Cooperation on Climate-Change Mitigation†

by

Charles F. Masona,b, Stephen Polaskyc, and Nori Taruid

October 31, 2016

Abstract

We analyze conditions under which it is possible to achieve efficient mitigation of greenhouse gas emissions with a self-enforcing international agreement in which all countries find it in their self-interest to abide by the agreement. We model the choice of emissions by countries as a dynamic game. We use a two-part punishment scheme for deviations from an agreement that is renegotiation-proof and show when this scheme supports the efficient outcome as a subgame perfect equilibrium. Using numerical examples, we show that an efficient subgame perfect equilibrium exists for a range of reasonable parameter values. The existence of such equilibrium may be non-monotonic in the discount rate and the ratio of slope of marginal abatement cost and marginal damages.

Keywords: International Agreements, Climate Change, Differential Games
JEL Codes: Q54, C73

†The authors thank Stephen Salant, Akihiko Yanase, and the seminar participants at the ASSA Meetings, CESifo area conference, University of California – Riverside, Doshisha, European Association of Environmental and Resource Economists, University of Hawaii, the Japan Economic Association Meeting, Hitotsubashi, Tokyo Tech, Tokyo, Tsukuba, Kobe, Keio University, University of Minnesota, Tinbergen Institute, University of Venice and the Occasional Workshop on Environmental and Resource Economics. Two anonymous referees and the guest editors provided valuable criticisms, which helped us focus our discussion. The usual disclaimer applies.

a: Department of Economics and Finance, University of Wyoming
b: Grantham Institute, London School of Economics
c: Department of Applied Economics, University of Minnesota
d: Department of Economics, University of Hawaii at Manoa and University of Hawaii Economic Research Organization (UHERO)
1. Introduction

Global climate change is the central environmental concern of our time: “Continued emission of greenhouse gases will cause further warming and long-lasting changes in all components of the climate system, increasing the likelihood of severe, pervasive and irreversible impacts for people and ecosystems” (IPCC 2014, p. 56). Global climate change is a particularly difficult problem to address precisely because it is global (Barrett 2008). Global environmental problems require concerted action by numerous sovereign countries. However, national sovereignty limits the effectiveness of international agreements because such agreements cannot force a country to do things that are not in the country’s national self-interest. For an international environmental agreement to be effective it should be “self-enforcing,” designed so that it is in the self-interest of each country to abide by the agreement. Designing a self-enforcing agreement is problematic given the nature of the global climate change problem in which each country would prefer to free ride on the efforts of other countries to reduce emissions.

These problems are evident in efforts to negotiate an international agreement on climate change. Starting in 1995 countries have gathered each year at the Conference of Parties under the U.N. Framework Convention on Climate Change. Two significant agreements have come from these meetings: the Kyoto Protocol in 1997, and the Paris Agreement in 2015. Emissions reductions under the Kyoto Protocol were small relative to the size of reductions necessary to avoid potentially dangerous climate change and were limited to developed countries. Even so, many countries failed to meet their commitments emissions under the protocol and the U.S., the largest emitter at the time of signing, failed to ratify the protocol. The Paris Agreement on Climate Change assembled pledges by individual countries to reduce emissions (“Intended Nationally Determined Contributions” or INDCs). While the Paris
Agreement was an important step forward, the sum of the INDCs falls far short of meeting the stated objective of the Paris Agreement to limit the increase in global mean temperature to well below 2 degrees (Rogejl et al. 2016). It is not clear that countries will voluntarily reduce emissions enough to meet the Paris agreement, or to achieve an efficient level of emissions reduction (which may be different than levels specified in the Paris agreement). Limiting emissions to achieve an efficient level of emissions reduction seems to require designing a stronger agreement that goes beyond what countries would individually volunteer to do (Nordhaus 2015).

In this paper, we analyze the issue of designing a self-enforcing climate change agreement to achieve an efficient outcome using a two-part punishment scheme for deviations from an agreement in a dynamic game-theoretic model. We think it is important to use dynamic game theory to account for central features of the climate change problem: Emissions of greenhouse gases (GHGs) from any one country affect global climate with impacts on all countries, GHGs have long residence times in the atmosphere with impacts lasting far into the future, and the severity of impacts from climate change depend on the level of atmospheric GHG stocks, most likely in a non-linear fashion (Broecker 1997; IPCC 2014; Schlenker et al. 2006; Schlenker and Roberts 2006).

While there is a rich literature analyzing climate change agreements, much of the extant literature employs static or repeated games (e.g., Barrett 1994; Barrett 2003; Carraro and Siniscalco 1993; Chander and Tulkens 1995; Finus 2001). Prior work that models climate change as a dynamic game allowing the stock of GHGs to change through time have simplified the analysis by assuming either that damages are linear in the stock of GHGs (Dutta and Radner 2004, 2006a, 2006b, 2009) or that benefits are linear in emissions (Dockner et al. 1996). Our
goal in this paper is to extend this work by providing a dynamic game analysis in a structure where the GHG stock exerts a non-linear impact on payoffs.

To support an international climate change agreement we use a strategy with a two-part punishment for deviations from the agreement (Abreu 1988). Under the agreement, each country initially chooses emissions that in aggregate generate an efficient outcome (cooperative strategy). Each country continues to play the cooperative strategy as long as all other countries do so. If a country deviates from the cooperative strategy, all countries then invoke a two-part punishment strategy. In the first phase, countries inflict punishment on the deviating country by requiring it to curtail emissions while other countries expand emissions. The punishment phase can be designed to achieve the efficient emissions level through choice of how much to curtail emissions of the deviating country and expand emissions of the other countries. We require the two-part punishment scheme to be subgame perfect. The punishment scheme is sufficiently severe so that it deters cheating from the cooperative strategy and is in the self-interest of all countries to carry out the punishment if called upon to do so.

The use of a two-part punishment strategy has several advantages compared to a simple trigger strategy used in prior work (e.g., Dockner et al. 1996). In simple trigger strategies, a defection induces perennial reversion to a less attractive outcome (i.e., once punishment begins it continues forever and the punishment is not Pareto optimal). A criticism of such strategies is that they are not robust against renegotiation: countries can do far better by restarting an agreement. By contrast, the two-part punishment strategy is robust against renegotiation because, by construction, countries remain on an efficient path during punishment and will revert back to the cooperative path upon completion of the first punishment phase. Our results here build on literature from repeated games that shows it is often possible to support an efficient
outcome that is subgame perfect and renegotiation-proof (Farrell and Maskin 1989; Rubenstein 1980; van Damme 1989). Our structure is also more compatible with actual treaties, as most international sanctions are temporary in nature (Hufbauer et al. 1985).\textsuperscript{1}

We identify conditions in which the two-part punishment strategy can support an efficient climate change agreement as a subgame perfect equilibrium. Though such conditions are necessarily complicated for dynamic games with nonlinear payoff functions, we exploit several properties of the game that simplify the analysis. We parameterize a linear-quadratic model to illustrate conditions where an efficient climate change agreement is self-enforcing. We also parameterize the model to mimic current conditions to show whether an efficient self-enforcing agreement is likely to be possible.

We also show that the existence of a self-enforcing efficient policy may depend non-monotonically on the discount factor – a result that does not obtain in either a static or repeated game. While sufficiently small discount factors do not support an efficient outcome for the standard reason that the threat of future punishment is insufficient to deter the current benefit from cheating, sufficiently large discount factors can also fail to support an efficient outcome. Our finding is consistent with findings for dynamic games (Dutta 1995b). We also find that non-monotonicity is possible with respect to the marginal benefits and costs of GHG emission reduction. We find cases where a self-enforcing efficient policy may not exist when the slope of the marginal benefits of GHG emission is too large or too small relative to the slope of the marginal abatement cost. We find these non-linear relationships are relevant over the range of values of key parameters (discount factor, elasticity of marginal utility, marginal benefits and

\textsuperscript{1} A related literature has used two-part punishment schemes to support efficient use of a common property renewable resource like a fishery or grazing lands (Dutta 1995b, Polasky et al. 2006, and Tarui et al. 2008). While use of a common property resource has similarities to the climate change problem, climate change damages are potentially unbounded while those in a commons problem are not, as a player can simply opt out of the commons.
costs of GHG emission reduction) used in previous numerical studies on climate change.

2. Basic model

We start by considering the problem confronting \( N \) identical countries, each of whom must select a time path of emissions; later we relax the assumption of homogeneity. In the main text, we summarize the key points; details are relegated to an appendix.

In the pursuant discussion, we denote country \( i \)'s emission in period \( t \) by \( x_{it} \), a non-negative value. We denote combined emissions for all countries other than \( i \) as \( X_{-it} \equiv \sum_{j \neq i} x_{jt} \), and total global emissions as \( X_t \equiv \sum_i x_{it} \). The transition of the atmospheric GHG stock, \( S \), is given by

\[
S_{t+1} = g(S_t, X_t) = S + \lambda (S_t - S) + \beta X_t,
\]

where \( 1 - \lambda \) represents the natural rate of decay of GHG per period (\( 0 \leq \lambda < 1 \)), \( S \) is the natural equilibrium level of GHG stocks (the level prior to the industrial revolution), and \( \beta \) is a conversion factor from emissions to atmospheric concentrations. There is a finite maximum feasible emission level \( \bar{x} \), so \( 0 \leq x_{it} \leq \bar{x} \). The upper bound on each individual county’s emissions implies a cap on total global emissions; in turn, this implies an upper bound \( \bar{S} = S + \frac{\beta \bar{x}}{1-\lambda} \) on the GHG stock.

To facilitate use of the key points below, we allow for idiosyncratic payoffs in our description of the model here. We assume the period \( t \) payoff to country \( i \) is

\[
\pi(x_{it}, S_t) = B_t(x_{it}) - D_t(S_t),
\]

---

2 We use the term “period” in an abstract manner here; in practice, it might refer to a year or a decade, as in many integrated assessment models.
where \( B_i(x_i) \) is the benefit from economic activity that causes emissions \( x_i \), and \( D_i(S) \) is the damage from climate change when the GHG stock is \( S \). We assume that \( B_i \) is a strictly concave function with a unique maximum \( x_i^b > 0 \), where \( B_i(0) = 0 \) and \( B_i'(x) > 0 \) for \( x < x_i^b \). We call \( x_i^b \) the “myopic business-as-usual” (myopic BAU) emission level; this corresponds to the level of economic activity that maximizes static social surplus, perhaps net of abatement costs. As flow benefits are increasing at lower levels, raising emissions would raise flow payoffs. We assume the climate damage function is increasing and convex in the GHG stock, \( D'_i > 0, D''_i > 0 \). All countries use (common) one-period discount factor \( \delta \in (0,1) \); this discount factor incorporates the growth rate of benefits and damages. To focus the analysis, we abstract from issues of uncertainty: each country has complete information about benefits and damages and observes the history of GHG stock evolution and all countries' previous emissions.

The socially optimal time path of emissions for each country \( i \) sets marginal flow payoffs equal to the social shadow value of carbon. In the version of the model with homogeneous payoffs, this path implies a common level of emissions for all countries; in the heterogeneous payoff version, emissions adjust so as to equate marginal net benefits across countries.

We propose a two-part strategy, which we denote as \( \phi^* \), to support the socially optimal emissions profile (Abreu, 1988). In the first phase of this scheme, which we often term the “cooperative” part, each country emits its socially efficient level of emissions. The second part of the phase, which we often term the “punishment” phase, follows a deviation by some country. In the punishment phase, the country that defected from the treaty – whom we call the “deviant country” – is assigned a lower level of emissions.

- Phase I: Each country \( i \) plays \( x_i^*(S) = x^*(S) \). If any country \( j \) chooses \( x_j \neq x^* \), resulting
in stock $S'$, then go to Phase II$_j(S')$ in the next period. Otherwise, repeat Phase I.

- **Phase II$_j(S')$**: The deviant country $j$ plays $x_j^P(S') = \alpha x^*(S')$, where $0 < \alpha < 1$.

Countries $i \neq j$ play $x_i^P(S') = \left(\frac{N-\alpha}{N-1}\right)x^*(S')$ for $T$ periods. If a country $k$ deviates, resulting in stock $S''$, go to Phase II$_k(S'')$ in the following period. Otherwise, return to Phase I after $T$ periods.

The idea underlying the strategy is that the threat of reduced payoffs during the punishment phase will deter cheating during the cooperative phase. Because the socially optimal emissions profile sets marginal net benefits equal to the social shadow value of carbon, and because the social shadow value of carbon is larger in magnitude than any individual country’s shadow value, each country’s marginal net benefits are positive at their assigned level of emissions in the cooperative phase; accordingly, they suffer lower payoffs in the punishment phase. For this threatened punishment to be credible, it must be in the best interest of every country to honor the terms of the treaty during the punishment phase. Accordingly, the treaty must satisfy two additional conditions: that deviant countries are willing to go accept their punishment (i.e., that no country prefers to repeatedly cheat) and that the other countries are willing to follow through on the punishment (i.e., it pays to punish). In each part of the strategy, and for all countries, the temptation to cheat is driven by the flow net benefit function $B_i(x_i)$, while the costs of cheating are based on the adverse effect on future payoffs. These adverse future effects arise from three sources: 1) cheating in the current period $t$ generates an increase in global emissions, which implies a larger GHG stock in period $t+1$, and hence larger climate damages for the deviant county; 2) cheating in period $t$ implies the deviant country will receive a lower allocation of emissions during the punishment phase, which translates into lower net
benefits in each of periods \( t+1, \ldots t+T \); 3) the increased GHG stock in the next period implies a lower aggregate emissions profile going forward, which will reduce the deviant’s future present discounted flow of payoffs under the treaty following the punishment phase. As the latter two effects are positively related to period \( t+1 \) stock, larger aggregate emissions in period \( t \) imply larger a cost from cheating; the larger is the combined emissions under the treaty, the larger is the reduction in future discounted payoffs. Accordingly, the optimal defection emissions are negatively related to the combined level of emissions from other countries; in this dynamic sense, emissions are strategic substitutes.

Notice that the treaty is designed so that total emissions equal the socially optimal level, based on the stock, in each phase. While this strategy need not generate the strongest possible deterrent ("worst perfect equilibrium"), incorporating this aspect greatly simplifies the task of verifying the existence of a strategy profile that yields a subgame perfect equilibrium. It also allows a concrete interpretation of the way the treaty could be enacted in practice.

Imagine that a global number of emissions permits are available, based on the stock for that period. In Phase I, each country is allocated \( 1/N \) of these permits. In Phase II, the deviant country forfeits a share \( 1-\alpha \) of the permits it would have received, with these forfeited permits distributed pro rata amongst the other countries. Under the plausible assumption that \( x_i^* < x_i^b \) (the myopic BAU emission level), each of the punishing countries benefits from the reallocation. Between the forfeited permits, and the increased future damages that result from the increased emissions from the punishing countries, the deviant country suffers lower payoffs during the punishment phase. As punishment is temporary, countries resume cooperation once the punishment is complete.

An obvious policy consideration under this interpretation is: are countries allowed to
trade permits? In the cooperation phase, for the problem with homogeneous countries, this issue is moot: by allocating each country an equal share of aggregate emissions, we guarantee marginal net benefits are equated across countries. In the punishment phase, a natural additional condition to impose on the deviant country is to prohibit it from participating in any trading scheme. This constraint implies a departure from the equi-marginal principle, which would lower aggregate payoffs; but since the deviant country is allocated a smaller share of the permits, it suffers the lion’s share of the loss in aggregate payoffs.3

To facilitate discussion of conditions where $\phi^*$ gives a subgame perfect equilibrium, we focus on the gain country $j=1,...,N$ obtains by defecting from the treaty when the GHG stock is $S$; because there are three possible arenas for deviation, there are three potential relations between $S$ and gains. Accordingly, we denote deviation gains in Phase I by $G_j^1(S)$, gains from deviation by country $j$ in phase II by $G_j^2(S)$, and gains from deviation by country $k \neq j$ in phase II by $G_k^3(S)$. The three conditions the treaty must satisfy are:

**Condition (1)** (no cheating) no country $j$ has an incentive to deviate in Phase I: $G_j^1 \leq 0$;

**Condition (2)** (no repeated cheating) no country $j$ has an incentive to deviate in Phase II:

$$G_j^2 \leq 0;$$

**Condition (3)** (it pays to punish) no country $k \neq j$ has an incentive to deviate in Phase II:

$$G_k^3 \leq 0;$$

---

3 An alternative mechanism to operationalize our strategy profile is to use a global carbon tax set at the social shadow value of carbon during the cooperation phase. During the punishment phase, a different tax would need to be imposed on the deviant country as compared to punishing countries. In principle, this could be accomplished by giving punishers a subsidy or tax rebate during the punishment phase, and imposing an extra tax on the deviant country. But as an anonymous referee points out, subsidy schemes can be difficult to remove, suggesting a practical complication to their use. Alternatively, the common tax could be reduced during the punishment phase (to the common level of marginal net emission benefits amongst punisher countries), with an add-on tax imposed upon the deviant. While such an approach might be more politically feasible, it seems clumsy in comparison with the permit allocation scheme we suggest in the text.
each of these conditions must hold for all possible stock levels.

Because each player's flow payoff 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 $\phi^*$ is subgame perfect, it is sufficient to show that any one-shot deviation cannot be payoff-improving for any player (Fudenberg and Tirole, 1991). 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 (Dutta, 1995a).

Our first result is that the three conditions can be reduced to one, namely condition (2), for the variant that has one punishment period. (Proposition proofs are given in an appendix.)

**Proposition 1** Suppose the punishment phase lasts one period, $T=1$. Then condition (2) implies conditions (1) and (3).

In a variant of the strategy with multiple punishment periods, a country may cheat in a number of periods, suggesting that many conditions need to be checked. The next proposition shows that it is sufficient to check condition (2) for the first period of Phase $II_j$.

**Proposition 2** Country $j$ has no incentive to deviate in any period during phase $II_j$ if it has no incentive to deviate in the first period in phase $II_j$.

Finally, we note that there is an upper bound on the GHG stock because combined emissions are nonnegative and bounded by the maximum feasible level. As a result, there are at most three candidate values for stock that could yield maximal deviation gains during phase $II_j$. If gains are monotonic in stock, maximal deviation gains either obtain at the lowest possible value or the largest possible value. If gains are non-monotonic, then either there is an interior
maximum (in which case the relevant stock value is that value which delivers the interior maximum) or there is an interior minimum, in which case maximal deviation gains arise at one of the two corners. In any event, it becomes a simple matter to check that deviation gains in phase IIj are never positive for any country j.4

3. A linear-quadratic example with homogeneous countries

In this section, we analyze a stylized version of our model, with a linear-quadratic specification for payoffs (Newell and Pizer 2003 Karp and Zhang 2006, 2012). The linear-quadratic model eases the burden of computing equilibria of dynamic games and it is “simple to calibrate and easy to interpret, making it possible to understand the effect of assumptions about parameters” (Karp and Zhang 2006). For now, we also impose homogeneity across countries’ payoff function; this assumption is relaxed below.

We assume that country i’s emission benefit and the climate damage in period t are both proportional to country i’s national income: yit, the country’s GDP in period t:

\[ B(x_{it}, y_{it}) = (a x_{it} - b x_{it}^2) y_{it}; \]
\[ D(S_t, y_{it}) = (c_i S_t + d_i S_t^2 + f_i) y_{it}; \]

with ai, bi, ci, di, fi > 0. The negative of the derivative with respect to emissions, -(ai - 2bx),

4 If \( \phi^* \) is not consistent with a subgame perfect equilibrium, there may be some other strategy profile that supports the efficient solution as a subgame perfect equilibrium outcome. A punishment is most effective as deterrence if it induces the worst perfect equilibrium payoff. Though a punishment that invokes the worst perfect equilibrium supports cooperation under the widest range of parameter values, finding the worst perfect equilibrium is quite complicated in our model and so we do not attempt to solve for the worst perfect equilibrium. Previous dynamic game studies analyzed cooperation with worst perfect equilibria punishment in the context of common-property resources (Dutta 1995b, Polasky et al. 2006). With common-property resources, the worst perfect equilibrium payoff is defined by the outside option for a resource user—the payoff that player would receive if they stopped using the resource. With climate change, a country cannot opt out: they will suffer damages as a function of the state of the climate regardless of whether or not they cooperate with the international agreement.
represents the marginal abatement cost associated with emissions $x_i$. Country $i$’s myopic BAU emission that maximizes the period-wise return is $x_i^b = \frac{a_i}{2b_i}$. Country $i$’s present-value return is then given by

$$\sum_{t=0}^{\infty} \delta^t \{ a_ix_{it} - b_ix_{it}^2 - ac_is_t - d_is_t^2 - f_i \}y_{it}.$$  

For now, we assume homogeneity in the per-capita payoffs, i.e. the parameter vector $(a_i,b_i,c_i,d_i,f_i)$ = $(a,b,c,d,f)$, for all $i$; we relax this assumption in section 4. It can be shown that the value function is quadratic and a unique linear policy function exists for the efficient solution.\(^5\)

A key parameter in our numerical analysis is the ratio of the slope of global marginal net benefits to the slope of marginal climate damages, which we denote by $\gamma$. With $N$ identical countries, $\gamma = b/(dN^2)$.\(^6\) As there is a wide range of uncertainty about the marginal abatement and marginal damage parameters, we consider a range of values for $\gamma$, including those used in the previous studies (e.g. Nordhaus and Boyer 2000, Newell and Pizer 2003, Karp and Zhang 2012).

Following Nordhaus and Yang (1996) and Newell and Pizer (2003), we assume the decay rate of CO$_2$ to be 0.83% and the retention rate of current emissions to be 64% (per year). The pre-industrial stock level is $S = 613$ GtC (gigatons of carbon equivalent). Thus the carbon stock transition is given by

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

The initial stock level is $S_0 = 787$ GtC (the level in 1995). We assume that the maximum feasible

\(^5\) Details are available in an ancillary appendix.

\(^6\) When $N$ identical countries choose the same emission level $x$, net global period-wise payoffs are $N(ax-bx^2-cS-dS^2) = aNx-(b/N)(Nx)^2 - NcS - NdS^2$. Thus, the ratio of slopes of global net marginal benefits to global marginal damages is $\gamma = (b/N)/(Nd)$. 

12
emission level is $\bar{x}_i = \bar{x} = a/b$ for all $i$. Thus, $\bar{S} = \frac{Na}{b(1-\lambda)}$.

In the first several results we discuss, the parameter describing forfeited emissions in the punishment regime, $\alpha$, is equal to 0.9. We also discuss the implications of varying this parameter, with results presented in Figure 5 below. Throughout the discussion, we assume $T = 1$.

We begin by showing a case where the efficient outcome can be sustained in a self-enforcing international agreement using the two-part punishment scheme ($\phi^*$ is a subgame perfect equilibrium); Figure 1 illustrates. Each curve in Figure 1 represents the net gains from playing $\phi^*$ versus the optimal deviation for country $j$ in Phase I, Phase II$j$, and Phase II$k$ at each stock level. (I.e., the curves represent $-G^1$, $-G^2$ and $-G^3$, respectively). That these curves are all positive over the complete range of potential stock sizes shows that there is no profitable deviation at any stage for any feasible stock level. Further, having non-negative net gains from playing $\phi^*$ in Stage II$j$, in which country $j$ has to go along with the punishment of itself, is the most difficult condition to satisfy – in accordance with Proposition 1.

We next consider the influence of the discount factor on whether the treaty generates a subgame perfect outcome; Figure 2 illustrates. There, we show the various combinations of the discount factors and the slope of the marginal climate damages for which $\phi^*$ is a subgame perfect equilibrium (shaded areas in Figure 2). While the folk theorem tells us that any outcome with individual rational payoffs can be supported in a subgame perfect equilibrium in a repeated game so long as players are sufficiently patient, this result need not be true in dynamic games (Dutta, 1995b). In our model, we find cases where $\phi^*$ is a subgame perfect equilibrium at some

---

7 At this level, flow benefits vanish: $B(\bar{x}) = 0$. 

discount factor and ceases to be subgame perfect as the discount factor is increased or decreased. For values of the slope of marginal damage function between 0.003 and 0.010, the profile $\phi^*$ is not subgame perfect when $\delta$ is too close to 1 or less than 0.96 but is subgame perfect for some intermediate values of the discount factor. In a repeated game, the only impact of a higher discount factor is to increase the weight on the future, which increases the weight of punishment relative to immediate gains from cheating. In a dynamic game like ours, however, changing the discount factor also changes the path of efficient emissions and the efficient steady state stock of GHGs in the atmosphere. As $\delta$ increases, the efficient level of emissions declines and the equilibrium GHG stock decreases. But this change makes cheating more valuable. Therefore, both the future payoff associated with $\phi^*$ and the payoff associated with optimal deviations increase. Movement along the arrow in Figure 2 indicates that the latter may increase by a larger amount than the former when the discount factor is sufficiently large. We note also that larger values of $d$ allow $\phi^*$ to be subgame perfect at smaller discount factors.

We next consider the role of $\gamma$, the ratio of the slope of marginal net global benefits to the slope of marginal climate damages, in determining whether the treaty $\phi^*$ is subgame perfect. As Figure 3 illustrates, $\phi^*$ is a subgame perfect equilibrium when $\gamma$ is neither too large nor too small. At points like H, where $\gamma$ is large, the magnitude of marginal damages from the GHG stock is small relative to marginal abatement costs. At such parameter combinations, the difference between the level of efficient emissions and the level of non-cooperative emission is small, which makes the potential gains from a shift to an efficient outcome relatively small. For smaller values of $\gamma$, marginal damages increase faster than the marginal abatement costs as pollution stock increases. Accordingly, the difference between the efficient emissions and non-
cooperative emission levels becomes larger. Because the efficient emission control calls for larger emission reduction for each country, both the gains from cooperation and temptations to deviate increase. When $\gamma$ is not too small, the former exceeds the latter and $\phi^*$ is subgame perfect. However, at points like L, the temptation to deviate exceeds the gains from cooperation and hence $\phi^*$ is not a subgame perfect equilibrium.

Figure 4 illustrates whether $\phi^*$ is subgame perfect for a range of the values of $\gamma$ adopted from the literature for discount factors ranging from 0.97 to 0.9999. The red lines indicate three values of $\gamma$ used in the literature: $\gamma=12,269$ (Karp and Zhang, 2012), $\gamma=53,630$ (Nordhaus and Boyer, 2000), and $\gamma=183,908$ (Newell and Pizer, 2003). This figure has several important implications. First, for smaller values of $\gamma$, there is small range of discount factors for which $\phi^*$ is subgame perfect. Therefore, more optimistic estimates of the slope of the marginal abatement costs or more pessimistic estimates about the slope of the marginal damages, both of which would reduce $\gamma$, could reduce the likelihood of a successful agreement. Second, for sufficiently small values of $\gamma$, the effect of the discount rate on whether $\phi^*$ is subgame perfect is non-monotonic, as discussed above.

Figure 5 shows the range of $\gamma$ and $\alpha$ that make $\phi^*$ subgame perfect. Lower values of $\alpha$ correspond to more severe punishment. The results illustrate here indicate that when punishment is mild ($\alpha$ is too close to 1), the treaty is incapable of deterring cheating in the first place. But when punishment is too sever ($\alpha$ is too far from 1), the deviant country $j$ would find it profitable to repeatedly cheat. For the treaty to be successful, the sanction must be neither too stringent nor

---

8 Other studies have used estimates of $\gamma$ of the same order of magnitude (e.g. Hoel and Karp 2002, Falk and Mendelsohn 1993, Reilly 1992). An ancillary appendix has a brief survey of the estimates of $\gamma$ used in the literature.
too lenient. The results illustrated in this figure also point to significant variation in the level of punishment (i.e., the value of $\alpha$ that would support a first-best outcome). Given the apparent uncertainty regarding the true value $\gamma$, this is a cause for concern. That said, if one were relatively confident that $\gamma$ exceeded 40,000, then values of $\alpha$ between 0.8 and 0.9 would seem likely to accomplish the desired goal. By contrast, if one relatively confident that $\gamma$ was less than 40,000, then values of $\alpha$ between 0.3 and 0.5 would be indicated. Thus, one way to address the concern related to uncertainty over $\gamma$ is to think about learning whether the parameter is smaller or larger than 40,000.

Figure 6 illustrates combinations of $\alpha$ and $\delta$ for which the treaty is sub-game perfect. There are no values of $\alpha$ that would support the socially efficient outcome when $\delta$ is too small, though the range of values of $\alpha$ would support the efficient outcome expands rapidly as less $\delta$ increases above .98; with $\delta \geq .99$, the range comprises much of the unit interval. Even so, at every value illustrated the treaty cannot succeed if $\alpha$ is too close to unity; this is intuitive: without the threat of sufficient punishment, as reflected by smaller values of $\alpha$, repeated cheating can not be deterred.

An important practical consideration for treaty negotiation is whether an agreement can work when there are a large number of countries involved. Figure 7 shows the impact of the number of countries on whether $\phi^*$ is subgame perfect. The most striking feature of the analysis is that for these particular set of parameter values there is a hard cap at $N = 8$. With more than 8 countries, there is no possibility of a self-enforcing efficient outcome; with fewer countries, $\phi^*$ can be subgame perfect for certain values of $\gamma$. For small values, an increase in $\gamma$ can facilitate a larger coalition. However, past a certain point, between the values of $\gamma$ associated with the Karp
and Zhang and the Nordhaus and Boyer studies – further increases in \( \gamma \) do not engender larger coalitions. While there are over 190 countries involved in the climate negotiations, the lion’s share of emissions can be attributed to a small number of countries. China, the European Union, India, Japan, Russia and the United States (\( N = 6 \)) are collectively responsible for nearly 70% of global CO2 emissions (WRI 2015).

4. An Example with Heterogeneous Countries

In reality, there are important differences between countries in terms of both the damages from climate damages and the costs of mitigation. In this section, we discuss an extension of the model to allow for heterogeneous payoffs. To this end, we consider a variant of the problem with four countries who are characterized by combinations of myopic BAU emissions and the ratio of the slope of marginal net benefits from emissions to the slope of marginal climate damages, \( \gamma_i \).

We use two values of \( a_i \), 10.0 and 10.2, and two values of \( \gamma_i \), 50,000 and 62,500. Countries 1 and 3 have low BAU emissions (\( a_i = 10.0 \)) while countries 2 and 4 have high BAU emissions (\( a_i = 10.2 \)); \( \gamma_i = 50,000 \) for countries 1 and 2 while \( \gamma_i = 62,500 \) for countries 3 and 4. One way to interpret differences in BAU emissions is in terms of the size of the countries’ economies, with lower BAU emissions corresponding to smaller economies. Differences in \( \gamma_i \) might reflect differences in technological capabilities for abatement, differences in carbon-laden resource endowments, or differences in exposure to climate damages. For example, a country like India – which is more exposed to sea level rise or temperature increases – would likely have a smaller value, while a country like Russia – which has significant holdings of oil and gas reserves – would likely have a smaller value. We assume \( \lambda = .99 \) and \( c = 0 \) for all four countries, that \( \alpha = 0.9 \) and that \( S_0 \leq S^* \)
We assume that aggregate cooperation payoffs are divided equally across countries; to that end, we allow transfers among countries. Let $\tau_{it}$ be the net transfer to country $i$ in period $t$, where $\sum_t \tau_{it} = 0$ in each $t$. Country $i$’s net one-period return in period $t$ is then $B_t(x_{it}) - D(S_t) + \tau_{it}$. The transfers could be determined based on cost burden sharing agreed on by the countries; alternatively, they could reflect political considerations.9

Figure 8 describes the gains from cooperation in phase II$_j$ for this example. We illustrate results for two levels of the discount rate: $\delta = 1/1.04$ (the left-most panel) and $\delta = 1/1.025$ (the right-most panel). For both values of $\delta$, the gains from cooperation in II$_j$ are increasing in the stock of GHGs for all four countries. When the discount rate is 4% ($\delta = 1/1.04$), the gains from cooperation for countries 3 and 4, are negative at low values of $S$; condition (2) fails here. On the other hand, when the discount rate is 2.5% ($\delta = 1/1.025$), the gains from cooperation in II$_j$ are positive for all four countries at all values of $S$. Accordingly, the strategy $\phi^*$ yields a subgame perfect equilibrium in this case. We also note that for a given value of $\gamma$, the gains from cooperation in phase II$_j$ are larger for countries with lower BAU emissions. Given equal sharing of aggregate cooperative payoffs, a country with higher BAU emissions has less to lose by deviation than a country with lower BAU emissions. We note also that a country with lower marginal damages has less to lose from deviation than does a country with higher marginal damages. Despite these differences, this example illustrates the potential for a self-enforcing agreement to exist, using a strategy profile such as we propose, even when payoffs are heterogeneous.

9 In practical terms, these side payments could be organized in process of allocating emissions permits, and then allowing countries to trade. As in the homogeneous case, however, it seems prudent to prohibit deviant countries from participating in permit trading.
5. Discussion

Climate change mitigation is a global public good. While mitigation by any one country benefits all countries, reducing GHG emissions is costly to undertake, which gives powerful incentives to free ride on the efforts of other countries. For sovereign countries to abide by an international agreement to control GHG emissions, the agreement must be self-enforcing for each country, which is a difficult proposition given the structure of the climate change problem. In this paper, we described a two-part punishment scheme that is self-enforcing: all countries find it in their self-interest to honor the agreement by choosing their agreed upon emissions level, and all countries have an incentive to carry out the punishment should that be required. In addition, the two-part punishment scheme can be designed to be renegotiation-proof so that countries would not find it advantageous to reopen the agreement in the punishment phase, which would undermine the credibility of punishment.

We examined conditions under which efficient GHG mitigation can be achieved as a subgame perfect equilibrium under the two-part punishment scheme. We find a range of plausible parameter values where the efficient outcome is achieved as a subgame perfect equilibrium. While one might expect that it should be easier for countries to avoid free riding and abide by the international agreement as discount factor or the stock of GHG in the atmosphere increases, our simulation results indicate that this is not necessarily the case. Whether the international agreement treaty is self-enforcing may depend nonlinearly on the countries’ discount factor and GHG stock. While the international agreement is not self-enforcing for sufficiently small discount factors, we also find cases where an increase in the discount factor may make the agreement no longer self-enforcing. We also find the potential for non-
monotonicity regarding the marginal benefits and costs of GHG emission reduction. These relationships are relevant over a range of parameter values for the discount factor, marginal benefits and costs of GHG emission reduction, used in previous numerical studies on climate change.

The approach to designing an international agreement at the Paris Climate Change Conference in December 2015 was quite different than the approach of designing a self-enforcing agreement analyzed in this paper. At Paris, individual countries made pledges to reduce their emissions of GHGs but there was no explicit enforcement mechanism to penalize a country that fails to follow through on its pledge. But what is in a country’s own self-interest will typically be quite different from what is efficient from a global perspective. Indeed, the pledges made by countries fall far short of what is needed to keep temperature from rising beyond the 2 degrees limit described by the Paris Agreement (Rogelj et al. 2016). Similarly, Nordhaus (2015) finds that sanctions are essential for reducing emissions beyond the noncooperative equilibrium that countries would choose with no international agreement.

While the dynamic-game formulation used here to analyze a self-enforcing treaty for climate-change mitigation provides insights not available in simpler static or repeated game analyses, we have abstracted from a number of important issues. First, we analyzed the model assuming that all countries are party to the agreement (i.e., no non-participants). Designing treaties so that countries are better off participating than free-riding is the subject of related literature on the stability of international environmental agreements (Battaglini and Harstad 2016; Bosello et al. 2003; de Zeeuw 2008; Eyckmans and Tulkens 2003; Harstad 2012, 2016; Nordhaus 2015; Rubio and Ulph 2007). An agreement is stable when no country in the agreement can improve its payoff by dropping out of the agreement, and no country outside the
agreement can improve its payoff by joining. Nordhaus (2015) discusses how to use trade sanctions for non-participating countries, which can provide sufficient incentives for countries to join the international agreement (see also Barrett 2003; Lockwood and Whalley 2010). This literature, however, typically uses static or repeated games and does not undertake a full dynamic analysis of whether countries have profitable incentives to cheat on the agreement as was done in this paper. A valuable next step would be to have a full model that included analysis of both participation and enforcement.

Second, our model assumes that the net benefits function for a country (excluding climate damages) depends only the emissions levels and is not changing through time \( B_i(x_{it}) \). In reality, investment in clean technology (e.g., renewable energy) or dirty technology (e.g., coal-fired power plants) would change the net benefits function. With investment in capital stock or technology, the benefits function could be modeled as \( B_i(x_{it}, K_{it}) \), where \( K_{it} \) is a measure of capital stock relevant to calculating benefits. A game involving choice of emissions and investment in capital could involve analysis of complex strategic incentives to manipulate other countries’ choice of capital stock and the related choice of future emissions. However, if the benefits functions of countries including how they are affected by choice of capital are known, the international agreement could be designed in such a way as to allocate permits through time based on efficient choice of investment and emissions.

Third, we have assumed that emissions are observable and that there is no uncertainty about emissions levels, benefits functions, or damages from climate change. Of course, in reality there is considerable uncertainty about all of these elements. Inability to directly observe emissions means either that it may not be possible to direct punishment to a specific country that deviates from the agreement. Tarui et al. (2008) consider two-part symmetric punishment
inflicted on all countries when it is clear at the aggregate level that at least one country has cheated. Green and Porter (1984) discuss enforcement issues with unobservable choices and uncertainty at the aggregate level.

Careful consideration of the design of international agreements to include analysis of enforcement mechanisms that give incentives of countries to abide by the agreement could improve outcomes for difficult global environmental problems like climate change. Expanding the model here to include additional components would make the analysis more realistic and more directly applicable to climate change policy.

References


Dutta, P.K. And R. Radner. (2006b) Population Growth and Technological Change in a Global


Stern, N.H., S. Peters, V. Bakhshi, A. Bowen, C. Cameron, S. Catovsky, D. Crane, S.


Figure 1. Gains from cooperation for country j in Phase I, Phase IIj, Phase IIk for an example where $\phi^*$ is a subgame perfect equilibrium. Parameter values: $a = 100, b = 1,200, c = 0, d = 0.001, N = 4, \delta = \lambda = 0.99, S = 0, \beta = 1, \alpha = 0.9$ and $T = 1$.

Figure 2. The effect of the discount factor on whether $\phi^*$ is a subgame perfect equilibrium. Parameter values: $a = 100, b = 1,200, c = 0, N = 4, \lambda = 0.99, S = 0, \beta = 1, 0.9 \leq \delta \leq 0.999, \alpha = 0.9$ and $T = 1$. 

Shaded area: self-enforcing agreement can support the efficient outcome.
Figure 3: The effect of the slope of marginal damages and the slope of marginal abatement costs on whether $\phi^*$ is a subgame perfect equilibrium. Parameter values: $a = 100, c = 0, N = 4, \lambda = \delta = 0.99, S = 0, \beta = 1, 500 \leq b \leq 5,000, 0.0001 \leq d \leq 0.005, \alpha = 0.9$ and $T = 1$.

Figure 4: An illustration of whether an efficient self-enforcing agreement exists for a range of realistic parameter values from the literature for the ratio of the slopes of marginal abatement cost and marginal damages, and different discount factors. Parameter values: $N = 6, c = -0.1421$, $d = 1.0032 \times 10^{-4}, b = Nd\gamma, a = 2(b/N)\bar{E}$, where $\bar{E} = 6.1586$ is global 1995 CO2 emissions missions from fossil-fuel burning (in million tC), $\bar{S} = 613, \beta = 0.64$; $\alpha$ is allowed to vary between 0 and 1.
Figure 5: An illustration of whether an efficient self-enforcing agreement exists for a range of realistic parameter values from the literature for the ratio of the slopes of marginal abatement cost and marginal damages, and different levels of sanctions. The severity of sanctions that enforce an agreement varies with gamma. Parameter values: \( N = 6, c = -0.1421, d = 1.0032 \times 10^{-4}, b = N \gamma, a = 2(b/N)\bar{E}, \) where \( \bar{E} = 6.1586 \) is global 1995 CO\(_2\) emissions missions from fossil-fuel burning (in million tC), \( S = 613, \beta = 0.64, \) and \( \delta = 1/1.01. \)

Figure 6: An illustration of whether an efficient self-enforcing agreement exists for a range of realistic parameter values from the literature for the ratio of the slopes of marginal abatement cost and marginal damages, and different levels of sanctions. The severity of sanctions that enforce an agreement varies with gamma. Parameter values: \( N = 6, c = -0.1421, d = 1.0032 \times 10^{-4}, \gamma = 53630, b = N \gamma, a = 2(b/N)\bar{E}, \) where \( \bar{E} = 6.1586 \) is 1995 global CO\(_2\) emissions missions from fossil-fuel burning (in million tC), \( S = 613, \beta = 0.64, \) and \( \delta = 1/1.01. \)
Figure 7: The impact of the number of countries on whether an efficient self-enforcing agreement exists. Parameter values: $c = -0.1421, d = 1.0032 \times 10^{-4}, b = N d y, a = 2(b/N)\tilde{E}$, where $\tilde{E} = 6.1586$ is 1995 global CO2 emissions missions from fossil-fuel burning (in million tC), $S = 613$, $\beta = 0.64$, and $\delta = 1/1.01$, $\alpha$ is allowed to vary between 0 and 1.

(a) $\delta = 1/1.04$

(b) $\delta = 1/1.025$

Figure 8: Gains from cooperation for heterogeneous countries. Parameter values: $N = 4, a = (10, 10.2, 10, 10.2), \gamma = (50000,50000,62500,62500), \lambda = 0.99, S = 1, \beta = 1, \alpha = 0.9$ and $T = 1$. 