate change policies (Goulder and Mathai, 2000). The sequential nature of the model resembles the problems of capacity building and competition on output (Brander and Spencer, 1983 and Dixit, 1986), and these types of models are commonly used to study non-cooperative behavior in the context of international environmental problems (Barrett, 1994 and Endres, 1997).

To physicists and natural scientists geoengineering is an option to be used only if society fails to reach an agreement to reduce emissions (Crutzen, 2006 and MacCracken, 2006). Alternatively, geoengineering has been proposed as part of a portfolio of technologies to deal with catastrophic climate change (Barrett, 2007; Schelling, 2007 and Summers, 2007). For both of these reasons, scientists agree that research on geoengineering is important because of the advantages this option offers (Keith et al 2010; Blackstock et al, 2009; Shepherd et al, 2009), but also agree that its implementation should be highly regulated (Barret, 2008; Victor, 2008 and Victor et. al. 2009).

While there is surely good reason for caution, it appears that geoengineering can achieve any given temperature target at a very low financial cost (Keith and Dowlatabadi, 1992; Keith, 2000, 2001; Wigley, 2006 and Rasch et. al. 2008). Unfortunately, this technical possibility may delay or eliminate mitigation by altering the strategic interaction among countries. For example, Scott Barret finds the introduction of geoengineering lowers the provision of mitigation (Barret, 2008). In addition, given the low costs of geoengineering, unilateral implementation is a real possibility. This introduces governance problems in excess of those existing from mitigation and creates the possibility of conflict (Schelling, 1996; Ricke et al 2010).

With this paper, I clarify some of the economic issues that arise with the introduction of geoengineering. By decomposing the best response function into a the technical substitution effect and a strategic effect, I show the impact that geoengineering has on mitigation choices is not so simple. I show how the impact of introducing geoengineering depends quite delicately on the degree of similarity between countries. In a world with similar countries, geoengineering is a Pareto improvement over a policy of only mitigation since the total cost of climate change fall. In a world where countries differ, the presence of geoengineering can lead to inefficiently high levels of mitigation and higher costs.

The rest of the paper proceeds as follows. In section 2 I show how mitigation and geoengineering affect radiative forcing to determine temperature. I then present the main assumptions regarding the costs of mitigation and geoengineering, the damage function and the objective functions in the two stages of the game in section 3. In section 4 I define the equilibrium concept and analyze the equilibrium levels of mitigation and geoengineering. Finally, in section 5, I summarize the main implications.

2 Mitigation, Geoengineering and Radiative Forcing

Climate change policy focuses on the relation between GHG concentrations and temperature changes. Due to the direct link between these two variables, policy has been designed to reduce the level of GHG concentration in order to keep surface temperature close to its current levels.

Recently, scientists have proposed ways to alter the climate and artificially achieve a given temperature level, independent of the concentration of GHG. These technologies are known as *solar radiation management* (SRM) and are meant to increase the reflectiveness of the earth's atmosphere by injecting reflective particles into the stratosphere; thus reducing the amount of radiation that reaches the surface of the earth.[2]

Radiative forcing describes how the balance between incoming short wave radiation and

[2]There are many other possible technologies that can achieve the same outcome (e.g. increasing the reflectivity of the clouds); however, this technology seems to be the most appropriate from a physical and cost effective point of view (MacCracken, 2006).

outgoing long wave radiation is affected by human activity (IPCC, 2007).[3] Mitigation reduces the concentration of GHG which, in turn, increases *outgoing long wave (or terrestrial) radiation*, which is the radiation leaving the atmosphere in the form of heat. Geoengineering technologies are meant to reduce *incoming short wave (or solar) radiation*, which is the radiation reaching the earth from the sun (Lenton and Vaughan, 2009). Thus, radiative forcing is the outcome of the balance between two types of particles in the atmosphere: greenhouse gases and reflective particles (Schelling, 1996). Defining the effects of mitigation and geoengineering in terms of radiative forcing (R) is useful because the change in surface temperature (ΔT) is approximately proportional to radiative forcing (IPCC, 2007):

$$\Delta T = \lambda R.$$

where λ is a constant known as the *climate sensitivity to a doubling of* CO_2. Formally, the effective radiative forcing after intervention is given by

$$R = R_0 - \widehat{M} - \widehat{G}.$$

where $\widehat{M}$ and $\widehat{G}$ represent mitigation and geoengineering in terms of radiative forcing potential. R_0 is exogenous in the model and it captures the radiative forcing equivalent to

[3] The annual global mean flux of solar radiation at the top of the atmosphere is 342 *watts-per-meter-squared*. Of that radiation, approximately 30% is reflected either by the atmosphere or by the surface of the Earth. The remaining 70% of the radiation is absorbed. The term geoengineering is now applied to a wide range of technologies ranging from giant mirrors in the L1 point (Angel, 2006) to ocean iron fertilization (Lampitt et. al. 2008). The literature distinguishes two modes of geoengineering: SRM and Carbon Dioxide Removal (CDR). In this paper we concentrate on SRM because this response mode differs most fundamentally from mitigation.

business as usual greenhouse emissions. Equivalently, the change in temperature is given by:

$$T(M, G) = T_0 - M - G. \tag{1}$$

where now mitigation, M, and geoengineering, G, are measured in terms of temperature changes, that is $M = \lambda\widehat{M}$ and $G = \lambda\widehat{G}$.

3 The Model

Consider a two-country partial equilibrium model. The two countries are indexed by $i \in \{1, 2\}$. The objective of each country is to minimize its own costs of managing climate change. The costs of climate change are the sum of the costs of mitigation, the cost of geoengineering and the economic damages. The costs of mitigation and geoengineering are quadratic and they are given by:

$$A_i(m_i) = \frac{1}{2}\alpha_i m_i^2 \text{ and } B_i(g_i) = \frac{1}{2}\gamma_i g_i^2, \text{ for all } i \in \{1, 2\} \tag{2}$$

where α_i and γ_i are positive constants representing the slopes of the marginal cost of mitigation and the marginal cost of geoengineering for country i.

There are two sources of economic damages: temperature damages and geoengineering damages. Temperature damages are those caused by the change in temperature as defined in equation (1), e.g. the sea level rising. Geoengineering damages are caused by the possible side effects from the implementation of geoengineering; e.g. ozone decay and changes in precipitation patterns.[4] The extent of the impacts from climate change and geoengineering

[4]The geoengineering technology I describe in this paper addresses only temperature related damages, while leaving other damages untreated (i.e. ocean acidification). For simplicity I do not consider damages from climate change different to those caused directly by global warming. For a complete treatment of

differ across countries. The damage function is country specific and it is given by:

$$D_i(T,G) = \frac{1}{2}\delta_i T(M,G)^2 + \frac{1}{2}\rho_i G^2 \text{ , for all } i \in \{1,2\} \tag{3}$$

where $M = m_1 + m_2$ and $G = g_1 + g_2$ represent the total level of mitigation and the total level of geoengineering, δ_i is a positive constant representing the slope of the marginal damages from climate change and ρ_i is a positive constant representing the slope of the marginal damages from geoengineering.

Given the long time delay between the implementation of mitigation and any significant reduction in temperature, mitigation can be thought of as a decision variable that affects future outcomes. The effects of geoengineering, on the other hand, are immediate. Thus, it is natural to model strategic climate intervention in the presence of geoengineering as a two-stage sequential game. In the first stage countries choose mitigation and in the second stage damages take place and countries choose geoengineering. This timing of events allows me to capture the specific inter-temporal trade-off associated to the possibility of geoengineering becoming available in the future while also highlighting the fact that geoengineering, by acting directly over temperature, eliminates the inertia of the carbon cycle.[5]

In the geoengineering stage, each country minimizes the costs of managing climate change while taking abatement levels as given. The solution to the problem is given by,

$$g^i(M) = \underset{\{g_i\}}{argmin} \{B_i(g_i) + D_i(T(M,G),G)\} \text{ , for all } i \in \{1,2\} \tag{4}$$

the different damages in a non-strategic environment please refer to Moreno-Cruz and Smulders (2009) "Revisiting the Economics of Climate Change: The Role of Geoengineering." Mimeo University of Calgary

[5]By assuming damages occur only in the second stage I eliminate the possibility of using mitigation and geoengineering simultaneously. As it will become clear later, as long as geoengineering is the only technology available in the last stage of the game, the results presented here hold.

where g_i are positive variables representing geoengineering choices. In the abatement stage, countries solve the following problem

$$\min_{\{m_i\}} A_i(m_i) + B_i(g^i(M)) + D^i(T(M, G(M)), G(M)) \text{ , for all } i \in \{1, 2\} \tag{5}$$

where m_i are positive variables representing mitigation choices, $g^i(M)$ is the solution to (4), and $G(M) = g^1(M) + g^2(M)$. The sub-game perfect equilibrium levels of mitigation solve (5).

4 Equilibrium

4.1 Geoengineering Stage

In the second stage, country 1 chooses the level of geoengineering that minimizes its own costs, while holding the decisions of country 2 constant. The first order condition with respect to geoengineering is:

$$\gamma_1 g_1 - \delta_1[T_0 - M - G] + \rho_1 G = 0 \tag{6}$$

The best response function for country 1 follows directly from (6), and it is given by:

$$g_1(g_2; M) = -\phi_1 g_2 + \psi_1[T_0 - M] \tag{7}$$

where $\phi_1 = (\delta_1 + \rho_1)/(\gamma_1 + \delta_1 + \rho_1)$ is the slope of the best response function and $\psi_1 = \delta_1/(\gamma_1 + \delta_1 + \rho_1)$ measures the strength of the response of country 1 to a change in mitigation levels. Because geoengineering is a global public good, it is under-provided in equilibrium due to free-riding. To see this, notice that the best response functions in the second stage are downward sloping — if g_2 is reduced, the marginal productivity of geoengineering in country 1 increases and g_1 will be raised, and viceversa. Also notice that if the mitigation levels are slightly larger, while holding country 2 response fixed, the geoengineering level decreases in country 1.

The equilibrium levels of geoengineering in both countries are determined by the solution to equation (6), and its counterpart for country 2. This solution can be written as a function of total mitigation, M, and it is given by:

$$g^1(M) = \begin{cases} \frac{\psi_1 - \phi_1\psi_2}{1-\phi_1\phi_2}[T_0 - M] & \text{if } \frac{1}{\phi_2} > \frac{\psi_1}{\psi_2} > \phi_1 \\ \psi_1[T_0 - M] & \text{if } \frac{1}{\phi_2} < \frac{\psi_1}{\psi_2} \text{ and } \frac{\psi_1}{\psi_2} > \phi_1 \\ 0 & \text{if } \frac{1}{\phi_2} > \frac{\psi_1}{\psi_2} \text{ and } \frac{\psi_1}{\psi_2} < \phi_1. \end{cases} \tag{8}$$

The condition $\psi_1 - \phi_1\psi_2 > 0$ (and the equivalent for country 2) has to hold in an equilibrium where both countries implement positive levels of geoengineering. That is, the direct effects of a change in mitigation in country 1, ψ_1, have to be larger than the indirect effects in country 2, $\phi_1\psi_2$. If a reduction in the mitigation level induces a change in the geoengineering level of country 1 that is larger than the direct effect in country 2, it is in country 2 best interest to set its own level of geoengineering to zero. In this case, it follows from (7) that the value of geoengineering for country 1 is $g^1(M) = \psi_1[T_0 - A]$. On the other hand, if $\psi_1 < \phi_1\psi_2$, then $g^1(M) = 0$. The parameter space capturing this result is presented in Figure 1.

The shaded area in Figure 1 shows the combination of parameters for which geoengineering levels are strictly positive in both countries. This area shows that for the equilibrium to be interior, damages from climate change and damages from geoengineering are similar across countries. In the limiting case where the costs and damages in the two countries are identical, the geoengineering stage equilibrium is always interior. It follows from (8) that

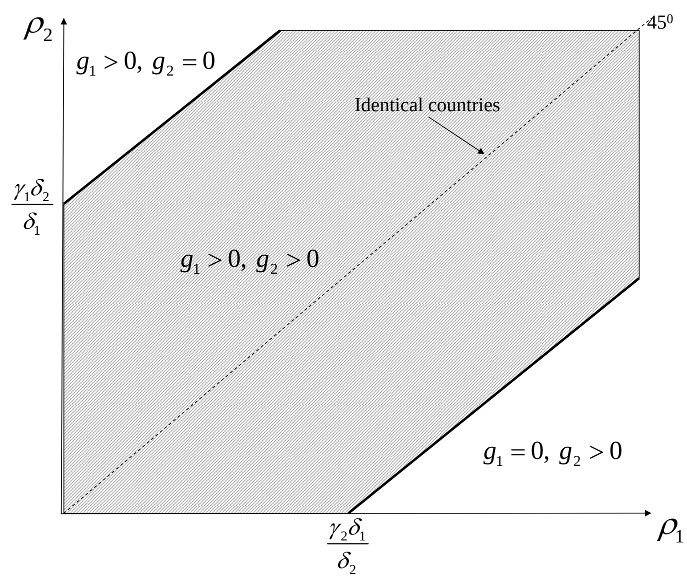

Figure 1: Parameter space—Interior Equilibrium and Corner Solutions. The horizontal axes shows the marginal damages from geoengineering in country 1 and the vertical axes shows the marginal damages from geoengineering in country 2. The shaded area shows the combination of parameters for which geoengineering is positive in both countries. The clear area shows the cases in which only one the countries implements geoengineering.

geoengineering levels decrease and approach zero when the damages from geoengineering approach infinity. The clear area shows that, for high levels of asymmetry, it is possible to have one country choosing not to implement geoengineering. To clarify, assume that decisions are made in isolation. If geoengineering damages are high and climate change damages are low in country 1, the optimal level of geoengineering would be very low for this country. If country 2's damages from geoengineering are low and damages from climate change are high, the optimal level of geoengineering would be high in this country. Then, it is possible that when countries take decisions simultaneously, country 2's level of geoengineering could be too high, forcing country 1 to reduce its level of geoengineering to zero. The results also suggest that in equilibrium at least one country implements geoengineering.

The total level of geoengineering as a function of mitigation is given by:

$$G(M) = g^1(M) + g^2(M) = \begin{cases} [1-\mu][T_0 - M] & \text{if } \frac{1}{\phi_2} > \frac{\psi_1}{\psi_2} > \phi_1 \\ \psi_1[T_0 - M] & \text{if } \frac{1}{\phi_2} < \frac{\psi_1}{\psi_2} \text{ and } \frac{\psi_1}{\psi_2} > \phi_1 \\ \psi_2[T_0 - M] & \text{if } \frac{1}{\phi_2} > \frac{\psi_1}{\psi_2} \text{ and } \frac{\psi_1}{\psi_2} < \phi_1. \end{cases} \tag{9}$$

where

$$\mu = \frac{\gamma_1\gamma_2 + \rho_1\gamma_2 + \rho_2\gamma_1}{\gamma_1\gamma_2 + \gamma_1[\delta_2 + \rho_2] + \gamma_2[\delta_1 + \rho_1]} < 1 \tag{10}$$

It can be noted, given $\mu < 1$, that geoengineering implementation in the second stage only partially compensates for the unmitigated changes in temperature. That is, in equilibrium there will be always some level of positive damages. The extent of damages depends on whether one or two countries implement geoengineering and on the mitigation decisions made in the first stage of the game. Equation (9) shows that geoengineering levels are a function of the total level of mitigation, and not of country specific levels of mitigation. The next proposition captures this interaction.

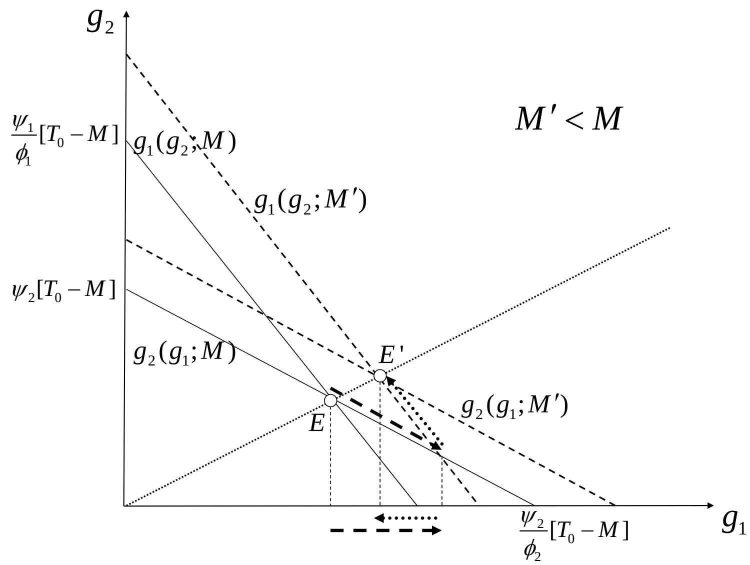

Figure 2: Geoengineering stage equilibrium. The horizontal axis shows the geoengineering level in country 1 and the vertical axes shows the geoengineering level in country 2. The solid lines show the best response functions for each country, as a function of the total level of mitigation M. The dashes lines show the best response function when the mitigation level is $M' < M$. Point E is the equilibrium level of geoengineering in the second stage as a function of mitigation, M. The new level of geoengineering evaluated at $M' < M$ is marked by point E'.

Proposition 1: *The equilibrium level of geoengineering in the second stage increases with a decrease in the total level of mitigation implemented in the first stage.*

Proof: Follows directly from taking derivatives of (8) with respect to M and the assumptions of perfect substitution in the temperature function and separability of costs and damages.

Figure 2 illustrates the results in Proposition 1 for the case in which both countries implement positive levels of geoengineering. A decrease in the level of mitigation in the first stage, by increasing the productivity of geoengineering in the second stage, shifts country 1's reaction function outward. Country 1 level of geoengineering has increase marginally, but geoengineering in country 2 has decreased slightly. This result is captured by the dashed arrow, representing the movement along country 2's best response function due to the shift of country 1's best response function. However, the decrease in mitigation levels has direct effects on the decisions of country 2. This is captured by the dotted arrow, which represents the effects of the shift outwards in country 2's best response function. Hence, a reduction in the first stage level of mitigation causes an increase in the total level of geoengineering in equilibrium.

4.2 Mitigation Stage

In the first stage, countries choos the level of mitigation that solves (5). When countries make their mitigation decisions they take into consideration the effects of their choice on the level of geoengineering that will be chosen in the second stage. That is, countries are aware of the relation between mitigation and geoengineering established in equation (9).

Using the envelope theorem and equation (6), the first order condition for the choice of mitigation in country 1 is given by

$$\alpha_1 m_1 - \delta_1[T_0 - M - G(M)] - [\delta_1[T_0 - M - G(M)] - \rho_1 G(M)]\frac{\partial g^2}{\partial M} = 0 \tag{11}$$

The exact form of equation (11) depends on whether the second stage equilibrium is a interior or a corner solution; which in turn depends on the degree of similarity of the two countries. The analysis below proceeds as follows: First, I analyze the case when both countries implement geoengineering, that is $G(M) = [1 - \mu][T_0 - M]$. Second, I analyze the case when country 1 implements geoengineering and country 2 does not; that is $G(M) = g^1(M) = \psi_1[T_0 - M]$.

4.2.1 Similar countries

When countries are similar (shaded area in Figure 1), equation (11) can be reduced to:

$$\alpha_1 m_1 - \mu\delta_1[T_0 - M] - [\mu\delta_1 - [1-\mu]\rho_1]\frac{\partial g^2(M)}{\partial M}[T_0 - M] = 0 \quad (12)$$

I identify two effects in the previous equation: the *technical substitution effect* given by $\mu\delta_1$, and the *strategic effect* given by $[\mu\delta_1 - [1-\mu]\rho_1]\frac{\partial g^2(M)}{\partial M}$. The technical substitution effect in equation (12) shows the marginal damages from climate change in country 1 are reduced from δ_1 to $\mu\delta_1$, where $\mu < 1$ by equation (10). Hence, the total costs of managing climate change are reduced do to the technical substitution effect. This effect holds even when mitigation and geoengineering are chosen simultaneously. The strategic effect appears in equation (12) due to the sequential choice of the problem: mitigation decisions have a direct, one way, impact on the choice of geoengineering. In particular, a marginal reduction in the level of mitigation by country 1 causes an increase in the level of geoengineering by country 2. The strategic effect is the weighted sum of two individual forces: a reduction in the marginal damages from temperature, $\mu\delta_1$, and an increase in the marginal damages directly caused by geoengineering, $[1-\mu]\rho_1$. Thus, the relative importance of climate change damages relative to geoengineering damages ultimately determines the magnitude of the strategic effect. With some manipulation, it can be shown that $[\mu\delta_1 - [1-\mu]\rho_1] = \gamma_1\frac{\partial g^1(M)}{\partial M}$. Hence, we can define the strategic effect as $\zeta = \frac{\partial g^1(M)}{\partial M}\frac{\partial g^2(M)}{\partial M}$, and equation (12) can be rewritten as:

$$\alpha_1 m_1 - [\mu\delta_1 - \zeta\gamma_1][T_0 - M] = 0 \quad (13)$$

Lemma 1: *When countries are similar, the technical substitution effect dominates the strategic effect; that is* $\mu\delta_1 - \zeta\gamma_1 > 0$*.*

Proof: Proof is in the Appendix.

It follows directly from Lemma 1 that the marginal damages are reduced relative to the scenario without geoengineering. Specifically, the slope of the marginal damages is reduced from δ_1 to $\mu\delta_1 - \gamma_1\zeta$. In equilibrium, this reduction in the slope of the marginal damages causes a reduction in the marginal productivity of mitigation. This change in the marginal productivity is common to the two countries (μ is not country specific); thus, both countries implement a lower level of mitigation in equilibrium. These results are illustrated in Figure 3 and they are summarized in the next proposition.

Proposition 2: *The level of mitigation in the equilibrium with geoengineering is lower than in the equilibrium without geoengineering.*

Proof: Proof is in the Appendix.

The reduction in the level of mitigation due to geoengineering, previously identified in the literature (Keith et. al. 2010), is in this case given by ζ as a form of inter-stage free-riding. This effect is one of the main reservations that scientists have on the promotion of geoengineering technologies. However, the presence of geoengineering also causes a reduction in mitigation due to the technical substitution effect; which reduces the costs for both countries in equilibrium. I have shown that, when the underlying characteristics of the two countries are similar, the technical effect dominates the strategic effect; thus, the equilibrium with geoengineering is a Pareto improvement over the equilibrium without it.

Nonetheless, an overall reduction in the costs of managing climate change do not necessarily represent a reduction in surface temperature. The next proposition shows that the temperature level in the equilibrium with geoengineering is lower than in the equilibrium without geoengineering if and only if the strategic effect is strongly dominated by the technical substitution effect.

Proposition 3: *If $\zeta < \frac{\alpha_1\alpha_2}{\gamma_1\alpha_2+\gamma_2\alpha_1}(1-\mu)$, then the equilibrium temperature with geoengineering is lower than without geoengineering.*

Proof: See the appendix

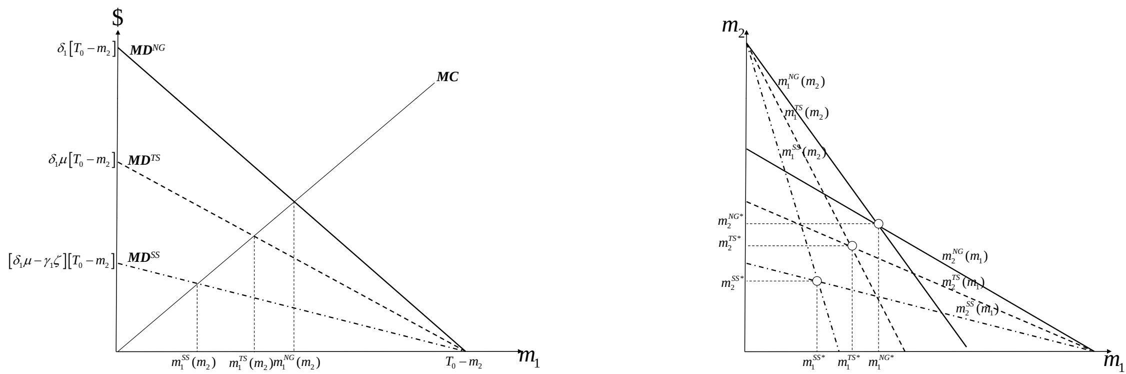

Figure 3: Mitigation stage equilibrium — Similar countries. The left panel shows the standard diagram of marginal mitigation costs (MC) and marginal damages (MD). The horizontal axis represents the level of mitigation in country 1 and the vertical axis represents either MC or MD measured in the same economic units (i.e. utils or dollars). The upward-sloping solid line represents the marginal mitigation costs curve. The downward-sloping solid line represents the marginal damages in the scenario without geoengineering (superscript NG). The dashed line represents the change in the marginal damages caused by the technical substitution effect (superscript TS). The technical substitution effect reduces the level of mitigation from m^{NG} to m^{TS}. The strategic effect (superscript SS), represented by the dot-dashed line, further reduces the slope of the marginal mitigation curve resulting on an even lower level of mitigation in country 1; mitigation moves from m^{TS} to m^{SS}. The right panel shows the reaction functions for both countries: In equilibrium, because the introduction of geoengineering affects both countries in a similar fashion, the equilibrium levels of mitigation are lower.

From Proposition 3, it is possible that the reduction in total costs is caused by a reduction in the technical implementation of the policy, that is $A_1(m)$ and $B_1(g)$, and not by a reduction in damages, $D_1(T, G)$. Specifically, the expression in Proposition 3 is more likely to hold when the costs of geoengineering are very low, which tends to make the right hand of the expression larger relative to ζ. Thus, in the presence of geoengineering the costs of managing climate change will be lower; however, this may also result in higher temperatures.

Recall that the results in this section depend on the assumption of an interior equilibrium; that is, I am assuming the underlying parameters of the model are similar across countries. In the next section I study the case where the two countries are asymmetric; to the extent in which only one of them implements geoengineering.

4.2.2 Asymmetric countries

In this section I analyze the corner solution (clear area in Figure 1). In particular, assume in this case that country 1 introduces geoengineering and country 2 does not.[6] Hence, in this case

$$G(M) = g^1(M) = \psi_1[T_0 - M]$$

and the first order conditions for country 1, equivalent to (11), can be written as:

$$\alpha_1 m_1 - \delta_1[1 - \psi_1][T_0 - M] = 0 \tag{14}$$

Equation (14) shows that the slope of the marginal damages from temperature is reduced by a fraction $[1 - \psi_1]$, relative to the case without geoengineering. This is equivalent to the technical substitution effect described above. However — given that country 1 is the only country implementing geoengineering — there is not strategic effect present in equation (14). As a result, the slope of country 1's best response function becomes unambiguously steeper

[6]Specifically I assume the conditions hold for the solution to be at the top and left corner in figure 1

in the presence of geoengineering.

The first order condition for country 2, following (11), is given by:

$$\alpha_2 m_2 - \delta_2[1-\psi_1][T_0 - M] - [[1-\psi_1]\delta_2 - \rho_2\psi_1]\frac{\partial g^1}{\partial M}[T_0 - M] = 0 \tag{15}$$

As in the interior equilibrium, I identify two effects in the previous equation: a technical substitution effect given by $[1-\psi_1]$ and a strategic effect given by $[[1-\psi_1]\delta_2 - \rho_2\psi_1]\frac{\partial g^1(M)}{\partial M}$. Using the definition of ψ_1, equation (15) can be reduced to:

$$\alpha_2 m_2 - \frac{\delta_2(\rho_1+\gamma_1)^2 + \rho_2\delta_1^2}{(\gamma_1+\rho_1+\delta_1)^2}(T_0 - M) = 0 \tag{16}$$

Contrary to the interior equilibrium, it cannot be unambiguously determined whether the technical substitution effect dominates, or is dominated by, the strategic effect.

Lemma 2: *In the corner equilibrium, the strategic effect dominates the technical substitution effect if and only if* $\rho_2 > 2\frac{\delta_2}{\delta_1}[\gamma_1+\rho_1] + \delta_2$.

Proof: Proof is in the Appendix.

Lemma 2 shows the condition needed for the strategic effect to dominate the technical substitution effect. This condition holds when damages from climate change are high and damages from geoengineering are low in country 1; and when damages from climate change are low and damages from geoengineering are high in country 2. That is, damages are orthogonal between countries.

Proposition 4: *i.) If* $\rho_2 < 2\frac{\delta_2}{\delta_1}[\gamma_1+\rho_1] + \delta_2$*, then mitigation decreases in both countries relative to the equilibrium without geoengineering. ii.) If* $\rho_2 > 2\frac{\delta_2}{\delta_1}[\gamma_1+\rho_1] + \delta_2$*, then mitigation in country 1 decreases and mitigation in country 2 increases relative to the equilibrium without geoengineering.*

Proof: See the appendix

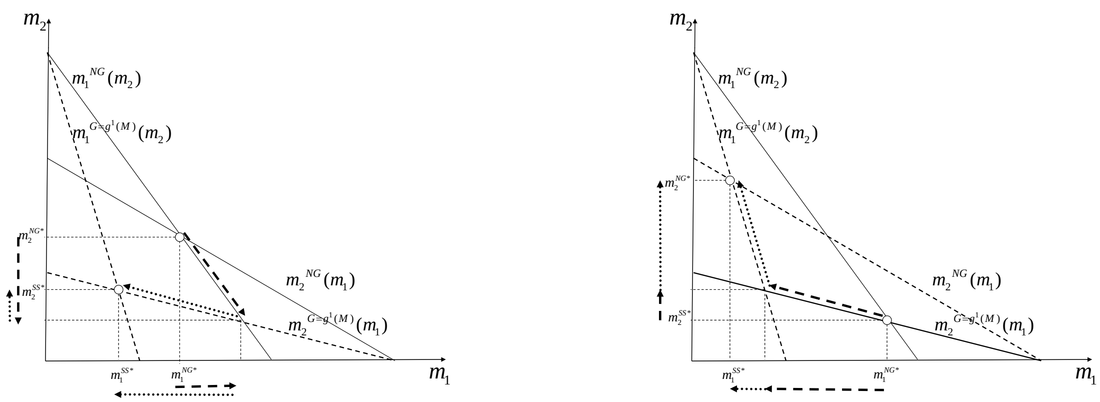

Figure 4: Mitigation stage equilibrium—Asymmetric countries. The horizontal axis represents the mitigation level in country 1, and the vertical axis represents the mitigation level in country 2. The downward sloping solid lines represent the best response functions in the absence of geoengineering for country 1 and 2 and they are denoted by $m_1^{NG}(m_2)$ and $m_2^{NG}(m_1)$, respectively. The dashed lines represent the best response functions with geoengineering for country 1 and 2, which are denoted by $m_1^{G=g^1(M)}(m_2)$ and $m_2^{G=g^1(M)}(m_1)$, respectively. The left panel shows the results of the first part in Proposition 4 and the right panel shows the results the second part in Proposition 4.

Figure 4 illustrates the results in Proposition 4. The left panel shows the results of the first part of Proposition 4. If the technical substitution effect dominates the strategic effect, then the slope of country 2's best response function becomes flatter. Given the best response function for country 1 is steeper, the resulting equilibrium levels of mitigation are lower in both countries. The right panel in Figure 4 shows the opposite result. If the technical substitution effect is dominated by the strategic effect, then the slope of the best response function for country 2 becomes steeper, which results in higher levels of mitigation in country 2. In other words, Proposition 4.ii implies that, if the damages from geoengineering in country 2 are high relative to the damages in country 1, then, country 2 has a greater incentive to increase its mitigation level in order to reduce the level of geoengineering chosen by country 1. In particular, in the limiting case where $\gamma_1 + \rho_1 = 0$, the condition in Proposition 4.ii holds when $\rho_2 > \delta_2$.

For even larger asymmetries, the presence of geoengineering could increase mitigation levels even beyond first best levels in the absence of geoengineering. The first best level of mitigation in the absence of geoengineering is given by the solution to the following program:

$$\min_{\{m_1,m_2\}} \frac{1}{2}\alpha_1 m_1^2 + \frac{1}{2}\alpha_2 m_2^2 + \frac{1}{2}[\delta_1 + \delta_2][T_0 - m_1 - m_2]^2$$

Proposition 5 shows that there is a combination of parameters for which the presence of geoengineering induces higher levels of mitigation, relative to the first best case.

Proposition 5: *If* $\rho_2 > \frac{\delta_2}{\delta_1}[\delta_1 + 2[\gamma_1 + \rho_1]] + \frac{[\gamma_1+\rho_1+\delta_1]^2}{\delta_1}$, *then mitigation in country 2 increases relative to the first best case without geoengineering.*

Proof: See the appendix

The condition in Proposition 5 implies that the possibility of achieving first best levels of mitigation depends radically on the asymmetries of damages. For example, if total costs of geoengineering in country 1 are very low ($\gamma_1 + \rho_1 = 0$), then the condition in Proposition 5 is reduced to $\rho_2 > \delta_1 + \delta_2$. That is, when marginal damages from geoengineering in country 2 are larger than the sum of the marginal damages from temperature in the two countries. In this case the strategic effect is very strong and country 1 forces mitigation in country 2 to be very high.

The results in Propositions 4 and 5 imply, contrary to the intuition, that it is possible to have *inefficiently high levels of mitigation in the equilibrium with geoengineering.* Two conditions have to hold simultaneously: first, large asymmetries in the damages from climate change and second, orthogonal asymmetries in the damages from geoengineering. Large asymmetries in the damages from climate change have been documented previously in the literature. In particular, the IPCC's Third Assessment Report compares different studies and shows that if surface temperature increases by 2.5^oC, countries like Russia will gain

0.7% in their GDP, while regions of the world like India or Africa will suffer damages on the order of 4% to 5% of GDP (IPCC, 2001). Thus, it is possible for the first part of the conditions in Proposition 4 and 5 to hold. The second part of the condition in Propositions 4 and 5 is more difficult to assess. However, recent computer experiments on the effects of geoengineering schemes in the hydrological cycle suggest damages from geoengineering will be highly asymmetric (Caldeira and Matthews, 2007 and Bala et. al. 2008). Thus, if the damages from geoengineering due to precipitation changes are larger in some countries relative to others, the second condition in Propositions 4 and 5 is more likely to hold.

Following the previous two propositions, it is easy to show that for large asymmetries in the damages from climate change and geoengineering, the cost to country 2 increases beyond the costs associated with the first best levels of mitigation absent geoengineering. This suggest that country 1 could attain a better outcome in a climate negotiation if it could credibly threaten to engage in geoengineering. Country 2 now has a real incentive to commit to higher levels of mitigation or else country 1 would resort to geoengineering strategies in the second stage, making country 2 worse off.

To summarize, when countries are asymmetric two possibilities arise. First, if the asymmetries from climate change and geoengineering are parallel — that is, if the relative winners with climate change are winners with geoengineering — geoengineering further increases costs in countries that were losers from climate change. In this case, mitigation levels are inefficiently low. However, if the asymmetries from climate change and geoengineering are orthogonal — that is, if the relative winners with climate change are losers with geoengineering — and if the costs of mitigation are not prohibitively high, it is possible to have more mitigation in an equilibrium with geoengineering available. In this situation, countries that were originally losers with climate change decrease their costs at the expense of an increase in the costs of countries that are losers with geoengineering.

5 Conclusions

This paper has shown that geoengineering does not necessarily increase the free-riding effect on mitigation. In fact, under asymmetry, it is possible that the prospect of geoengineering may induce inefficiently high levels of mitigation. This possibility should be considered when discussing the international implications of introducing geoengineering.

This paper also suggests that strategic effects play a major role in determining the impact of geoengineering on the analysis of climate change. In particular, the presence of geoengineering may introduce new leverage that favors developing countries in future negotiations on climate change.

The analysis was performed using a model that is purposely simple. I have done so to concentrate on the strategic interaction between countries. Although some of my results are contrary to standard results in the literature, the method I use is very familiar. In fact, these results follow from seriously considering the differences between mitigation and geoengineering, which lend themselves to the application of the same standard two-stage equilibrium methods as those used in the analysis of capacity building (or R&D) and output.

At this moment it is difficult to conclude whether geoengineering technologies are essential for dealing with climate change; however, the same lack of evidence makes it very difficult to conclude that the best option is to preclude their use. A serious understanding of the interaction between geoengineering and mitigation, both theoretically and empirically, is necessary to be able to determine whether or not geoengineering is worth considering as a tool to manage climate change. This paper is a step towards this understanding.

Financial Support

This research was made possible through support from the Climate Decision Making Center (CDMC) located in the Department of Engineering and Public Policy. This Center has been created through a cooperative agreement between the National Science Foundation (SES-0345798) and Carnegie Mellon University.

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Appendix

Proof Lemma 1: From equation (10), $\mu = \frac{\gamma_1\gamma_2+\rho_1\gamma_2+\rho_2\gamma_1}{\gamma_1\gamma_2+\gamma_1[\delta_2+\rho_2]+\gamma_2[\delta_1+\rho_1]}$, and from the definition of ζ I can rewrite $\zeta = \frac{\partial g^1}{\partial M}\frac{\partial g^2}{\partial M} = \frac{[\psi_1-\phi_1\psi_2][\psi_2-\phi_2\psi_1]}{[1-\phi_1\phi_2]^2} = \frac{[\delta_1\gamma_2+\delta_1\rho_2-\rho_1\delta_2][\delta_2\gamma_1+\delta_2\rho_1-\rho_2\delta_1]}{[\gamma_1\gamma_2+\gamma_1[\delta_2+\rho_2]+\gamma_2[\delta_1+\rho_1]]^2}$. To proof Lemma 1 we need the sign of $\mu\delta_1 - \zeta\gamma_1$; replacing definitions we have:

$$\mu\delta_1 - \zeta\gamma_1 = \frac{\delta_1[\gamma_1\gamma_2+\rho_1\gamma_2+\rho_2\gamma_1][\gamma_1\gamma_2+\gamma_1[\delta_2+\rho_2]+\gamma_2[\delta_1+\rho_1]]}{[\gamma_1\gamma_2+\gamma_1[\delta_2+\rho_2]+\gamma_2[\delta_1+\rho_1]]^2} - \frac{\gamma_1[\delta_1\gamma_2+\delta_1\rho_2-\rho_1\delta_2][\delta_2\gamma_1+\delta_2\rho_1-\rho_2\delta_1]}{[\gamma_1\gamma_2+\gamma_1[\delta_2+\rho_2]+\gamma_2[\delta_1+\rho_1]]^2}$$

Expanding the previous expression, reorganizing and canceling terms I obtain:

$$\frac{\gamma_2^2\delta_1\rho_1[\delta_1+\rho_1]+\gamma_1^2[\gamma_2^2\delta_1+\delta_2^2\rho_1+2\gamma_2\delta_1\rho_2+\delta_1\rho_2^2]+\gamma_1[\gamma_2^2\delta_1[\delta_1+2\rho_1]+2\gamma_2\delta_1[\delta_1+\rho_1]\rho_2+[\delta_2\rho_1-\delta_1\rho_2]^2]}{[\gamma_1\gamma_2+\gamma_1[\delta_2+\rho_2]+\gamma_2[\delta_1+\rho_1]]^2} > 0. \text{ QED}$$

Proof Proposition 2: Lemma 1 implies that the marginal damages from climate change are reduced in country 1, which implies there is a lower incentive to implement mitigation. This is true for the two countries, which translates on a steeper slope of the reaction functions (a greater incentive to free ride). Hence, there is less mitigation in equilibrium. See Figure 3 for an illustration of this proof. QED

Proof Proposition 3: In the interior equilibrium the total level of geoengineering is given by $G = [1-\mu][T_0-M]$ and the total level of mitigation is given by $M = \frac{\frac{1}{\alpha_1}[\mu\delta_1-\zeta\gamma_1]+\frac{1}{\alpha_2}[\mu\delta_2-\zeta\gamma_2]}{1+\frac{1}{\alpha_1}[\mu\delta_1-\zeta\gamma_1]+\frac{1}{\alpha_2}[\mu\delta_2-\zeta\gamma_2]}T_0$.
Thus, temperature is given by $T = T_0 - M - G = \frac{\mu}{1+\frac{1}{\alpha_1}[\mu\delta_1-\zeta\gamma_1]+\frac{1}{\alpha_2}[\mu\delta_2-\zeta\gamma_2]}T_0$

In the absence of geoengineering, $\mu = 1$ and $\zeta = 0$, which implies $T^{NG} = \frac{1}{1+\frac{\delta_1}{\alpha_1}+\frac{\delta_2}{\alpha_2}}T_0$

Now, it is straight forward to show that $T > T^{NG}$ *if and only if* $\zeta > \frac{\alpha_1\alpha_2}{\gamma_1\alpha_2+\gamma_2\alpha_1}[1-\mu]$. QED

Proof Lemma 2: The strategic effect is dominated by the technical substitution effect when the slope of the marginal damages with geoengineering is lower than without geoengineering, that is: $\delta_2 > \frac{\delta_2[\rho_1+\gamma_1]^2+\rho_2\delta_1^2}{[\gamma_1+\rho_1+\delta_1]^2}$, which implies $\rho_2 < 2\frac{\delta_2}{\delta_1}[\gamma_1+\rho_1]+\delta_2$. QED

Proof Proposition 4: Given Lemma 2, marginal damages from climate change in country 2 are reduced, which results in a greater incentive to reduce its level of mitigation. Country 1's marginal damages are always lower in the presence of geoengineering; hence, both countries implement lower levels of mitigation in the presence of geoengineering. If the condition in Lemma 2 is violated; that is, if $\rho_2 > 2\frac{\delta_2}{\delta_1}[\gamma_1+\rho_1]+\delta_2$, then country 2 has an incentive to increase its level of mitigation because the marginal damages from climate change are larger when geoengineering is available. Thus, in equilibrium, country 2 implements higher levels of mitigation with geoengineering than without. Country 1 implements even lower levels of mitigation. QED

Proof Proposition 5: The slope of the marginal damages in the first best without geoengineering is equal to $\delta_1 + \delta_2$. Geoengineering causes and increase in the levels of mitigation beyond the first best levels if $\delta_1 + \delta_2 < \frac{\delta_2[\rho_1+\gamma_1]^2+\rho_2\delta_1^2}{[\gamma_1+\rho_1+\delta_1]^2}$, which implies $\rho_2 > \frac{\delta_2}{\delta_1}\left[\delta_1 + 2[\gamma_1 + \rho_1]\right] + \frac{[\gamma_1+\rho_1+\delta_1]^2}{\delta_1}$. QED