Cooperation on Climate-Change Mitigation[*]
(Preliminary Draft)

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Abstract

We model greenhouse gas (GHG) emissions by countries as a dynamic game in which the emissions increase atmospheric concentrations of GHG that negatively affect all countries' welfare. Each country in each time period chooses a level of emissions, understanding that the combination of all countries' emissions influences the evolution of the GHG stock. We allow for heterogeneities in countries' payoffs. Within this setting, we analyze self-enforcing climate-change treaties which are supportable as subgame perfect equilibria of the dynamic game. We provide a simulation model to illustrate the conditions when it is possible to support a first best outcome. We also parameterize the simulation model to mimic current conditions to show whether a self-enforcing agreement that achieves optimal climate change policy is possible, the structure of what such a solution might look like, and which countries have the most to gain from such a agreement.

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1 Introduction

As the recent discussions about the Stern Review on the economics of climate change indicate, there is no agreement about how much and how fast to control greenhouse gas (GHG) emissions in order to mitigate climate change (Nordhaus 2006, Dasgupta 2006). Even if there were an agreed-upon globally optimal GHG emissions allocation, sovereign countries would need to solve another question: how to support their cooperation to achieve the optimal emissions allocation given that emissions control is a global public good. Sovereignty of nations implies that any international agreement to mitigate climate change must be self enforcing for every country.

We model GHG emissions by countries as a dynamic game in which economic activity in a country generates emissions that increase atmospheric concentrations of GHG that negatively affect all countries' welfare. Each country in each time period chooses a level of emissions, understanding that the combination of all countries' emissions influences the evolution of the stock of GHG. We allow for heterogeneities in countries' payoffs. These heterogeneities are likely to occur as a result of differences in abatement cost and damage functions. Within this setting, we analyze self-enforcing climate-change treaties.

We identify conditions under which a subgame perfect equilibrium supports a first best outcome. We consider countries' equilibrium strategy profiles with cooperation and two-part penal codes, in which a country that deviates from the first-best emission level is punished by the other countries for a number of periods before countries resume cooperative emissions. This two-part punishment scheme is similar to that used by Polasky et al. (2006) to analyze cooperation in a dynamic game of harvesting a common property resource. Unlike a harvesting game in which a player can always guarantee at least zero payoffs simply by not harvesting, the GHG emissions game can have arbitrarily large negative payoffs. Damages increase with the stock of GHGs and the stock of GHGs is outside the control of any single country. In the context of the GHG emissions game, we analyze the effectiveness of two-part penal codes by assuming that countries interact over emissions choice and that punishment is imposed in the form of increased emissions.

We provide a simulation model to illustrate the conditions when it is possible to support a first best outcome. We also parameterize the simulation model to mimic current conditions to show whether a self-enforcing agreement that achieves optimal climate change policy is possible, the structure of what such a solution might look like, and which countries have the most to gain from such a agreement (or to lose from failure to agree).

Several prior studies have analyzed the issue of climate change by incorporating the dynamics of climate change and accumulation of GHGs (Manne and Richels 1992, Nordhaus 1994, Nordhaus and Yang 1996, Nordhaus and Boyer 2000, Cline 1992). These studies assume that countries do not choose emissions strategically.[2] Analyzing countries' strategic interactions is important in the context of climate-change mitigation: as countries' negotiations over Kyoto Protocol illustrate, participation of current and future major emitters of GHGs (e.g., US and China) is crucial for effective climate-change mitigation. A number of studies apply static or repeated games to consider countries' strategic choice of GHG emissions (Barrett 2003, Finus 2001). Bosello et al. (2003) and Eyckmans and Tulkens (2002) incorporate the dynamics of GHG stock to analyze an international agreement on climate change. These game theoretic studies focus on the stability of an environmental treaty by a subset of countries where the treaty members are assumed to cooperate even when cheating may improve a treaty member's welfare. In contrast, our analysis examines each country's incentive to deviate from cooperation and illustrates a self-enforcing treaty for climate change mitigation in the context of a subgame perfect equilibrium. Prior dynamic approaches assume that countries adopt open-loop strategies, where countries commit to future emissions at the outset of the game while we analyze feedback strategies where countries recondition their emissions choice in each period given the history of actions and current GHG stock level.

Dutta and Radner (2000, 2005) find conditions under which a subgame perfect equilibrium supports cooperation, where each country finds it self-enforcing to cooperate and punish a country with excess GHG emissions. The punishment phase against an over-emitter consists of over-emissions by all countries in one period followed by infinite periods of punishment against the initial over-emitter.

We build on Dutta and Radner's approach and modify their model in the following ways. First, we consider a two-part punishment scheme where countries resume cooperative emissions control after a deviator is punished for a short period of time. Such a two-part scheme is useful for analyzing international treaties. Unlike a trigger-strategy profile which induces mutually assured

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[2] An exception is Nordhaus and Yang (1996) which solved for an open-loop Nash equilibrium emissions allocation by countries as well as a Pareto optimal GHG emissions allocation.

over-accumulation of GHGs, the two-part scheme is more robust against renegotiation upon a country's deviation because the countries restart cooperation once a temporary sanction is completed. In addition, most international sanctions are temporary in nature.[3]

Second, unlike Dutta and Radner, we assume nonlinear damage effects of GHG stock on each country. Though there is a large degree of uncertainty about the economic effects of future climate change, scientists predict that the effects may be nonlinear in the atmospheric greenhouse gas concentration. Studies predict nonlinear effects of climate change on agriculture (Schlenker et al. 2006, Schlenker and Roberts 2006). Nonlinearity may also arise due to catastrophic events such as the collapse of the thermohaline circulation (THC) in the North Atlantic Ocean: climate change may alter the circulation, which would result in significant temperature decrease in Western Europe. Our numerical example with quadratic functions captures this nonlinearity.

In what follows, section 2 describes the assumption of the game and a two-part strategy profile with a simple penal code to support the cooperative outcome. Using an example with quadratic functions, section 3 discusses the condition under which the two-part strategy profile is a subgame perfect equilibrium. In Section 4 we choose the parameter values of the quadratic functions based on previous climate-change models in order to illustrate the implication to climate-change mitigation. Section 5 concludes the paper.

2 Basic model

2.1 Assumptions

$N \geq 0$ countries choose emission in each period $t = 0, 1, \ldots$. Let $x_{it} \geq 0$ be the GHG emission by country i in period t. The transition of the GHG stock in the atmosphere is given by

$$S_{t+1} = g(S_t, x_t) = \underline{S} + \lambda(S_t - \underline{S}) + bX_t,$$

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[3] Based on 103 case studies of economic sanctions between World War I and 1984, Hufbauer et al. (1985) find that the average length of successful and unsuccessful sanctions were 2.9 and 6.9 years. Success of a sanction is defined in terms of the extent to which the corresponding foreign policy goal is achieved (p.79).

where $X_t \equiv \sum_i x_{it}$, $1-\lambda$ represents the natural rate of decay of GHG per period ($0 \leq \lambda < 1$), $\underline{S}$ the GHG stock level prior to the industrial revolution, and b the retention rate of current emissions.[4] Let x_{-i} be a vector of emissions by all countries other than i and $X_{-i} \equiv \sum_{j \neq i} x_j$, the total emissions by all countries other than i.

Let $\pi_i(x_i, S)$ be the periodwise return of country i with emission x_i when the GHG stock is S. Emissions are linked to output, and hence generate net benefits from consumption. On the other hand, there may be flow damages associated with any such emissions. The function summarizes the combination of these effects. Because emissions are linked to net benefits, reducing emissions is costly for the country in question. On the other hand, each country suffers damages from GHG concentration; these damages are increasing in the GHG stock.

We assume that each country's periodwise return equals the economic benefit from emissions B_i, which is a function of its own emissions, minus the climate damage D_i, a function of the current GHG stock:

$$\pi_i(x_{it}, S_t) = B_i(x_{it}) - D_i(S_t).$$

We assume that B_i is strictly concave and has a unique maximum $\overline{x}_i$ with $B_i(0) = 0$ and $B_i'(x) > 0$ for all $x \in (0, \overline{x}_i)$. We call $\overline{x}_i$ the "myopic business-as-usual" (myopic BAU) emission level of country i. This is the level that maximizes period-wise returns, without taking into account any future implications associated with contributions to the stock of GHGs. The damage function satisfies $D_i' > 0, D_i'' > 0$ and captures nonlinear effects of climate change.

We allow transfers among countries. Let τ_{it} be the net transfer to country i in period t where $\sum_i \tau_{it} = 0$ for all t. Country i's net one-period return in period t is given by $\pi_i(x_{it}, S_t) + \tau_{it}$. In the context of climate-change mitigation, the transfers would be determined based on cost burden sharing agreed on by the countries.

Countries have the same one-period discount factor $\delta \in (0, 1)$. All countries' return functions are measured in terms of a common metric. We assume that the payoffs are transferable. Countries have complete information and there is no uncertainty in the model. In each period, each country observes the history of GHG stock evolution and all countries' previous emissions.

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[4] Many studies have used this specification of GHG stock transition (Nordhaus and Yang 1996, Newell and Pizer 2003, Karp and Zhang 2004, Dutta and Radner 2004).

2.2 First best solution

The first best emissions path solves the following problem.

$$\max \sum_{t=0}^{\infty} \delta^t \sum_i \pi_i(x_{it}, S_t)$$

$$\text{s.t.} \quad S_{t+1} = g(S_t, x_t) \quad \text{for } t = 0, 1, \ldots \text{ given } S_0.$$

The solution to this problem generates a sequence of emissions $\{x_t^*\}_{t=0}^{\infty}$ where $x_t^* = \{x_{it}^*\}_{i=1}^{N}$. The corresponding value function solves the following functional equation.

$$V(S) = \max_x \textstyle\sum_i \pi_i(x_i, S) + \delta V(S')$$

$$\text{s.t.} \quad S' = g(S, x).$$

We assume the solution is interior. The optimal emission profile given S, $x^*(S) = \{x_1^*(S), x_2^*(S), \ldots, x_N^*(S)\}$, satisfies the following.

$$\frac{\partial \pi_i(x_i^*(S), S)}{\partial x_i} + \delta V'(g(S, X^*(S)))b = 0$$

for all i. The first term represents the marginal benefit of emissions in country i while the second term is the discounted present value of the future stream of marginal damages in all countries from the next period. Thus, under the first best allocation, the marginal abatement costs of all countries in the same period must be equalized, and they equal the shadow value of the stock.

The unique steady state S^* satisfies the following equation:

$$\frac{\partial \pi_i(x_i^*(S^*), S^*)}{\partial x_i} + \frac{\delta b}{1 - \delta \lambda} \frac{\partial \sum_j \pi_j(x_j^*(S), S)}{\partial S} = 0.$$

Given $S_0 < S^*$, the stock increases monotonically to the steady state S^*. For the rest of the paper we assume $S_0 < S^*$. In what follows, we describe a strategy profile that supports x^* as a subgame perfect equilibrium.

2.3 A strategy profile to support cooperation

Consider the following strategy profile ϕ^*, which may support cooperative emissions reduction with a threat of punishment against over-emissions.[5]

Suppose the value to country i is given by $\gamma_i V$ where $\gamma_i \geq 0$ and $\sum_i \gamma_i = 1$. Define a transfer τ^* where

$$\tau_i^*(S) \equiv \gamma_i \sum_j \pi_j(x_j^*(S), S) - \pi_i(x_i^*(S), S)$$

for all S and all i. By choosing x^* and τ^*, the countries realize the first best outcome with the shares induced by γ.

Strategy profile ϕ^*

- Phase I: Countries choose $\{x_i^*, \tau_i^*\}$. If a single country j chooses over-emission (or chooses a transfer $\tau_i > \tau_i^*(S)$ when $\tau_i^*(S) < 0$), with resulting stock S', go to Phase II$_j(S')$. Otherwise repeat Phase I in the next period.
- Phase II$_j(S')$: Countries play $x^j = (x_1^j, \ldots, x_i^j, \ldots, x_N^j)$ for T periods. If a country k deviates with resulting stock S'', go to Phase II$_k(S'')$. Otherwise go back to Phase I.

The idea of the penal code x^j is to induce country j (which cheated in the previous period) to choose low emissions for T periods while the others enjoy high emissions. Each sanction is temporary, and the countries resume cooperation once the sanction is complete. The punishment for country j in Phase II$_j$ works in two ways, one through its own low emissions (and hence low benefits during Phase II) and the other through increases in its future stream of damages due to an increase in the other countries' emissions during Phase II. Under some parameter values and with appropriately specified penal codes $\{x^j\}$, each country's present-value payoffs upon deviation will not exceed the present-value payoffs upon cooperation. We will discuss the condition under which ϕ^* is a subgame perfect equilibrium.

When ϕ^* is not a subgame perfect equilibrium, there may be another strategy profile which supports the first best as a subgame perfect equilibrium outcome. A punishment is most effective as deterrence against over-emitting if it induces the over-emitter's minmax (i.e. the worst perfect equilibrium) payoff. Though such punishment supports cooperation under the widest range of

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[5] The design of the penal code to support cooperation is similar to those discussed in Abreu (1988).

parameter values, a two-part punishment scheme inducing the worst perfect equilibrium may be too complicated to generate useful insights about self-enforcing treaties. Previous dynamic game studies have analyzed cooperation with worst perfect equilibria in the context of local common-property resource use (Dutta 1995b, Polasky et al. 2006). With local common-property resource use, the minmax level is defined by outside options for resource users—the payoffs that they would receive if they quit resource use. With a global commons problem such as climate change, there are no outside options: a country can never escape from changed climate (without spending potentially large amounts of resources for adaptation). With linear damage functions, Dutta and Radner (2004) find that the worst perfect equilibria take a simple form (constant emissions by all countries). With nonlinear damage functions, the worst perfect equilibria will be more complicated because they my depend nonlinearly on the state variable. In this study, we restrict our attention to ϕ^*, a strategic profile with a simple penal code, in order to gain insights about countries' incentives to cooperate in a treaty.

2.4 Sufficient conditions for first best sustainability

Let $V_j^C(S, \mathrm{I})$ and $V_j^D(S, \mathrm{I})$ be country j's payoff upon cooperation and the maximum payoff upon deviation in Phase I given current stock S. Similarly, let $V_j^C(S, \mathrm{II}_i), V_j^D(S, \mathrm{II}_i)$ be j's payoff upon cooperation and an optimal deviation starting in Phase II_i given stock S. With these notations, the above strategy profile is a subgame perfect equilibrium if the following conditions are satisfied for country $j, j = 1, \ldots, N$:

Condition (1) Country j has no incentive to deviate in phase I: $V_j^C(S, \mathrm{I}) \geq V_j^D(S, \mathrm{I})$;

Condition (2) Country j has no incentive to deviate in phase II_j: $V_j^C(S, \mathrm{II}_j) \geq V_j^D(S, \mathrm{II}_j)$; and

Condition (3) Country j has no incentive to deviate in phase II_k for all $k \neq j$: $V_j^C(S, \mathrm{II}_k) \geq V_j^D(S, \mathrm{II}_k)$;

for all possible stock levels given initial stock S_0. Because each player's periodwise return is bounded from above and the discount rate is positive, the principle of optimality for discounted dynamic programming applies to this game. Hence, in order to prove that ϕ^* is subgame perfect, it is sufficient to show that any one-shot deviation cannot be payoff-improving for any player (Fudenberg and Tirole 1991). Because this is a dynamic game, we need to verify that no player has an incentive to deviate from the prescribed strategy in any phase and under any possible stock level .[6]

3 Example

Assume that N countries' periodwise return functions are quadratic:

$$\pi_i(x_i, S) = a_i x_i - b_i x_i^2 - d_i S^2,$$

where $a_i, b_i, d_i > 0$ for all i. The negative of the derivative with respect to emissions, $-(a_i - 2b_i x_i)$, represents the marginal abatement cost associated with emissions x_i. Country i's myopic BAU emission which maximizes the periodwise return is $\overline{x}_i \equiv \frac{a_i}{2b_i}$. As in the appendix, the value function is quadratic and a unique linear policy function exists for the first best problem. The values $2b_i$ and $2d_i$ represent the slopes of the marginal costs of emission reduction and the marginal damages from pollution stock.

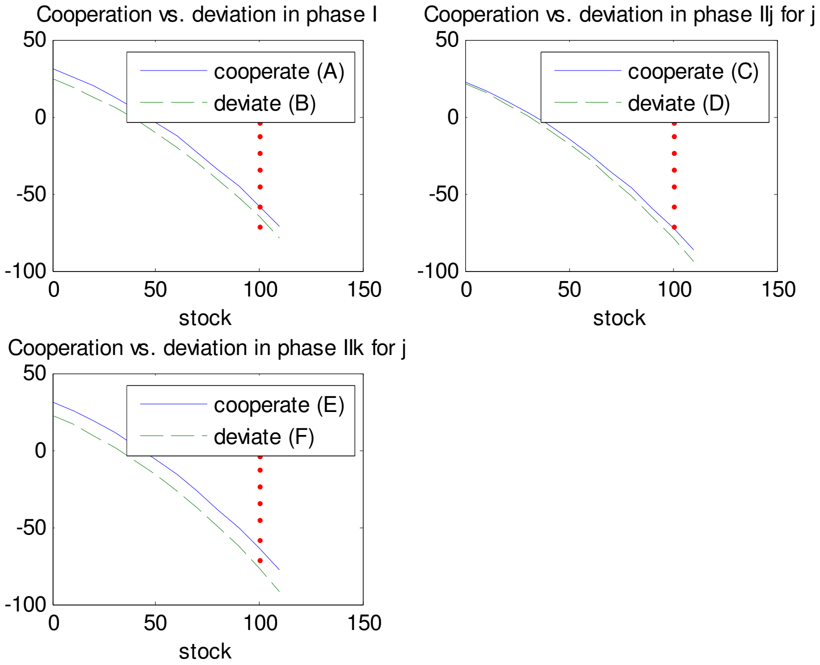
3.1 Homogeneous countries

First we consider a simple case with homogeneous countries in order to describe the conditions under which ϕ^* is (is not) a subgame perfect equilibrium. Assume the following.

- $S_0 \leq S^*$;
- $(a_i, b_i, d_i) \equiv (a, b, d) > 0$ for all i;
- $x_j^j(S) \equiv z > 0$, a constant, for all $S \geq 0$ and all j such that $z < x^*(S^*)$.
- $x_i^j(S) \equiv y(S) \equiv \frac{X^*(S) - z}{N-1}$ for all $i \neq j$.

With the above penal code (z, y), all countries $i \neq j$ choose the optimal aggregate emissions $X^*(S)$ collectively for all S.

Figure 1 illustrates a case where ϕ^* is a subgame perfect equilibrium. Each panel represents the payoff upon cooperation with a solid curve and the payoff upon optimal deviation with a dotted curve. The optimal steady state is around 100. Under the assumed combination of parameter values, the payoffs upon cooperation exceed the payoffs upon optimal deviation under all relevant stock levels in each phase.



The figure assumes $a = 100, b = 3, d = 0.0007, T = 1, z = 0, N = 8, \delta = .9, \lambda = .99$.

Figure 1: An example where ϕ^* is a subgame perfect equilibrium.

Figure 2 represents a case where ϕ^* is a subgame perfect equilibrium when the ratio of the slopes of marginal abatement costs and marginal damages, b/d is neither too large large (as point A indicates) or too small (as point C indicates). At point A, the magnitude of damages from pollution stock is relatively small compared to the magnitude of the costs of reducing emissions. In this case, the difference between the optimal emissions and noncooperative emission levels are small, implying that the gains from cooperation might be too small for each country. For a smaller value of b/d, the marginal damages increase faster than the marginal abatement costs as pollution stock increases. This fact implies that the difference between the optimal emissions and noncooperative emission levels becomes larger. Because the optimal emission control calls for larger emission reduction to each country, both the gains from cooperation and temptations to deviate increase. At a point like B, the former exceeds the latter and ϕ^* supports cooperation. However, at a point like C. the temptation to deviate exceeds the gains from cooperation and hence ϕ^* is not a subgame perfect equilibrium.

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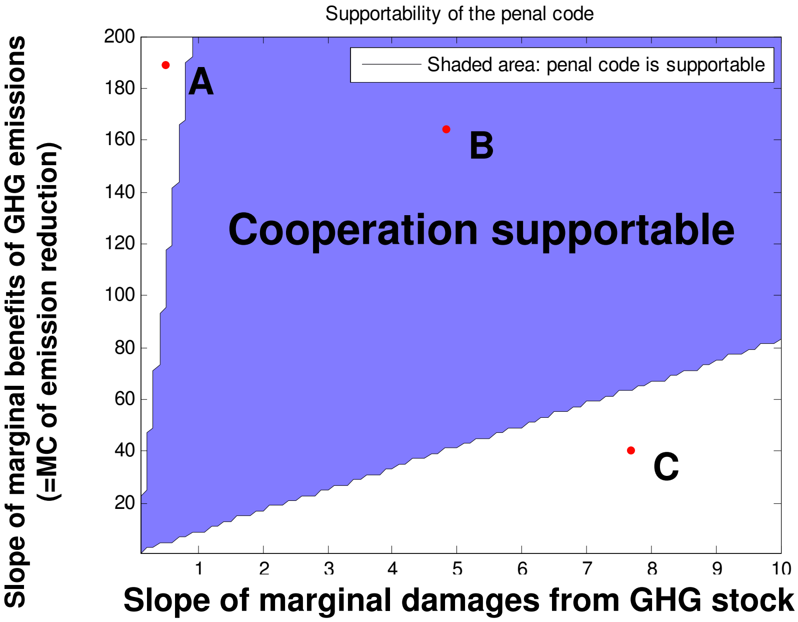
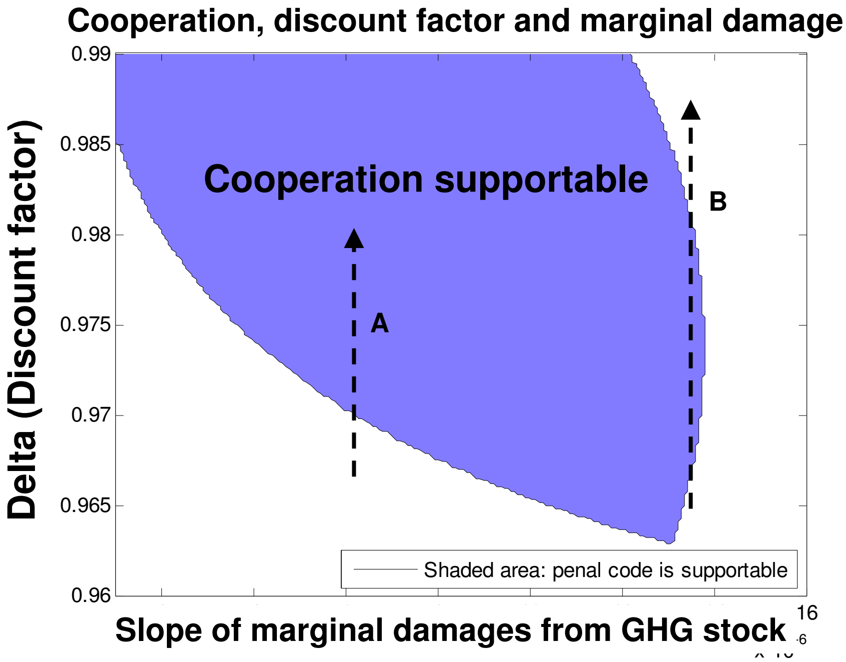
[6] See Dutta (1995a) for a similar analysis in a dynamic game context.



The figure assumes $a = 100, T = 1, z = 0, N = 8, \delta = .99, \lambda = .99$. The vertical and horizontal axes measure b and d respectively.

Figure 2: Supporting cooperation. (I)

A similar logic explains why supportability of ϕ^* as a subgame perfect equilibrium is not necessarily monotonic in the discount factor (see the arrow B in Figure 3). As Dutta (1995b) proved, the claim that cooperative outcomes are supportable only by patient players—an implication of the folk theorem for repeated games—does not necessarily hold for a general class of dynamic games. Figure 3 implies that the dynamic GHG emissions game in this paper is no exception. An intuition behind this result is the following. When *delta* is very low, cooperation is not supportable because the future payoff upon cooperation is discounted too heavily. As δ increases, the payoff upon cooperation increases while the first-best emission level decreases. This implies that both the future payoff upon cooperation and the payoff upon optimal deviations increase. Movement along arrow B in Figure 3 indicates that the latter may increase more than the former when the discount factor is large enough.



The figure assumes $a = 100, b = 1, T = 1, z = 0, N = 8, \lambda = .99$. The vertical and horizontal axes measure δ and d, respectively.

Figure 3: Supporting cooperation. (II)

3.2 Heterogeneous countries

How does heterogeneity across countries influence supportability of ϕ^*? Here we investigate this question assuming the following.

- $S_0 \leq S^*$;
- $x_j^j(S) \equiv 0$ for all $S \geq 0$ and all j;
- $x_i^j(S) \equiv \overline{x}_i$ (the myopic BAU emission) for all $i \neq j$.

Table 1 describes whether condition (2) holds under different discount factor values for a game with 8 heterogeneous countries. We assume two values—high and low—for each of the benefit and damage function parameters $\{a_i, b_i, d_i\}$ and the eight countries have different combinations of these parameter values. The table assumes $v_i = V/N$ for all i, i.e. the payoffs upon cooperation are divided equally across countries. With this example, conditions (1) and (3) under which ϕ^* is a subgame perfect equilibrium holds given all discount factor values considered (2.5–10%). Condition (2) also holds (and hence ϕ^* is a subgame perfect equilibrium) when the discount rate is 2.5%. For a

Table 1: Condition (2) with heterogeneous countries.

	Reward function parameters			Discount rate ($1/\beta - 1$)					
Country (i)	a_i	b_i	d_i	2.5	3	3.9	4	6	10
1	High	Low	Low	Y	NL	N	N	N	N
2	High	High	Low	Y	NL	N	N	N	N
3	Low	Low	Low	Y	Y	NH	N	N	N
4	Low	High	Low	Y	Y	NH	N	N	N
5	High	Low	High	Y	Y	Y	Y	NL	NL
6	High	High	High	Y	Y	Y	Y	NL	NL
7	Low	Low	High	Y	Y	Y	Y	Y	NL
8	Low	High	High	Y	Y	Y	Y	Y	NL

Note: In all cases we assume $\lambda = .99$ and $v_i = V/N$ for all i. $a_i = 10.2$ (10.0), b_i =5.0001 (5), d_i = .00002 (.000025) for High (Low) cases, and $\alpha = 0$. Conditions (1) and (3) hold for all $S \leq S^*$ for all countries in all cases.
Y: Condition (2) holds for all $S \leq S^*$, NL: Condition (2) does not hold when S is low relative to S^*, NH: Condition (2) does not hold when S is close to S^*, N: Condition (2) does hot hold for any $S \leq S^*$.

larger discount rate, condition (2) is violated—first for the countries with larger BAU emissions (i.e. larger $\frac{a_i}{2b_i}$) and low marginal damages d_i, then for those with low BAU emissions and high marginal damages. Given equal sharing of V, a country with a higher BAU emission and lower marginal damages has less to lose by deviation than countries with lower BAU emissions and higher marginal damages. This example illustrates different incentives for controlling emissions by countries with different benefits and damages.

4 Illustration of a climate-change treaty

4.1 Assumptions

This section illustrates the implications of our analysis on a treaty to mitigate climate change. We apply the above quadratic model and choose the parameter values used in existing climate-change models (Nordhaus and Boyer 2000). Several studies have used quadratic models to approximate the global benefit and damage functions (Falk and Mendelsohn 1993, List and Mason 2001, Newell and Pizer 2003, Karp and Zhang 2005, 2006). We combine these models with an estimate of regional benefits and damages by Nordhaus and Yang and Nordhaus and Boyer.

The base year is 1995. A time period corresponds to one year. We model the emissions and accumulation of CO_2 and do not consider other GHGs. What follows is a list of assumptions about the parameter values.

Discount factor

We use the discount factor of $\delta = 1/1.03$, a value often assumed in most previous climate-change models. Later we will conduct a sensitivity analysis.

Carbon stock transition

Following Nordhaus and Yang (1996) and Newell and Pizer (2003), we specify the long-term and short-term decay rates of CO_2 to be .83% and 36%. The pre-industrial stock level is $\underline{S} = 613$ GtC (gigatons of carbon equivalent). So the carbon stock transition is given by

$$S_{t+1} = 0.9917(S_t - 613) + 613 + 0.64X_t.$$

The initial stock level S_0—the stock level in 1995—is 6.16 billion tC.

Country/regional classification

We assume $N = 13$ and use the following classification because the corresponding regional benefit and damage functions are available from Nordhaus and Boyer's previous study (2000).

US, Europe, Japan, OHI (Other high income countries), Russia, EE (Eastern Europe), HIO (High-income oil producers), MI (Middle income), LMI (Low-Middle income), China, Low (Low-income), India, Africa.

Benefit functions

We specify the benefit functions using the following functional form:

$$B_i(x_i) = -\frac{(\bar{e}_i - x_i)^2}{2\theta_i}.$$

This specification allows us to aggregate the benefit functions to derive the global benefit in a simple way. A function B where $B(X) \equiv -\frac{(\bar{E}-X)^2}{2\Theta}$ with $\bar{E} = \sum_i \bar{e}_i$ and $\Theta \equiv \sum_i \theta_i$ satisfies

$$B(X) = \max_{\{x_i\}} \left\{ \sum_i -\frac{(\bar{e}_i - x_i)^2}{2\theta_i} \middle| \sum_i x_i = X \right\}.$$

This function B represents the global net benefit function. We choose $\bar{E}$ and $\{\bar{e}_i\}$ to be equal to the CO_2 emissions from the corresponding regions in the year 1995. We chose Θ so that the global total abatement cost of reducing the global CO_2 emissions by 100% is 7% of the world GDP (Nordhaus and Boyer 2000). We then chose $\{\theta_i\}$ so that $\sum_i \theta_i = \Theta$ and the regional marginal abatement costs are consistent with an estimate by Nordhaus and Yang (1996) (implying $\Theta = 1/64$). We also consider an alternative case where $\Theta = 1/160$ (Newell and Pizer 2003) and where θ_i's are scaled down to sum up to 1/160.

Damage functions

Let

$$D_i(S) = d_i(S - \underline{S})^2 + g_i(S - \underline{S}) + f_i.$$

Nordhaus (1998) estimates the damage in terms of a fraction of GDP as a function of changes in the average atmospheric temperature relative to the preindustrial level. We multiply Nordhaus's estimates by an estimated World GDP in 1995 (22,687 billion 1990 US dollars, Nordhaus and Boyer 2001) to express the damage in terms of output. Following Kattenberg et al (1996) and Newell and Pizer (2003), assume that a doubling of carbon concentrations leads to a 2°C warming and that temperature change is proportional to the change in the log of the carbon stock.[7] This implies that the carbon stock levels associated with 2.5°C and 6°C warming are 1,458 and 4,904 GtC. We calibrated $\{d_i, g_i, f_i\}$ so that $D_i(\underline{S}) = 0$ for all i and $\{D_i(1,458), D_i(4,904)\}$ is consistent with Nordhaus's estimated damages due to 2.5°C and 6°C warming.

We assume that the benefit and damage functions are time-invariant. Future research will consider the effects of change in these functions—due to population, income and technological

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[7] Specifically, let $T(S)$ be the increase in temperature, relative to the preindustrial level, associated with the CO_2 concentration S. Then

$$T(S) \approx 2.885 \ln\left(\frac{S}{\underline{S}}\right).$$

changes—on countries' incentive for cooperation.

Share of the value under cooperation

The share parameter γ represents the cost burden of climate-change mitigation across countries. No agreed-upon burden sharing rule exists though many policymakers argue that richer countries should bear larger burdens. We consider two rules: equal sharing where $\gamma_i = 1/N$ for all i and GDP proportional sharing where $\gamma_i = \frac{GDP_i}{\sum_j GDP_j}$. Though equal sharing is highly unrealistic given the model's coarse partition of the world into 13 regions, it is useful for assessing the effect of heterogeneity on each country or region's incentive to cooperate.

4.2 Preliminary findings

We wish to illustrate the effect of heterogeneity on the condition under which ϕ^* is a subgame perfect equilibrium. For this purpose, first we consider a case where the 13 regions are identical where the global benefit and damage functions are calibrated in the way explained in the previous subsection. Then we introduce heterogeneity in the benefit and damage functions.

With quadratic functions and heterogeneity, a corner solution is possible (i.e. the first best emission levels for some countries may be zero). For countries with larger marginal damages than others, the optimal deviation may imply zero emissions. However, in all cases considered, we verified that the first best outcomes are always interior solutions and the optimal deviations lie between the first best emissions and the myopic BAU emissions.

4.2.1 No heterogeneity

Given $\delta = 1/1.03$ and equal sharing, ϕ^* is subgame perfect if $\alpha \geq .87$ (that is, a punishment of a 13% or less emission reduction for the cheater). For more severe punishment ($\alpha < .87$), condition (2) for supporting ϕ^* (the condition under which country j does not deviate in phase II_j) does not hold. This implies that repeated cheating cannot be deterred if the punishment is too harsh.

With no heterogeneity, GDP proportional sharing implies that US and Europe would be the first to deviate from cooperation because of their larger shares in world GDP.

4.2.2 BAU emissions heterogeneity

Next we introduce heterogeneity in BAU emissions by letting $\bar{e}_i$ be region i's actual emissions in 1995.

Under equal sharing with $\Theta = 1/64$, ϕ^* is subgame perfect for $\alpha \geq 0.96$. As α becomes smaller, condition (2) starts being violated for the countries with large BAU emissions. US will be the first to deviate in Phase II because of its large BAU emissions.

With $\Theta = 1/160$, ϕ^* is subgame perfect if $\alpha = .99$. Condition (2) is violated for US when $\alpha \leq .98$.

Under GDP proportional sharing, conditions (1), (2) and (3) do not hold for US, Japan, and Europe—the countries with high BAU and large GDP—when $\alpha = .99$. For lower and higher values of α, at least one of conditions (1), (2) and (3) does not hold for these countries. Hence, Europe and Japan are the weak link for cooperation in addition to US. This result may be due to the fact that the cost shares to these regions and countries are over-proportioned to their BAU emissions. (The BAU-GDP ratio for US is twice or more than those for Europe and Japan).

4.2.3 Abatement-cost heterogeneity

We consider a case where both the BAU emissions $\{\bar{e}_i\}$ and the marginal abatement cost parameter $\{\theta_i\}$ are heterogeneous. Under equal sharing with $\Theta = 1/64$, ϕ^* is subgame perfect when $\alpha \geq .96$. Condition (2) is violated for US when $\alpha \leq .95$. With proportional sharing, conditions (1), (2) and (3) do not hold for US, Japan, and Europe.

With equal sharing and $\Theta = 1/160$, ϕ^* is subgame perfect when $\alpha \geq .99$. Condition 2 is violated for US and Europe when $\alpha = .98$.

4.2.4 Damage heterogeneity

We introduce damage heterogeneity and assume homogeneity in benefit functions, Under equal sharing with $\alpha = .98$, conditions 1,2, and 3 do not hold for all regions except LMI (low-middle income countries). This result may be due to LMI's high damages and vulnerability to climate change relative to others. (LMI includes Mexico, South Africa, Chile, Thailand, and Turkey—most of which are said to be vulnerable to sea level rise and/or temperature changes.) With smaller values of α, conditions (1), (2) and (3) hold for Europe and India. These countries may constitute a group of countries most vulnerable to climate change next to LMI.

4.2.5 Combined heterogeneity in benefits and damages

Under equal sharing, with $\alpha = .99$, conditions (1), (2) and (3) are violated for all regions except for Europe and LMI. The difference between the payoffs upon cooperation and the payoffs upon optimal deviation is much larger in magnitude for Europe than for the rest of the world. This result may be due to the combination of relatively low abatement cost and large potential climate damages for Europe—the combination of characteristics not observed for other high-income countries. For smaller α, conditions (1), (2) and (3) hold for US, Middle-income countries as well as Europe.

Under proportional sharing, conditions (1), (2) and (3) hold for a larger set of countries than under equal sharing. In addition to Europe, US and MI, HIO, LMI, Low, India and Africa are willing to cooperate. This finding may be due to the magnitude of climate damages for these countries.

In all cases, it is hardest to support the incentive for Russia and other Eastern European countries to cooperate. This is because of their low (or possibly negative) damages due to climate change for these countries.

5 Discussion

Climate change mitigation is a global public good where reducing GHG reduction is costly for each country while the GHG stock accumulation in the atmosphere is likely to cause damages to many countries. In order for sovereign countries to cooperate through an international agreement to control GHGs, the agreement must be self-enforcing for each country. We applied a dynamic game to illustrate an international agreement with a simple rule of sanctions in order to support the first best, cooperative climate-change mitigation. Instead of a trigger strategy where all countries choose over-emissions forever upon some country's cheating, we considered a two-part penal code where the sanction against an over-emitter is temporary and where countries resume cooperation upon completion the sanction. With numerical examples and illustration using a simple climate-change model, we examined the conditions under which such a simple two-part sanction scheme—where the country being sanctioned chooses a low emission and the others choose over-emissions for one period—is a subgame perfect equilibrium. In particular, we studied how heterogeneous countries' incentive for cooperation may change over time given GHG stock dynamics and nonlinear effects of GHG on each country's payoff.

Our numerical example confirmed that each country's incentive to cooperate may change as the stock level changes. We might expect that it may become easier for countries to avoid free riding and cooperate as GHG stock increases; however, we found that a larger stock level does not necessarily imply that the sanction scheme is more likely to be a subgame perfect equilibrium.

Because sanctions are more severe when the number of countries is larger, the sanction scheme which is not an equilibrium for a given total number of players can be an equilibrium given a larger number of players.

Our linear-quadratic climate-change model with parameter values from existing studies illustrates different incentives to support cooperation held by countries with different benefits from GHG emissions and different potential damages from increases in the GHG stock. Given heterogeneous benefits from emissions, countries such as US and Europe, which have larger baseline GHG emissions than the other countries, have larger incentive to deviate from the first best emissions reduction than the others. Considering heterogeneity in potential damages from climate change, we found that lower-middle income countries and Western European countries will have the most to gain from cooperation due to relatively larger vulnerability to climate change. This finding about heterogeneity is similar in spirit to Mason and Polasky (2003), who found that an oil-producing country's OPEC membership is significantly associated with the country's larger oil reserves (implying larger benefits from cooperation) and smaller domestic oil consumption (implying smaller benefits in consumer surplus from non-cooperation).

Our climate-change model also suggested the weak link for cooperation—those countries which have the most to gain from deviation—depends on how the burden of GHG emission control is distributed across countries. In international negotiation and under Kyoto Protocol, policymakers argue that richer countries including US or those countries with large GHG emissions in the past should bear larger cost burden. Our simulation suggests that US is unlikely to cooperate with the simple sanction scheme if the cost burden is proportional to GDP (because of its relatively large benefits from GHG emissions and relatively moderate potential damages from US). In contrast, Western Europe may have incentive to cooperate under the same cost sharing rule despite its relatively large GDP because Western Europe is likely to be more vulnerable to climate change than US. These findings imply that the cost sharing rule must be correctly specified in order for climate-change mitigation to be self-enforcing to all countries and that the self-enforcing cost sharing rule may not coincide with a rule perceived to be fair in an international context.

Further sensitivity analysis will be necessary for our linear-quadratic climate-change model. Future research should also address a number of assumptions that we made to keep our analysis simple. We assumed that each country's periodwise return function is time-invariant. However, the benefit from GHG emissions and damages from climate change will change over time due to changes in population, economic growth and technological progress. In addition, the benefits and damages may change at different rates for different countries. Our analysis on heterogeneity does not consider these possibilities.

A natural extension of our model would be to incorporate uncertainty regarding climate change. Another useful extension would be to consider sanctions through means other than increased emissions such as trade (Barret 2003). A temporary trade sanctions may be less costly for each country than sanctions with increased emissions, the effect of which will last for a long time because of the nature of GHG as a stock pollutant. Future research may study the extent to which the availability of trade sanctions increases the likelihood of a self-enforcing treaty.

Our findings, despite their tentativeness, implies that dynamic-game formulation provides a useful framework for analyzing a self-enforcing treaty for climate-change mitigation and a useful insight which may not be available from static-game or repeated-game analysis.

Appendix A: Conditions for first-best sustainability

Suppose $T = 1$. Consider countries' incentive to deviate in Phase I. In period t, given current stock S_t, country j's payoff upon cooperation is $V_j(S_t)$. Country j's payoff upon deviation, with over-emission x_j^D in period t, is given by

$$\pi_j(x_j^D, S_t) + \max\left\{0, \gamma_j \sum_i \pi_i(x_i^*(S), S) - \pi_j(x_j^*(S), S)\right\} + \delta\pi_j(x_j^j(S'_{t+1}), S'_{t+1}) + \delta^2 V_j(S'_{t+2})$$

where $S'_{t+1} = g(S_t, x_{-j}^j, x_j^D)$ and $S'_{t+2} = g(S_{t+1}, x^*(S_{t+1}))$. This is a discounted sum of a current gain by over-emitting in period t, a low return in period $t+1$ due to punishment, and continuation payoffs with a larger GHG stock due to its own over-emission. Therefore, no country deviates from Phase I if

$$V_j(S) \geq \pi_j(x_j^D, S) + \max\left\{0, \gamma_j \sum_i \pi_i(x_i^*(S), S) - \pi_j(x_j^*(S), S)\right\}$$

$$+\delta\pi_j(x_j^j(g(S, x_j^D, x_{-j}^*(S))), g(S, x_j^D, x_{-j}^*(S)))+\delta^2 V_j(g(g(S, x_j^D, x_{-j}^*(S)), x^j(g(S, x_j^D, x_{-j}^*(S))))) \quad (1)$$

for all $x_j^D \geq 0$, $S \geq S_0$ and all j.

In Phase II$_j$, country j does not deviate from cooperation if

$$\pi_j(x_j^j(S), S) + \delta V_j(g(S, x^j(S))) \geq \pi_j(x_j^D, S) + \delta\pi_j(x_j^j(g(S, x_j^D, x_{-j}^j(S))), g(S, x_j^D, x_{-j}^j(S)))$$

$$+\delta^2 V_j(g(g(S, x_j^D, x_{-j}^j(S))), x^j(g(S, x_j^D, x_{-j}^j(S)))) \quad (2)$$

for all $x_j^D \geq 0$ and all possible stock levels given S_0 (i.e. for all $S \geq g(S_0, (x_{-j}^*(S_0), x_j^D)))$.

Similarly, in Phase II$_k$, country j has no incentive to deviate if

$$\pi_j(x_j^k(S), S) + \delta V_j(g(S, x^k(S))) \geq \pi_j(x_j^D, S) + \delta\pi_j(x_j^j(g(S, x_{-j}^k, x_j^D)), g(S, x_{-j}^k, x_j^D))$$

$$+\delta^2 V_j(g(g(S, x_{-j}^k, x_j^D), x^j(g(S, x_{-j}^k, x_j^D)))) \quad (3)$$

for all $x_j^D \geq 0$ and all $S \geq g(S_0, (x_{-k}^*, x_k^D))$.

To summarize, the strategy profile is a subgame perfect equilibrium if conditions (1), (2), and (3) (for all $k \neq j$) hold for all possible deviations, all $S \geq S_0$ and all j.

Appendix B: The first best solution of a quadratic example with heterogeneous countries

Let $q = (q_1, q_2, \ldots, q_N)$, $r = (r_1, r_2, \ldots, r_N)$, and $d = (d_1, d_2, \ldots, d_N)$ be column vectors. Let $G = \sum_i g_i$ and $F = \sum_i f_i$. Let Q_m be an N by N diagonal matrix whose diagonal entries are q. Given stock sS and an emissions profile x, The total periodwise return of N countries is

$$x'Q_m x + r'x + DS^2 + GS + F,$$

where $D = \sum_i d_i$. (Assume that $Q < 0, r > 0$ and $d < 0$. The state transition is given by

$$S_{t+1} = kS + b'x + h$$

where $k \in (0,1)$, b a column vector where $1 - b_i$ represents the short-run decay rate, and h is a constant. Let V be the total value function of all N countries:

$$V(S) = \max_x x'Q_m x + r'x + DS^2 + GS + F + \delta V(S') \tag{4}$$

s.t. $S' = kS + b'x + h$. Because V is quadratic, let $V(S) = Ps^2 + ts + u$ where P, t, u are scalars. We have

$$V(S') = (kS + b'x + h)'P(kS + b'x + h) + t'(kS + b'x + h) + u$$

$$= (kS + h)'P(ks + h) + (kS + h)'Pb'x + x'bP(kS + h) + x'bPb'x + t'kS + t'b'x + t'h + u.$$

So

$$\frac{\partial}{\partial x}V(s') = bP'(kS + h) + bP(kS + h) + 2bPb'x + tb.$$

The first order condition is

$$2Q_m x + r + \delta[2bP(ks + h) + 2bPb'x + tb] = 0.$$

Hence

$$x = (-1/2)[Q_m + \delta bPb']^{-1}[r + 2\delta bP(ks + h) + \delta tb].$$

Substitute this expression into the functional equation and we obtain the following expression:

$$P = D + \delta k^2 P - \delta^2 k^2 P^2 b' F(P) b,$$

where $F(P) \equiv [Q_m + \delta b P b']^{-1}$. Solve this function for P, and we can solve for the remaining unknown t and u.

$$t = \frac{-\delta P k r' F(P) b + G - 2\delta^2 P^2 k h b' F(P) b + 2\delta k h P}{1 + \delta^2 P k b' F(P) b - \delta k},$$

$$u = \frac{1}{1-\delta} \left\{ -\frac{1}{4}(r' + \delta t b') F(P)(r + \delta t b) - (r' + \delta t b') F(P) \delta b P h - \delta^2 P^2 b' F(P) b h^2 + \delta t h + F + \delta h^2 P \right\}.$$

Appendix C Regional aggregates used for simulation

	Japan	USA	Europe	OHI	HIO	MI	Russia	LMI	EE	LI	China	India	Africa	World
(A) GDP (1995)	3,420	6,176	6,892	1,087	234	1,138	334	1,156	380	570	654	447	199	22,687
(B) CO_2 (1995)	0.308	1.407	0.851	0.249	0.129	0.298	0.496	0.561	0.368	0.327	0.871	0.248	0.045	6.159
(C) D1	-0.00418	-0.00257	-0.00095	-0.01079	0.00412	0.0039	-0.01078	0.00223	-0.00516	0.00628	-0.00414	0.00741	0.0156	0.00071
(D) D2	0.00247	0.00174	0.00491	0.00369	0.00148	0.00134	0.00327	0.00255	0.00187	0.00249	0.00201	0.00492	0.00097	0.0027
(E) C1	0.05	0.07	0.05	0.05	0.1	0.1	0.15	0.1	0.15	0.1	0.15	0.1	0.1	0.07

(A), (B): Nordhaus and Boyer (2000), Table 3.2, p. 39. (C) (D): Nordhaus 1998 Table 12, (E): Nordhaus and Yang (1996), Table 2, p.746.
(A) is measured in billion 1990 US GDP with market exchange rates and (B) in billion metric tons of carbon equivalent.
D1, D2 are damage function paramters such that D1T+D2T^2 represents regional damage (percentage of regional GDP) when temperature increase is given by T.
C1 is an abatement cost function parameter and represents the fraction of annual output required to reduce net CO_2 emissions to 0.

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