We study the effects of environmental policy commitments in a futuristic world in which solar radiation management (SRM) can be utilized to reduce climate change damages. Carbon and sulfur dioxide emissions (correlated pollutants) can be reduced through tradable permits. We show that if nations simultaneously commit to carbon permit policies, national SRM levels rise with carbon quotas. Alternatively, if they simultaneously commit to SRM policies, the global temperature falls with each unit increase in the global SRM level. A nation always wishes to be a leader in policymaking, but prefers carbon to SRM policymaking. The globe prefers SRM policy commitments.

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1. Introduction

If in the near future multiple instruments are available (e.g., carbon pricing and solar radiation management) and governments are able to commit to a particular type of policy instrument, which instrument will they prefer? Are there clear game theoretic predictions of play? This paper is an attempt to answer these questions.

There is not much reason for optimism with respect to the prospects of implementation of an effective, cooperative, international agreement to curb the evils produced by climate change. The Kyoto protocol has not produced enthusiastic results and a post-Kyoto agreement does not promise to be much different. The high national costs associated with mitigation of greenhouse gas emissions appear to be the main culprit. Such high costs were the main motivation for the US government to reject Kyoto, and may again be the main argument utilized by powerful nations, such as the USA and China, to reject a post-Kyoto agreement.

Revealed preference informs us that some nations prefer the status quo of no significant mitigation of greenhouse gas emissions to a commitment to reduce greenhouse emissions by a significant percentage amount relative to 1990 levels. However, this fact does
not rule out the possibility that governments, which have rejected Kyoto as well as those that may reject a post-Kyoto agreement, are currently contemplating adopting cheaper alternatives to mitigation of greenhouse gas emissions in order to reduce their potential damages caused by climate change. In fact, there appears to be a credence in the scientific community that some nations are seriously considering producing climate change engineering products—such as solar radiation management (SRM) generated by injections of sulfate aerosols into the stratosphere—that may effectively control the global temperature (see, e.g., the discussion of the scientific findings in Moreno-Cruz (2011)). One must also account for some of the potential negative effects associated with climate change engineering. SRM, for example, is expected to produce droughts, ozone depletion and to change the color of our blue skies.

This paper studies some of the effects associated with uncoordinated policy commitments with respect to provision of SRM relative to policy commitments for mitigation of greenhouse gas (e.g., carbon dioxide) emissions. We envision environmental policy making in a future global economy in which SRM is a proven and mature technology, which can be deployed at will and unilaterally by any nation. Among other things, we analyze whether there will be an incentive for a nation to be a policy leader in mitigation of carbon dioxide emissions or SRM provision, where the nations are perfectly informed about the benefits and costs of providing SRM.3 Solar radiation management is expected to produce droughts, ozone depletion and to change the color of our blue skies.

The fact that SRM may soon prove to be a cheaper and effective alternative to mitigation of carbon dioxide emissions implies that unilateral action in SRM will not only be credible (see, e.g., Barrett (2008)), but also that nations may then wish to commit to SRM policies and subject their carbon mitigation policies to SRM policy commitments. Recent and noteworthy contributions to the literature have considered some of the potential reactions we may observe with future implementation of geoengineering technologies (e.g., Goeschl et al. (2013), Millard-Ball (2012), Moreno-Cruz (2011), Moreno-Cruz and Keith (2012), Moreno-Cruz et al. (2011), Urpelainen (2012)). Moreno-Cruz (2011) examines non-cooperative games in which two nations are either symmetric or asymmetric with respect to drought damages. In the symmetric game, he finds that the prospect of SRM will create greater incentives for free riding on carbon mitigation. When nations are asymmetric, he finds that SRM provision can induce inefficiently high levels of mitigation. Millard-Ball studies the impact of geoengineering deployment on the formation of a mitigation agreement. He shows that a credible unilateral threat of utilizing geoengineering may strengthen global abatement and lead to a self-enforcing climate treaty with full participation. Urpelainen shows that geoengineering may induce significant reductions in emissions in the present if it produces severe negative externalities, since the latter may lead to a very harmful geoengineering race in the future. If the externalities are not overly severe, unrestricted utilization of geoengineering can be globally beneficial.

Our paper contributes to this literature in at least three significant ways. First and foremost, we examine the effects associated with strategic environmental policy commitments, whereby SRM policy may precede carbon policy. This may indeed occur in the future when SRM technology is mature. SRM policy may be (politically or even socially) cheaper and easier to implement than carbon policy. Our motivation here is therefore to consider a likely future event and then make a prediction concerning the equilibrium policies. As in the papers cited above, we assume that SRM provision generates global damages—in our setting SRM produces drought damages and the drought damage function is increasing at an increasing rate.

Second, our model accounts for the fact that emissions of carbon dioxide are correlated with emissions of sulfur dioxide due to important common sources, such as energy production. Our model builds on Caplan and Silva (2005).4 As in Caplan and Silva, sulfur dioxide emissions cause acid rain damage in the emitting nation. We show that the instruments a nation utilizes to control carbon and sulfur dioxide emissions are strategic complements. Hence, whenever SRM provision leads to an increase in carbon emissions, it also leads to an increase in sulfur emissions, with a resulting increase in acid rain damage. Finally, unlike the cited papers, we examine environmental policy making within a general equilibrium framework. This will enable us to see how consumers and industry emitters respond to strategic policy choices made by the governments.

2. Modeling strategies and brief discussion of main results

We consider a global economy consisting of two nations, which are identical in all respects, except for the drought and acid rain damage functions.5 This is a modeling strategy. We wish to highlight the effects that differences in both drought and acid rain damages may promote in the formulation of non-cooperative carbon and SRM environmental policies and on the incentives for policy commitments.

Each nation has three policy instruments at its disposal: namely, SRM provision and carbon and sulfur pollution permits. Our choice of pollution permits as the means to price emissions is motivated by the Kyoto Protocol, the European Union Emissions Trading System and the 1990 US Clean Air Act Amendments, which created a national program in tradable sulfur dioxide emission permits.

Although we consider the making of uncoordinated environmental policies in a future time when policy makers have SRM at their disposal, our analysis involves a single period. The various timings of the games examined in this paper are strictly motivated by individual costs and benefits of policy commitments. We wish to predict which timing is likely to emerge in equilibrium. The timings are not motivated by the historical evolution of the utilization of environmental policy instruments. An alternative and interesting avenue for research is to explicitly consider an intertemporal model in which the sequence of policy instruments mimics the historical evolution of environmental policy, with sulfur pollution permits preceding carbon pollution permits and the latter preceding SRM. In such a case, the sequencing is exogenous and one considers the

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3 Policy leadership in transboundary pollution contexts has been studied in the literature. See, for example, Caplan and Silva (1999) and Nagase and Silva (2007, 2007) show that the policy effects produced by China’s first-move advantage seem to be consistent with the policy choices made by China and Japan to address their acid rain problems. To our knowledge, however, the impacts of policy leadership in a setting in which the nations have instruments to reduce carbon emissions and produce SRM have not yet been examined in the literature.

4 See also Silva and Zhu (2009). Our framework can also be seen as an extension of the impure public good model studied in the literature (see, e.g., Cornes and Sandler (1994) and Silva and Yamaguchi (2010)) to a context in which there are two impure public goods, namely, SRM provision and mitigation of carbon dioxide emissions. SRM provision yields global pure public good benefits, but entails national-specific drought damages. Reduction of carbon emissions also yields global pure public good benefits, but entails national-specific costs in terms of reduction of the consumer surplus associated with energy consumption. Our analysis makes a contribution to the public goods literature in that we consider both simultaneous and sequential strategic interactions between these two types of impure public goods.

5 For an analysis in which there is strategic policymaking concerning greenhouse gas emissions in the presence of asymmetric damages and benefits of greenhouse gas emissions, see Caplan et al. (1999).
impacts associated with the sequential introduction of environmental policy instruments.

We start our analysis by considering two benchmarks in which environmental policy making with respect to SRM provision and carbon-permit quotas are chosen simultaneously: (i) uncoordinated policy making; and (ii) fully coordinated policy making. Following Caplan and Silva (2005), in all games examined in this paper, we assume that environmental policy with respect to sulfur quotas are chosen after the other two types of environmental policy instruments. One can explain this on the basis that our analysis concerns likely future events when climate change policies receive priority in environmental policy making. This is a global setting in which there is global consensus that climate change dangers need to be addressed and in which nations are endowed with various instruments to control the negative effects caused by climate change. The main purpose of this paper is to examine strategic effects for the mostly likely environmental policy scenarios in such a futuristic world.

In the next two games, we examine sequential choices of SRM and carbon quotas, but the nations make simultaneous choices of SRM provision or carbon pollution quotas. These games consist of three stages. In game III, the nations make choices with respect to carbon quotas in the first stage, make choices with respect to SRM provision in the second stage and make choices with respect to sulfur quotas in the last stage. In game IV, the first stage consists of simultaneous SRM choices and the second stage of simultaneous choices of carbon quotas.

The last two games consider the effects of policy leadership in carbon or SRM policy. These are four stage games. In game V, a nation chooses its carbon quota in the first stage, the other nation chooses its carbon quota in the second stage, and the two nations simultaneously choose sulfur quotas in the last stage. In game VI, a nation chooses its SRM provision in the first stage, and the two nations simultaneously choose carbon quotas in the third stage and sulfur quotas in the last stage.

We have several important findings. We show that if both nations simultaneously commit to carbon permit policies, national SRM levels rise with the carbon quotas. The global temperature rises following each unit increase in the global carbon quota. If, on the other hand, both nations simultaneously commit to SRM policies, national carbon quotas rise with national SRM levels. The global temperature falls following each unit increase in the global SRM level. We also find that a nation always has an incentive to be a policy leader in either carbon or SRM policy. For various values of parameters of utility and technological functions, we can also show that a nation prefers being a leader in carbon policy to being a leader in SRM policy, but the globe prefers leadership in SRM policy to leadership in carbon policy. In addition, the globe prefers simultaneous policy commitments in SRM policy to simultaneous policy commitments in carbon policy. As for SRM provision, we show that it is overprovided whenever carbon policy is determined prior to SRM policy and it is underprovided otherwise. Global carbon emissions are always larger than the globally efficient amount, but the second lowest level of global carbon emissions is observed in the setting in which there is leadership in SRM policy. Carbon emissions follow the same pattern as sulfur emissions.

The remainder of the paper is organized as follows. Section 3 describes the general equilibrium framework, Section 4 provides the analysis for the various policy games, Section 5 considers whether or not the settings involve first-mover advantage, Section 6 offers key results of comparisons across equilibria, and Section 7 concludes.

### 3. General equilibrium framework

Consider a global economy that, for simplicity, consists of two nations, indexed by \( j = 1, 2 \). We normalize the population of each nation, letting it be equal to 1. We assume that both nations suffer from droughts caused by solar radiation management (SRM), global warming caused by emissions of carbon dioxide and acid rain caused by emissions of sulfur dioxide. Carbon dioxide and sulfur dioxide emissions are by-products of energy production in each nation. Solar radiation management, through injections of sulfur aerosols, is provided by each national government.

Let \( H^j(C, M) \) denote the harm function associated with global warming in each nation, where \( C = \sum_{j=1}^{2} C_j \) and \( M = \sum_{j=1}^{2} M_j \) are global levels of carbon dioxide and SRM, respectively. For concreteness, we shall assume that \( H^j(C, M) = h^j(C - M)^2 \), where \( h^j > 0 \). Let \( H^j(y_j, S_j) \) be the harm function of acid rain deposition in nation \( j \), where \( S_j \) is the level of sulfur dioxide in nation \( j \) and \( \theta_j \equiv (0,1)_{j=1,2} \) denotes its sensitivity rate to acid rain damage. We assume that \( H^j(y_j, S_j) = h^j y_j S_j \), where \( h^j > 0 \). The drought damage caused by SRM in nation \( j \) is represented by \( H^j(y_j, M_j) \), where \( \delta_j \equiv (0,1)_{j=1,2} \) denotes its sensitivity to drought damage. We assume that \( H^j(y_j, M_j) = \delta_j h^j M_j^2 \), where \( h^j > 0 \). Nation \( j \)’s total level of environmental damages is

\[
H_j = H_j(C, M, S_j) = H^j(C, M) + H^j(y_j, S_j) + H^j(y_j, M_j).
\]

The representative consumer in nation \( j \) consumes \( x_j \) units of composite good (numeraire), \( e_j \) units of energy and is harmed by \( H_j \) units of environmental damages. Let \( u(x_j, e_j, H_j) \) denote consumer \( j \)’s utility function. Assume that \( u_j \) is quasi-linear (linear in \( x_j \)), and increasing and strictly concave in \( e_j \). More precisely, we assume that \( u(x_j, e_j, H_j) = x_j + f(e_j) - H_j \) where \( f(e_j) = e_j(b - a e_j) \) and \( b \geq 1 > a > 0 \).\(^6\) The representative consumer’s income is denoted \( w_j \), where

\[
w_j = \bar{x}_j + p_C Q_{C_j} + p_S Q_{S_j} + \pi_j - K^M(M_j).
\]

The consumer is initially endowed with \( \bar{x}_j \) units of the numeraire good, is the sole shareholder of profits earned by her nation’s energy industry, \( \pi_j \) is the recipient of the revenues generated with sale of pollution permits, \( p_C Q_{C_j} + p_S Q_{S_j} \) (\( p_C \) and \( p_S \) are prices of carbon and sulfur permits and \( Q_{C_j} \) and \( Q_{S_j} \) are the carbon and sulfur quotas in nation \( j \)) and pays a tax equal to her nation’s cost of provision of SRM, \( K^M(M_j) \). We shall assume that \( K^M(M_j) = K^M M_j^2 \), where \( 1 > K^M > 0 \). For future use, it is important to note that \( C = Q_{C_1} + Q_{C_2} = Q_C \) and \( S_j = Q_{S_j}, j = 1, 2 \).

Throughout, we assume that markets are competitive, with consumers and energy firms taking prices as given. Consumers also take their incomes and the levels of pollution damages as given. Consumer \( j \) chooses non-negative \((x_j, e_j)\) to maximize \( u(x_j, e_j, H_j) \) subject to \( x_j + p_e e_j = w_j \), where \( p_e \) is nation \( j \’s \) energy price. This is equivalent to choosing \( e_j \geq 0 \) to maximize \( f(e_j) - p_e e_j \). Assuming interior solutions, the first-order condition is:

\(^6\) Quadratic pollution damage functions are widely used in the environmental economics literature that considers game-theoretic applications (see, e.g., Nagase and Silva (2000)). Provided the damage functions are strictly convex, the nations’ policies will be strategic. The results with different strictly convex specifications of the damage functions will be qualitatively identical to the ones we obtain in this paper.

\(^7\) The quasi-linear utility function characterization is frequently used in general-equilibrium models because of its desirable aggregation properties (demand side). In addition, quasi-linearity together with the assumption that the utility function from energy consumption is quadratic yields a linear demand function for energy. This type of demand function is commonly used in the regulation literature. The assumption that the utility function is separable in energy consumption and pollution damages is also standard in the environmental economics literature.
\[ f'(e_j) - p_{e_j} = 0. \] (3)

Condition (3) informs us that the optimal level of energy to be consumed is the one at which the marginal utility from energy equates the price of energy. Since the second-order condition is \( f''(e_j) = -2a > 0 \), the solution to the consumer’s maximization problem is unique. Equation (3) yields \( e_j(p_{e_j}) = (b - p_{e_j})/2a \), consumer \( j \)'s energy demand. Her demand for the numeraire good is \( x_j(p_{e_j}, w_j) = w_j - p_{e_j} e_j(p_{e_j}) \) and \( v_j(p_{e_j}, w_j, H_j) = x_j(p_{e_j}, w_j) + f(e_j(p_{e_j})) - H_j \) is her indirect utility function.

In nation \( j \), the energy industry’s profit function is.

\[
\pi_j(E_j, R_C, R_S) = p_{e_j} E_j - p_{c_j} (E_j - R_C) - p_{s_j} (E_j - R_S) - K^c(E_j) - K^c(R_C) - K^s(R_S) 
- p_{e_j} E_j - p_{c_j} \Delta^c(E_j, R_C) - p_{s_j} \Delta^s(E_j, R_S) - K^c(E_j) - K^c(R_C) - K^s(R_S),
\]

where \( E_j, R_C, \) and \( R_S \) are levels of energy production, carbon dioxide reduction and sulfur reduction, respectively. We denote by \( \Delta^c(E_j, R_C) \equiv E_j - R_C \) and \( \Delta^s(E_j, R_S) \equiv E_j - R_S \) the quantities of carbon and sulfur permits demanded by nation \( j \)'s energy industry, respectively. To simplify notation, we shall assume that the size of the energy industry in each nation is equal to 1 and thus refer to it as an energy “firm”. We also assume that the costs of energy production, carbon dioxide reduction and sulfur dioxide reduction are \( K^c(E_j) = k^c E_j^2 \), \( K^c(R_C) = k^c R_C^2 \) and \( K^s(R_S) = k^s R_S^2 \), where \( 1 > k^c > 0 \), \( 1 > k^s > 0 \), and \( 1 > k^s > 0 \). Each firm chooses non-negative \( (E_j, R_C, R_S) \) to maximize \( \pi_j \) taking all prices as given. The first-order conditions for interior solutions are

\[
p_{e_j} - p_{c_j} = p_{c_j} \frac{dK^c}{dE_j} = 0, \] (4a)
\[
p_{c_j} - p_{c_j} \frac{dK^c}{dR_C} = 0, \] (4b)
\[
p_{s_j} - p_{c_j} \frac{dK^s}{dR_S} = 0. \] (4c)

Condition (4a) informs us that the optimal amount of energy to be produced in a nation should equate the marginal revenue to the sum of marginal production and regulatory costs of energy production. Equation (4b) states that the optimal level of carbon abatement should equate the marginal revenue from carbon abatement (i.e., the marginal cost saving in expenditure on carbon permits) to the marginal cost of carbon abatement. Equation (4c) is similar; it equates marginal revenue from sulfur abatement to the marginal cost of sulfur abatement.

Solving the system of equations (4a) to (4c), we obtain nation \( j \)'s energy supply function, \( E_j(p_{e_j}, p_{c_j}, p_{s_j}) = (p_{e_j} - p_{c_j} - p_{s_j})/2k^2 \), and the carbon and sulfur abatement supply functions, \( R_C(p_{c_j}) = p_{c_j}/2k^2 \), and \( R_S(p_{s_j}) = p_{s_j}/2k^3 \), respectively. Thus, we have (for \( j = 1, 2 \))

\[
\frac{\partial E_j}{\partial p_{e_j}} = \frac{\partial E_j}{\partial p_{c_j}} = \frac{\partial E_j}{\partial p_{s_j}} = \frac{1}{2k^2} > 0, \] (5a)
\[
\frac{dR_C}{dP_{c_j}} = \frac{1}{2k^2} > 0, \] (5b)
\[
\frac{dR_S}{dP_{s_j}} = \frac{1}{2k^2} > 0. \] (5c)

As expected, conditions (5a) inform us that each energy firm’s supply function is increasing the price of energy and decreasing in the prices of carbon and sulfur permits. Conditions (5b) reveal that each firm supplies more carbon abatement as the price of the carbon permit in its nation increases. Conditions (5c) are similar to conditions (5b): they state that each firm produces more sulfur abatement as the price of its nation’s sulfur permit increases. Combining the definitions of the quantities of carbon and sulfur permits demanded with conditions (5a) – (5c) yields.

\[
\frac{\partial \Delta^c}{\partial p_{e_j}} = \frac{\partial \Delta^c}{\partial p_{c_j}} = \frac{\partial \Delta^c}{\partial p_{s_j}} = \frac{1}{2k^2} > 0, \] (5d)
\[
\frac{\partial \Delta^c}{\partial p_{c_j}} = \frac{\partial \Delta^c}{\partial p_{s_j}} = \frac{1}{2k^2} - \frac{1}{2k^2} < 0, \] (5e)
\[
\frac{\partial \Delta^s}{\partial p_{s_j}} = \frac{1}{2k^2} - \frac{1}{2k^2} < 0. \] (5f)

Conditions (5d) inform us that the quantities of carbon and sulfur permits demanded rise with the price of energy. This is natural since the firms will expand energy production as the price of energy increases. Conditions (5d) also reveal the quantities of carbon and sulfur permits demanded are complements, since the quantity of carbon permits demanded by firm \( j \) falls as the price of nation \( j \)’s sulfur permit rises and the quantity of sulfur permits demanded by firm \( j \) falls as the price of nation \( j \)’s carbon permit rises. Conditions (5e) and (5f) state that the demands for carbon and sulfur permits fall as their respective prices increase.

Market-clearing conditions for the national energy market, and carbon and sulfur permit markets, respectively, are as follows:

\*The cost functions are assumed to be quadratic for tractability purposes and in order to generate linear supply functions. Provided the cost functions are increasing and strictly convex and the marginal willingness to pay for the energy good is sufficiently high, an interior and unique equilibrium is guaranteed. The results under other strictly convex specifications of the costs functions will be qualitatively identical to the ones we obtain in the text.
Furthermore, we define the following conditions:

\[ pS_j = \frac{b(k^C + k^E + k^S)}{a + k^E + k^C + k^S}. \]  

(6a)

\[ pC_j = \frac{b(k^C - 2k^E(k^C_j + k^S_j))}{a + k^E + k^C + k^S}. \]  

(6b)

\[ pS_j = \frac{2k^C k^S_j}{a + k^E + k^C + k^S}. \]  

(6c)

Conditions (6a) inform us that in each nation the demand for energy must be equal to the supply of energy. Conditions (6b) state that in each nation, the demand for carbon permits must be equal to the supply of carbon permits. Conditions (6c) are similar to conditions (6b): in each nation, the demand for sulfur permits equals the supply of sulfur permits. Solving the system of equations (6a)–(6c), we obtain the price functions in terms of pollution quotas:

\[ pS_j(QC_j, QS_j) = \frac{b(k^C + k^E + k^S)}{a + k^E + k^C + k^S}. \]  

(7a)

\[ pC_j(QC_j, QS_j) = \frac{bk^C - 2k^E(k^C_j + k^S_j)}{a + k^E + k^C + k^S}. \]  

(7b)

\[ pS_j(QC_j, QS_j) = \frac{bk^C + 2k^E(k^C_j - (a + k^E + k^S_j))}{a + k^E + k^C + k^S}. \]  

(7c)

Then the following comparative static results are immediate:

\[ \frac{\partial pS_j}{\partial QC_j} = -\frac{2bk^C}{a + k^E + k^C + k^S} < 0, \]  

(8a)

\[ \frac{\partial pC_j}{\partial QC_j} = \frac{2k^C(a + k^E + k^S)}{a + k^E + k^C + k^S} < 0, \]  

(8b)

\[ \frac{\partial pS_j}{\partial QS_j} = \frac{2k^C k^S}{a + k^E + k^C + k^S} > 0, \]  

(8c)

\[ \frac{\partial pC_j}{\partial QS_j} = \frac{2k^C k^S}{a + k^E + k^C + k^S} > 0, \]  

(8d)

\[ \frac{\partial pS_j}{\partial QC_j} = \frac{2k^C(a + k^E + k^S)}{a + k^E + k^C + k^S} < 0, \]  

(8e)

\[ \frac{\partial pC_j}{\partial QS_j} = \frac{2k^C(a + k^E + k^S)}{a + k^E + k^C + k^S} < 0. \]  

(8f)

We summarize our findings about the equilibrium price functions in the following proposition.

**Proposition 1.** \[ \frac{\partial pS_j}{\partial QC_j} < 0, \frac{\partial pC_j}{\partial QC_j} > 0, \frac{\partial pS_j}{\partial QS_j} < 0, \frac{\partial pC_j}{\partial QS_j} > 0 \] and \[ \frac{\partial pS_j}{\partial QC_j} < 0, \] \( j = 1, 2. \)

We are now ready to write consumer \( j \)'s indirect utility as function of pollution quotas and SRM provision levels:

\[ v_j(QC_j, QC_{-j}, QS_j, M_j, M_{-j}) = x_j + f_j(p_{jS}) - K^S_j(E_j(p_{jS}, p_{Cj}, p_{C_{-j}})) - K^C_j(R_{C_j}(p_{Cj})) - K^E_j(R_S(p_S)) - K^M_j(M_j) - H_j^A(\theta_j, QS_j) - H_j^T(QC_j, M_j) - H_j^D(\delta_j, M). \]

(9)

where \( p_{ej} = p_{jS}(QC_j, QS_j), p_{Cj} = p_{Cj}(QC_j, QS_j), \) \( p_S = p_S(QC_j, QS_j) \) and \( M = M_j + M_{-j}, j = 1, 2. \) We let \( -j = 1 \) if \( j = 2 \) and \( -j = 2 \) if \( j = 1. \)

### 4. Effects of environmental policy commitments

We now examine the effects of timing in environmental policy making. We consider six sequential policy games as described below. In all games, we assume that the national governments select their sulfur quotas at the last stage. The equilibrium concept utilized is subgame perfection. Table 1 summarizes the timings of the six games considered in the analysis.

We establish two benchmarks under which policy making on carbon quotas and SRM levels occur simultaneously in the first stage of two-stage games: (1) uncoordinated policy making; and

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Environmental policy games.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Timing</td>
<td>Descriptions</td>
</tr>
<tr>
<td>Simultaneous SRM and Carbon Quotas</td>
<td>The four choices, both nations' carbon quotas and SRM levels, are made simultaneously.</td>
</tr>
<tr>
<td>1) Uncoordinated</td>
<td>Carbon quotas and SRM levels are coordinated between the two nations, respectively.</td>
</tr>
<tr>
<td>2) Coordinated</td>
<td>Carbon quotas and SRM levels are uncoordinated between the two nations, respectively.</td>
</tr>
<tr>
<td>Sequential SRM and Carbon Quotas</td>
<td>No National Leadership</td>
</tr>
<tr>
<td>3) First Stage: Carbon Quotas</td>
<td>Nations decide carbon quotas simultaneously in the first stage and choose SRM levels simultaneously in the second stage.</td>
</tr>
<tr>
<td>4) First Stage: SRM Levels</td>
<td>Nations choose SRM levels simultaneously in the first stage and decide carbon quotas simultaneously in the second stage.</td>
</tr>
<tr>
<td>National Leadership</td>
<td>5) First Stage: Nation 1's Carbon Quota</td>
</tr>
<tr>
<td></td>
<td>In the first stage, nation 1 decides its carbon quota, followed by nation 2's carbon decision in the second stage. Both nations choose SRM levels simultaneously in the third stage.</td>
</tr>
<tr>
<td></td>
<td>6) First Stage: Nation 1's SRM Level</td>
</tr>
<tr>
<td></td>
<td>In the first stage, nation 1 chooses its SRM level, followed by nation 2's SRM choice in the second stage. Both nations decide carbon quotas simultaneously in the third stage.</td>
</tr>
</tbody>
</table>

**Table 2**

Main results of baseline comparisons across equilibria

<table>
<thead>
<tr>
<th>Rankings</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
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<td>IV</td>
<td>VI</td>
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<td>III</td>
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<tr>
<td>v_1</td>
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<td>VI</td>
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<td>VI</td>
<td>III</td>
<td>V</td>
</tr>
<tr>
<td>H^A</td>
<td>V</td>
<td>III</td>
<td>I</td>
<td>IV</td>
<td>VI</td>
<td>V</td>
</tr>
<tr>
<td>H^B</td>
<td>V</td>
<td>III</td>
<td>I</td>
<td>IV</td>
<td>VI</td>
<td>V</td>
</tr>
<tr>
<td>H^D</td>
<td>V</td>
<td>III</td>
<td>I</td>
<td>IV</td>
<td>VI</td>
<td>V</td>
</tr>
</tbody>
</table>


(2) coordinated policy making. Sulfur quotas are chosen simultaneously in the second stage of the game. These benchmarks will enable us to capture both the effects caused by the timing of policy making and the effects caused by non-cooperative behavior (i.e., departures from socially efficient behavior). The next two sequential games involve simultaneous choices of either (3) pollution quotas; or (4) SRM levels; in the first stage, with simultaneous choices of either SRM (in game (3)) or pollution quotas (in game (4)) in the second stage. Thus, unlike the games in which pollution quotas and SRM are chosen simultaneously, games (3) and (4) involve three stages, since sulfur quotas are simultaneously chosen in the third stage of the game. The last two sequential games involve four stages. In game (5), nation 1 chooses its carbon quota in the first stage, nation 2 chooses its carbon quota in the second stage, SRM levels are chosen simultaneously in the third stage and sulfur quotas are chosen simultaneously in the fourth stage. In game (6), nation 1 chooses its sulfur level in the first stage, nation 2 chooses its sulfur level in the second stage, carbon quotas are chosen simultaneously in the third stage and sulfur quotas are chosen simultaneously in the fourth stage.

Consider the last stage of any game, namely, the stage in which the nations choose sulfur quotas simultaneously after having observed the other policy choices, \((Q_{Sj}, M_j, M_{-j})\). The optimization problem faced by nation j’s government is to choose non-negative \(Q_{Sj}\) to maximize the national indirect utility function (9), taking \(Q_{Sj}\) as given. Assuming interior solutions, we obtain the following first-order conditions:

\[
\frac{\partial H^j}{\partial Q_{Sj}} = 0, \quad j = 1, 2. \tag{10}
\]

Conditions (10) inform us that in each nation the amount of sulfur quota should be set at the level that equates the national permit price to the national marginal damage caused by acid rain. Since \(H^j = h^j Q_{Sj}^2\), we have:

\[
Q_{Sj} = \frac{p_{Sj}}{2h^j}, \quad j = 1, 2. \tag{11}
\]

Substituting equation (11) into (7a)-(7c) yields

\[
Q_{Sj} = \frac{k^2 (b + 2k^2 Q_{Cj})}{2[k^2(a+k^2+k^2)+h^j \theta_j(a+k^2+k^2+k^2)]}. \tag{12a}
\]

\[
p_{Sj} = \frac{b[k^2(a+k^2+k^2)+h^j \theta_j(a+k^2+k^2+k^2)-2ak^2(k^2+h^j \theta_j)Q_{Cj}]}{k^2(a+k^2+k^2)+h^j \theta_j(a+k^2+k^2+k^2)}, \tag{12b}
\]

\[
p_{Cj} = \frac{k^2 [b(k^2+h^j \theta_j)-2[k^2(a+k^2)+h^j \theta_j(a+k^2+k^2)]]Q_{Cj}}{k^2(a+k^2+k^2)+h^j \theta_j(a+k^2+k^2+k^2)}, \tag{12c}
\]

\[
p_{Cj} = \frac{k^2 h^j \theta_j (b + 2k^2 Q_{Cj})}{k^2(a+k^2+k^2)+h^j \theta_j(a+k^2+k^2+k^2)}. \tag{12d}
\]

Hence, we can now obtain comparative static results when sulfur quotas are chosen optimally by the national governments:

\[
\frac{\partial p_{Cj}}{\partial Q_{Cj}} = -\frac{2ak^2(k^2+h^j \theta_j)}{k^2(a+k^2+k^2)+h^j \theta_j(a+k^2+k^2+k^2)} < 0, \tag{13a}
\]

\[
\frac{\partial p_{Sj}}{\partial Q_{Cj}} = \frac{2k^2 h^j \theta_j}{h^j (a+k^2+k^2+k^2)} > 0, \tag{13b}
\]

\[
\frac{\partial p_{Sj}}{\partial Q_{Cj}} = \frac{k^2}{k^2(a+k^2+k^2)+h^j \theta_j(a+k^2+k^2+k^2)} > 0. \tag{13c}
\]

Unlike in Proposition 1, the sulfur quotas are now adjusted optimally when the carbon quotas are increased. Condition (13d) informs us that a nation’s sulfur and carbon quotas are strategic complements. As a nation’s carbon quota increases, its sulfur quota is also increased, implying that the inelastic curve representing the supply of sulfur permits shifts to the right when the carbon quota is increased. Since, as we have discussed after Proposition 1, the demand for sulfur permits shifts out when the carbon quota is increased, the final effect of increasing the carbon quota on the sulfur permit price is potentially ambiguous. However, as condition (13c) demonstrates, the net effect on the sulfur permit price is positive. The optimal adjustment in the sulfur quota reduces but does not eliminate the hike in the sulfur permit price relative to a situation where sulfur quota is not adjusted at all (i.e., when the sulfur quota policy is exogenous). The net effects of an increase in the carbon quota on the energy and carbon permit prices captured by conditions (13a) and (13b), respectively, are the expected ones.

4.1. Game I: simultaneous choices of carbon quotas and SRM levels

In the first stage, the government of nation j chooses non-negative \((Q_{Cj}, M_j)\) to maximize (9) subject to \(Q_{Sj} = Q_{Cj}(Q_{Cj}; \theta_j)\), taking \((Q_{Cj}, M_{-j})\) as given. Assuming interior solutions, the set of first-order conditions are (for \(j=1,2\)):

\[
p_{Cj} = \frac{\partial H^j}{\partial Q_{Cj}}. \tag{14a}
\]

\[
\frac{dH^j}{dM} \frac{dM^j}{dM} + \frac{dH^j}{dM} = 0. \tag{14b}
\]

Conditions (14a) reveal that the carbon quota in nation j should be set at the level that equates the national carbon permit price to the national marginal damage of global warming. Conditions (14b) are similar in spirit, since the level of SRM that should be provided at nation j is the one under which the national marginal benefit from SRM provision is equal to the national marginal cost. The latter is the sum of the marginal cost of provision and the marginal damage caused by droughts in nation j.

Since \(H^j = h^j (C-M)^2\), \(H^j = \delta h^j P M^2\) and \(K^M = k^M M^2\), equation (14b) yield:

\[
M_j = \frac{h^j Q_{Cj} [k^M + h^j (\delta_{-j} - \delta_j)]}{k^M (2k^D + 2h^j + k^M)} \tag{15}
\]

where \(-j=2\) if \(j=1\) and vice versa. Equation (15) make it clear that the assumption that the equilibrium is interior requires us to consider situations where the national sensitivity indexes associated with the damage functions from droughts are not too different from each other. Henceforth, we shall assume that
\[ \delta_2 + (\frac{\partial M}{\partial D}) \geq \delta_1 \] Furthermore, given our assumptions, the sufficient second order condition for this game is satisfied. The equilibrium is unique.39

### 4.2. Game II: simultaneous coordinated choices

Suppose now that there is full coordination between the two nations regarding the choices of carbon quotas and SRM levels in the first stage of the game. Assume that a utilitarian bi-national environmental agency chooses non-negative \( (Q_c, Q_{c,1}, M_c, M_{1,2}) \) to maximize global indirect utility \( V(\cdot) = v_1(\cdot) + v_2(\cdot) \) (where \( v_1(\cdot) \) and \( v_2(\cdot) \) correspond to function (9) by setting \( j = 1,2 \), respectively) subject to (12a). Assuming interior solutions, the first-order conditions are as follows (\( j = 1,2 \)):

\[
p_c = 2 \left( \frac{\partial H_T}{\partial Q_c} \right),
\]

\[
-2 \frac{\partial H_T}{\partial M} = \frac{dH_{M,1}}{dM_1} + \sum_{j=1}^{2} \frac{dH_{M,j}}{dM_j},
\]

Conditions (16a) tell us that the amount of carbon quotas in nation \( j \) is chosen to equate the national carbon permit price to the social marginal damage of global warming - that is, the sum of the national marginal damages from global warming. Conditions (16b) state that nation \( j \) should provide SRM at a level that equals the global marginal benefit from SRM provision (i.e., the sum of national marginal benefits from a reduction in the global temperature) to the global marginal cost of SRM provision (i.e., the sum of national marginal production cost and the sum of national marginal damages from droughts caused by SRM provision).

### 4.3. Game III: simultaneous commitments on carbon permit policies

Having observed \( (Q_c, Q_{c,1}) \), government \( j \) chooses non-negative \( M_j \) to maximize its indirect utility function (9), subject to (12a), taking \( M_{1-j} \) as given in the second stage. Assuming interior solutions, the first-order conditions yield equation (15). These best-response functions reveal that SRM provision in nation \( j \) expands with the global quantity of carbon dioxide. Adding the best-response functions, one gets the global SRM level as function of the global carbon dioxide quantity. The global SRM quantity rises with the global carbon dioxide quantity, but at a rate that is less than one.40

In the first stage, the first-order conditions are (\( j = 2 \) if \( j = 1 \) and vice versa):

\[
P_c = \frac{\partial H_T}{\partial Q_c} + \left( \frac{\partial H_T}{\partial M} + \frac{dH_{M,j}}{dM} \right) \frac{\partial M_{1-j}}{\partial Q_c} \tag{17}
\]

Conditions (17) inform us that the optimal carbon quota level for each nation is the one that equates the slope of the nation’s iso-

utility curve, \( \left( \frac{p_c - \frac{\partial u}{\partial Q_c}}{\frac{\partial u}{\partial Q_c} + \frac{\partial u}{\partial M}} \right) \) to the slope of the best response function of the other nation, \( \frac{\partial M_{1-j}}{\partial Q_c} \).

### 4.4. Game IV: simultaneous commitments on SRM policies

Having observed \( (M_c, M_{1,2}) \), government \( j \) selects non-negative \( Q_c \) to maximize its indirect utility function (9) subject to (12a), taking \( Q_{c,1} \) as given, in the second stage. The first-order conditions are equation (14a). Differentiating each equation (14a) with respect to \( M \) yields:

\[
\frac{\partial Q_c}{\partial M} = -2h_T \left( \frac{\partial u_c}{\partial Q_c} + \frac{\partial u_c}{\partial Q_{c,1}} \right) > 0,
\]

where the sign of the each of the two equations in (18) follows from the facts that both the denominator and the numerator of the ratio in the right side of each equation (18) are positive - see Proposition 2. Note that each nation’s carbon quota rises with the global SRM level at a rate that is less than one. In addition, it also follows that the global carbon emission level rises at a rate that is less than one when the global SRM level expands. Thus, an expansion in global SRM leads to a net decrease in the global temperature!

In the first stage, the first-order conditions are (\( j = 1,2, \text{ } -j \neq j \)):

\[
\frac{dH_T}{dM} + \frac{dH_{M,j}}{dM_j} + \frac{dH_{M_{1-j}}}{dM_{1-j}} + \frac{\partial H_T}{\partial Q_c} \frac{\partial Q_c}{\partial M} = 0.
\]

Equation (19) tell us that the optimal SRM level for each nation is the one at which the slope of the nation’s indifference curve, \( -\left( \frac{\partial u_c}{\partial Q_c} + \frac{\partial u_c}{\partial Q_{c,1}} \right) \) is equal to the slope of the best response function of nation \( -j \), \( \frac{\partial u_c}{\partial Q_{c,j}} \). We can summarize the temperature outcomes of the sequential games as follows.

#### Proposition 2

If both nations simultaneously commit to carbon permit policies, national SRM levels rise with the carbon quotas. The global temperature rises following each unit increase in the global carbon quota. If both nations simultaneously commit to SRM policies, national carbon quotas rise with national SRM levels. The global temperature falls following each unit increase in the global SRM level.

### 4.5. Game V: national leadership in carbon permit policy

In this game, nation 1 is the leader in carbon policy. Nation 2 observes the carbon quota chosen by nation 1 and chooses its carbon quota in the second stage. In the third stage, both nations choose SRM levels simultaneously. In the fourth stage, both nations choose sulfur quotas simultaneously. Thus, this game adds one stage to the timing of game III. Relative to the policy setting captured by game III, it enables us to discover the effects associated with a nation being a leader in carbon policy.

Having observed \( Q_{c,1} \), nation 2 chooses non-negative \( Q_c \) to maximize its payoff function subject to (12a) and (15). The first- and second-order conditions for the problem solved by government 2 are the same as in the first stage of game III. Hence, we can get \( Q_{c,2}(Q_{c,1}) \) from condition (17):

---

39 The sufficient second order conditions are satisfied in all games examined in this paper. Hence, the equilibrium for each game is unique. These results are available from the authors upon request.

40 As stated in the introduction, SRM provision and reduction of carbon emissions are impure public goods in our model. They are imperfect substitutes as equation (15) reveal. Our paper contributes to the public economics literature by considering the strategic interactions between these two impure public goods. It is also important to notice that the imperfect substitutability between the two impure public goods is not implied by our modeling assumptions with respect to the functional forms of damage and cost functions. It follows from the facts that there are national-specific benefits associated with expansions in carbon emissions (consumer surplus produced by energy consumption) and national-specific costs associated with expansions in SRM provision (damages from droughts).
\[ \frac{\partial Q_2}{\partial Q_1} = \left( \frac{\partial \bar{v}_2}{\partial v_2} \right) \left( \frac{\partial^2 v_2}{\partial Q_1^2} \right) - 1. \]  

(20)

It is straightforward to show that \( 0 < \left( \frac{\partial \bar{v}_2}{\partial v_2} \right) < 1 \). Thus, equation (20) yields \(-1 < \partial Q_2/\partial Q_1 < 0\). Each unit increase in nation 1’s carbon quota leads to a reduction in nation 2’s carbon quota at a rate smaller than one. The net effect of each unit increase in nation 1’s carbon quota is an increase in global carbon emissions and a subsequent increase in the global temperature.

Consider now the first stage. The first-order condition for an interior solution is:

\[ P_C - \left[ \frac{\partial H^T}{\partial Q_C} + \left( \frac{\partial H^T}{\partial M} + \frac{\partial H^D}{\partial M} \right) \right] \left( 1 + \frac{\partial Q_C}{\partial Q_C} \right) = 0. \]  

(21)

Condition (21) informs us that the optimal quota level for nation 1 is determined by the condition that equates indirect utility, subject to (14a) and (14b). The first- and second-order conditions are the same as in the first stage of game IV. Then we can obtain \( M_2(M_1) \) from condition (20). Hence,

\[ \frac{\partial M_2}{\partial M_1} = -\frac{h^D(\delta_1 + \delta_2) + 2h^T \left( 1 - \frac{\partial \bar{v}_2}{\partial Q_1} \right) \left( 1 - \frac{\partial Q_C}{\partial Q_1} \right)}{2k^M + \frac{h^D(\delta_1 + \delta_2) + 2h^T \left( 1 - \frac{\partial \bar{v}_2}{\partial Q_1} \right) \left( 1 - \frac{\partial Q_C}{\partial Q_1} \right)}{2}} < 0. \]  

(22)

Condition (22) reveals that SRM levels are strategic substitutes and that the rate of substitution is less than one in absolute value.

In the first stage, nation 1 determines \( M_1 \) to maximize its indirect utility, subject to (14a) and \( Q_C(M) \). The first- and second-order conditions are the same as in the first stage of game IV. Then we can obtain \( M_2(M_1) \) from condition (20). Hence,

\[ \frac{\partial M_2}{\partial M_1} = -\frac{h^D(\delta_1 + \delta_2) + 2h^T \left( 1 - \frac{\partial \bar{v}_2}{\partial Q_1} \right) \left( 1 - \frac{\partial Q_C}{\partial Q_1} \right)}{2k^M + \frac{h^D(\delta_1 + \delta_2) + 2h^T \left( 1 - \frac{\partial \bar{v}_2}{\partial Q_1} \right) \left( 1 - \frac{\partial Q_C}{\partial Q_1} \right)}{2}} < 0. \]  

(23)

Condition (23) shows that the optimal SRM level for nation 1 is determined by the tangency condition which states that the slope of nation 1’s indifference curve, \( \frac{\partial M_2}{\partial M_1} / \left( \frac{\partial \bar{v}_2}{\partial Q_1} + \left( \frac{\partial h^D}{\partial Q_1} + \frac{\partial \bar{v}_2}{\partial Q_1} \right) \right) - 1 \), is equal to the slope of nation 2’s best response function, \( \frac{\partial M_2}{\partial M_1} \).

5. First-mover advantage

We now demonstrate that a nation always benefits from being a policy leader, either in carbon policy or in SRM policy. Consider carbon policy first. By being a leader in carbon policy, nation 1 selects its optimal quantity in game V on firm 2’s reaction curve. Thus, the choice nation 1 makes in game III (in which carbon policies are chosen simultaneously) is available to this nation when it makes its choice in game V. Since nation 1 selects a different carbon quantity quota in the equilibrium of game V and the equilibrium for this game is unique, nation 1 strictly prefers the carbon quota of game V to the carbon quota of game III. This is a revealed preference argument. Revealed preference and the fact that the equilibrium for game VI is unique also implies that nation 1 strictly prefers the choice it makes in game VI to the choice it makes in game IV. Thus, nation 1 strictly prefers to move first in each type of policy to moving simultaneously with nation 2.

We now demonstrate that nation 1 prefers to be the leader than to be the follower. As before, it is straightforward to show that:

\[ \frac{\partial Q_C}{\partial Q_C} < 0, \]  

(24)

\[ \frac{\partial M_1}{\partial M_2} < 0. \]  

(25)

Result (24) informs us that carbon quotas are strategic substitutes. Result (25) informs us that SRM levels are strategic substitutes. Hence, we have the following facts:

\[ H^T = h^T(C - M)^2 \]

\[ C = Q_C^1 + Q_C^2 \]

are technologically perfect substitutes. (i)

\[ H^D = \delta h^D M^2 \]

\[ M = M_1 + M_2 \]

are technologically perfect substitutes. (ii)

Conditions (21) and (25) \( \Rightarrow Q_C^1 \) and \( Q_C^2 \) are strategic substitutes. (iii)

Conditions (23) and (26) \( \Rightarrow M_1 \) and \( M_2 \) are strategic substitutes. (iv)

Proposition 3. Given (i) and (iii), a nation always prefers to be the leader rather than the follower in carbon quota policy. Given (ii) and (iv), a nation always prefers to be the leader rather than the follower in SRM policy.  

Proof. It is a direct application of Varian's proof for the preference of quantity leadership in duopoly games. See Varian (1992), p. 297.

Together with the revealed preference results, we can affirm:

Proposition 4. A nation always prefers to move first in either type of policy, carbon quota or SRM.

6. Comparisons across equilibria

Proposition 4 is important because it enables us to predict that, under our modeling assumptions, a nation will always attempt to be the leader in climate change policies. We are, however, unable to predict whether the leader has a policy preference. We now assign specific values to parameters of the utility, cost and harm functions in order to compare payoffs across equilibria and then to expand our predictions of play.

6.1. Symmetric economy

We first assume that the economy is symmetric. In this case, drought and acid rain damage functions are identical. In the baseline case, let \( a = 1/2, b = 1, k^C = k^S = k^M = k^F = h^C = h^S = h^M = h^F = h^D = 1/2, \delta_1 = \delta_2 = 1, q_1 = \theta_2 = 1 \) and \( \tau_j = 0, j = 1, 2 \). Solving consumer \( h^D \) and producer \( h^D \) maximization problems, the general equilibrium results in nation \( j \) are: \( e_j = E_j = (1 + Q_C + \)
The rankings of payoffs and environmental damages in descending order (i.e., column 1 displays the highest values and column 6 displays the lowest values) are as follows:

**Proposition 5.** The rankings of payoffs and environmental damages in descending order (i.e., column 1 displays the highest values and column 6 displays the lowest values) are as follows:

**Proof.** It is available from the authors upon request.

The results summarized in Proposition 5 are remarkable. Given the first-move advantage, the most likely non-cooperative scenarios are games V and VI, since these appear as the first and second most preferable options from the point of view of the leader, if we discard the cooperative game II as an option. If, in addition, we allow the leader to choose between leadership in carbon policy and leadership in SRM policy, the leader chooses carbon policy.

Now, consider the ranking for global welfare. Not surprisingly, the highest level of global welfare is obtained at the equilibrium in which carbon and SRM policies are fully coordinated - game II. However, the other ranking positions provide us with very interesting messages for the inefficient allocations: (i) global welfare is higher when SRM policy is determined before carbon policy; (ii) for each type of policy commitment, global welfare is higher when there is no leadership; (iii) SRM policy commitments are superior to no policy commitment and the latter is superior to carbon policy commitments; (iv) SRM policy commitment without national leadership is second best; and (v) policy leadership in carbon policy is the worst scenario for the globe!

The first message follows from two comparisons: (a) between the global welfare levels implied by the equilibrium for games IV and III; and (b) between global welfare levels implied by the equilibria for games IV and VI. The second message follows from the second message and two comparisons: (a) between the global welfare levels implied by the equilibrium for games IV and VI. The third message follows from the second message and two comparisons: (a) between the global welfare levels implied by the equilibrium for games I and III. The comparisons reveal that the global welfare level produced by the equilibrium for game IV is higher than the global welfare level produced by the equilibrium for game I and the latter is higher than the global welfare level produced by the equilibrium for game III. The fourth message is straightforward, since the level of global welfare implied by the equilibrium for game IV is the highest among those produced by the inefficient equilibria. The last message is obvious.

For the inefficient allocations, one can understand the ranking for global welfare if in the comparisons we are able to rationalize the combined effects of policy leadership and “easy riding” on the provision of SRM and on the setting of carbon quotas. Not only the leader (nation 1) receives in the equilibrium for game V the highest payoff obtained by this nation in the set of inefficient games, the payoff received by nation 2 in the equilibrium for game V is the lowest obtained by this nation in the set of inefficient games. The equilibrium for game V features the highest global warming and drought damages, implying that the setting in which nation 1 is a policy leader in carbon policy yields the highest levels of carbon emission and SRM provision. To show this, note that Proposition 6 informs us that \( H^{D^P} > H^{D^P} > H^{D^P} > H^{D^P} > H^{D^P} \). Since \( H^{P^2} = M^2 / 2 \), we have \( M^{II^P} > M^{II^P} > M^{II^P} > M^{II^P} > M^{IV^P} \). Proposition 6 also reveals that \( H^{II^P} > H^{II^P} > H^{II^P} > H^{II^P} > H^{II^P} \). Since \( H^{II^P} = (Q^S - M)^2 / 2 \), we can combine the results to obtain \( Q^S = \max(Q^{II^P}, Q^{II^P}, Q^{II^P}, Q^{II^P}) \).

The equilibrium for game V yields the highest levels of acid rain damage and sulfur dioxide emission in nation 1 - recall that \( H^{II^P} = Q^S - M^{II^P} / 2 \). As clearly revealed by equation (27), the carbon quota in nation 1 is an increasing function of the sulfur quota. Hence, the equilibrium for game V also features the highest level of carbon dioxide emission in nation 1. This setting, therefore, is characterized by overprovision of SRM (i.e., the amount of SRM provided is higher than the globally efficient amount obtained in the equilibrium for game II), the highest degree of easy riding on mitigation of carbon emissions and the highest levels of sulfur and carbon emissions in nation 1.

If we remove the policy leadership status of nation 1 in carbon policy, but still consider a setting in which carbon policy is determined before SRM policy, we are able to capture the effects promoted by leadership in carbon policy by comparing the national outcomes obtained in the equilibria for games III and V. The payoffs for nations 1 and 2 in the equilibrium for game III are the lowest and second lowest payoffs earned by these nations, respectively. Since the global warming and drought damages associated with the equilibrium of game III are smaller than their counterparts in the equilibrium for game V, removing policy leadership in carbon policy reduces global benefits - both the degree of overprovision in SRM and the degree of easy riding in carbon mitigation are reduced. However, there are also national impacts associated with the removal of leadership in carbon policy - acid rain damages are reduced in nation 1 but increased in nation 2, implying that sulfur and carbon emissions in nation 1 are reduced, but sulfur and carbon emissions in nation 2 are increased.

Policy leadership in SRM, on the other hand, is more desirable from a global perspective. Not only the payoff that nation 1 receives in game VI is third best, the payoff earned by nation 2 in the...
equilibrium for game VI is the highest among the inefficient payoffs earned by this nation. The level of drought damage associated with the equilibrium for game VI is the lowest among all scenarios, implying that SRM is underprovided in the equilibrium for game VI.

The level of acid rain damage faced by nation 1 in the equilibrium for game VI is the second lowest among all scenarios. This implies that the degrees of sulfur and carbon emission mitigation in nation 1 are second best. By comparing the equilibria for games V and VI we can capture the effects of switching the type of policy leadership. Since the equilibrium for game V features overprovision of SRM and the highest degree of easy riding in policy leadership. Since the equilibrium for game V features overprovision of SRM and the highest degree of easy riding in carbon and sulfur mitigation in nation 1 and the equilibrium for game VI features suboptimal provision of SRM and second best degrees of mitigation of carbon and sulfur emissions, we see that the policy leader always chooses its policy instruments to minimize its contributions to improving the negative effects promoted by climate change.

The findings illustrated in Proposition 6 yield an interesting policy prescription other than forcing the nations to behave cooperatively. The policy prescription concerns the implementation of a global agreement on SRM policy in full anticipation that the nations will behave non-cooperatively. Provided this agreement leads the nations to make simultaneous commitments with respect to SRM policy, the resulting outcome will be second best for the globe. Even if the agreement is unable to prevent one nation from becoming a leader in SRM policy, the outcome will be superior to the most likely outcome in absence of the agreement – game IV is third best for the globe.

### 6.2. Robustness: asymmetric drought and acid rain damages

The numerical analysis in subsection 6.1 considers symmetric drought and acid rain damage functions. It also assumes identical values for most parameters. In this section, we check whether the rankings of payoffs are robust to differences in drought damages, acid rain damages and changes in the values of some parameters.

The most important results of our analysis in the symmetric case concerned our predictions with respect to the “choice of a scenario” that a policy leader will make and the contrasting (non-cooperative) choice that the globe will make if it can exercise this option. The leader prefers the scenario that arises under game V. The non-cooperative choice of the globe is scenario IV. If the globe is unable to make simultaneous commitments with respect to SRM policy, the resulting outcome will be second best for the globe. Even if the agreement is unable to prevent one nation from becoming a leader in SRM policy, the outcome will be superior to the most likely outcome in absence of the agreement – game IV is third best for the globe.

Table 3 below shows the results of some mathematical simulations. It reveals that these conclusions remain true even in the presence of asymmetric drought and acid rain damages. The table reports results for four situations in which the drought damage in nation 1 is larger than the drought damage in nation 2: (i) when the relative damage is ten times larger in nation 1; (ii) when the relative damage is four times larger in nation 1; (iii) when the relative damage is two times larger in nation 1; and (iv) when the relative damage is 1.33 times larger in nation 1 than in nation 2.

In each situation, we consider the effects of incremental changes in theta 1 and theta 2. To understand this, first row for the global payoff V. We use the baseline values for the parameters other than delta 1, delta 2, theta 1 and theta 2. We then start by considering how the ranking displayed in Table 2 changes (if there is any change at all) when we fix theta 1 equal to 0.1 and let theta 2 be equal to 0.2. We compute the results and move to the next iteration, where we set theta 1 equal to 0.2 and let theta 2 to be equal to 0.1. The next iteration keeps the value of theta 1 constant and increases the value of theta 2 to 0.2, and so on until theta 2 is equal to 1. After this, we set theta 1 equal to 0.2 and let theta 2 to be equal to 0.1. The next iteration keeps the value of theta 1 constant and increases the value of theta 2 to 0.2, and so on until theta 2 equals 1. The computations end when both theta 1 and theta 2 equal 1. The results in the first row demonstrate that the baseline ranking for the global payoff remains unchanged in the four situations for all possible combinations of theta 1 and theta 2 values.

The second row of the table shows that the baseline ranking for the global payoff remains unchanged under the first three asymmetric-drought-damage situations even when one of the taste parameters, a, is evaluated in the range [0.05, 0.7] and the other parameters are kept constant at their baseline values. The baseline ranking for the global payoff changes in the last asymmetric-drought-damage situation. For 0.05 incremental changes in a, the ranking changes because the relative positions of scenarios I and VI alternate (i.e., for some a values in the interval [0.05, 0.7], V is larger in scenario I than in scenario VI, but for some other a values the opposite is true. Alternating pairwise rankings are also observed for different values of b (another taste parameter) in the interval [1, 10] in the first two asymmetric-drought-damage situations. For k_2 (a technological parameter) in [0.05, 1], the baseline ranking for the global payoff remains unchanged. We could have offered similar conclusions for the other types of parameters regarding the broad range of parameter values under which the baseline ranking for the global payoff remains unchanged, but decided to keep the table

### Table 3

Rankings with asymmetric drought and acid rain damages.

<table>
<thead>
<tr>
<th>Payoffs</th>
<th>Parameter Values</th>
<th>(δ_1, δ_2)=(1,0.1)</th>
<th>(δ_1, δ_2)=(1,0.25)</th>
<th>(δ_1, δ_2)=(1,0.5)</th>
<th>(δ_1, δ_2)=(1,0.75)</th>
</tr>
</thead>
<tbody>
<tr>
<td>V</td>
<td>Baseline</td>
<td>Robust</td>
<td>Robust</td>
<td>Robust</td>
<td>Robust</td>
</tr>
<tr>
<td></td>
<td>a=[0.05,0.7]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>b=[1,10]</td>
<td>Alternate</td>
<td>Alternate</td>
<td>Alternate</td>
<td>Alternate</td>
</tr>
<tr>
<td></td>
<td>k=[0.05,1]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>v_1 Baseline</td>
<td>Alternate</td>
<td>Alternate</td>
<td>Alternate</td>
<td>Alternate</td>
</tr>
<tr>
<td></td>
<td>a=[0.1,1]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>b=[1,10]</td>
<td>Alternate</td>
<td>Alternate</td>
<td>Alternate</td>
<td>Alternate</td>
</tr>
<tr>
<td></td>
<td>k=[0.05,1]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>v_2 Baseline</td>
<td>Change</td>
<td>Change</td>
<td>Change</td>
<td>Change</td>
</tr>
<tr>
<td></td>
<td>a=[0.15,1]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>b=[1,10]</td>
<td>Change</td>
<td>Change</td>
<td>Change</td>
<td>Change</td>
</tr>
<tr>
<td></td>
<td>k=[0.05,1]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
small and display the results for “representative” taste and technological parameters.

When we consider the potential changes in the baseline rankings for the payoffs earned by the leader and the follower, we notice that there are not as many circumstances under which the baseline ranking for each type of player remains unchanged as in the baseline ranking for the global payoff. However, the message that the leader prefers scenario V among all non-cooperative scenarios remains unchanged. In addition, restricting our attention to the most likely non-cooperative scenarios V and VI, the follower still prefers scenario VI to V.

7. Conclusion

This paper represents an initial exercise on the effects promoted by policy commitments on competing instruments designed to reduce the negative effects associated with global warming. We consider a global economy consisting of two nations and in which production of energy generates both sulfur and carbon emissions and the nations can use carbon quotas and SRM provision to reduce the negative effects associated with global warming. Although solar radiation management is a global public good with respect to climate change, its provision has two types of monetary costs (namely, technological and drought damage), which formally make it an impure public good. We show that a nation always views carbon and sulfur quotas as strategic complements. We also show that a nation always prefers to be a policy leader, irrespective if the leadership is in carbon policy or SRM policy. For various values of parameters of utility and technology, we can demonstrate that, among the inefficient scenarios, a nation prefers to be a policy leader in carbon policy, but the globe prefers a setting in which SRM policy is simultaneously determined by the competing nations before these nations simultaneously determine carbon policy. If the globe is faced with situations in which a nation displays policy leadership and it can choose between policy leadership in carbon and SRM policies, it will choose policy leadership in SRM. From the globe’s perspective, if a fully coordinated agreement is unavailable, it prefers the settings in which SRM policy is determined before carbon policy.

The low cost alternative produced by SRM provision relative to mitigation of carbon emissions leads us to believe that nations will engage in the provision of SRM in the near future. Due to questions of national security and sovereignty, nations may not be forthcoming in disclosing key information about their activities related to development of SRM. In future work, we plan to incorporate uncertainty and asymmetric information in national provision of SRM into the model and study the predictions of play of imperfectly informed governments.13 Another interesting avenue for future work is to utilize the recent developments in aggregative games to examine extensions of our model to a general setting with a large number of nations.14

References

Moreno-Cruz, J., 2011. Mitigation and the Geoengineering Threat unpublished manuscript.

13 See, e.g., Cornes and Silva (2000, 2002), Kahn et al. (2001), Silva and Kahn (1993) and Silva et al. (2007) for papers that examine the constraints imposed by moral hazard or adverse selection on the design of governmental policy.
14 See, e.g., Cornes and Hartley (2007) and Buchholz et al. (2011).