A proposal for the reform of the Kyoto Protocol: escape clauses under cost uncertainty

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Abstract

A reform to the Kyoto Protocol that allows signatories to avoid achieving the target level of abatement upon payment of a fine, would achieve two goals. First, it would defuse one U.S. objection to the agreement: the concern that the cost of achieving the target might turn out to be extremely high. Second, unlike other cost-reducing measures (such as trade in pollution permits) it would increase the equilibrium number of signatories in a non-cooperative participation game. We study the participation game under an escape clause using both a Nash Equilibrium and the concept of a Stable Set when nations are "Farsighted".

Keywords: Kyoto Protocol, escape clause, cost uncertainty, participation game, International Environmental Agreement, stable set with farsight, coalitional games.

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1 Introduction

The control of greenhouse gasses (GHGs) requires international cooperation. The U.S. withdrawal from the Kyoto Protocol ("Kyoto"), and the questionable compliance of signatories, may render the agreement ineffective. The U.S. objected to (amongst other things) the Protocol's imposition of an aggregate emissions ceiling, expressing the concern that the economic cost of achieving this target might be very large. If signatories discover that abatement costs are larger than anticipated, their compliance may erode. Since the treaty extends only to 2012, it is worth understanding how its successor should be designed. A reform to the Kyoto Protocol that allows signatories to avoid achieving the target level of abatement upon payment of a fine, would achieve two goals. First, it would defuse one U.S. objection to the agreement: the concern that the cost of achieving the target might turn out to be extremely high. Second, unlike other cost-reducing measures (such as trade in permits) it would increase the equilibrium number of signatories in a non-cooperative participation game. We study the participation game under an escape clause using both a Nash Equilibrium and the concept of a Stable Set when nations are "Farsighted".

Although there is much more uncertainty about the benefit of GHG abatement than about the cost of abatement, arguably cost uncertainty is more important to the design of an International Environmental Agreement (IEA). Kyoto will be in force for only four years; the duration of its successor is also likely to be fairly short. During this period, we will learn the costs of a particular level of abatement. Barring a catastrophic event, our information about the benefit of this abatement will probably change only slightly during this period. Therefore, for the purpose of designing a short-term IEA, it makes sense to treat abatement costs as a random variable whose value will be realized during the lifetime of the IEA, and the abatement benefit as a random variable that will be realized in the distant future.

Many papers (including Carraro and Siniscalco (1993), Barrett (1994), Bloch (1997), and Dixit and Olson (2000)) and several books (including Finus (2001), Batabyal (2000), and Barrett (2003)) treat an IEA as the non-cooperative Nash equilibrium (NE) of a participation game. Details vary across the models, but the basic structure of this "standard model" is that in the first stage (the participation game) homogeneous countries decide whether to join an IEA, and in the second stage (the abatement game), the IEA decides the signatories' abatement level. The critical assumption is that when nations decide whether to participate in the IEA they anticipate that in the next stage the IEA's abatement decision will maximize member's joint welfare.

Hereafter, by "standard model" we mean the model in which the abatement decision is conditioned on the number of IEA members. In this model, the IEA (typically) contains two or more signatories.

If the timing was changed so that the IEA made its abatement decision before nations make their participation decisions, the IEA size in the NE would (typically) be zero. Nations are willing to join the IEA only if they think that their membership will change the actions taken by *other* members. If the IEA has made the abatement decision before nations decide whether to participate, each nation understands that it has no leverage over IEA members. In that case, the temptation to free-ride (by not signing the IEA) eliminates the incentive to join and IEA.

An important result from the standard model is that the equilibrium size of the IEA tends to be small in circumstances when the potential benefits from cooperation are large. Holding fixed the benefit from abatement, the potential benefit from cooperation is large when abatement costs are small. Other things equal, an *increase* in the abatement cost (weakly) increases the equilibrium size of the IEA, with an ambiguous effect on the benefit from cooperation. Although this result is somewhat counter-intuitive, its explanation (discussed below) is straightforward.

This result implies that efforts to reduce the costs of IEA compliance might backfire, by reducing equilibrium membership. There has been substantial interest in reforms to enable Kyoto members to achieve a given level of abatement more cheaply. After initial resistance, Kyoto signatories accepted tradeable permits and "joint implementation", and are discussing the use of "clean development mechanisms".[1] Another possibility is a hybrid policy that uses tradeable permits with a price ceiling; a regulator has the power to increase the allocation of permits to defend the price ceiling ((Pizer 2002), (Kopp, Morgenstern, Pizer, and Ghersi 2002), (Victor 2003)). The current carbon reduction agreement amongst northeastern U.S. States uses a similar policy. This policy caps abatement costs and therefore reduces expected costs. If applied to Kyoto, this kind of policy would have weakened one of the U.S. objections to the agreement. The irony is that if the standard model of IEAs is a reliable description, the hybrid policy would have *decreased* nations' incentive to join Kyoto.

The standard model implies that the central impediment to a successful IEA is the difficulty of inducing sovereign nations to voluntarily refrain from free-riding, rather than design flaws

[1]Under joint implementation, a signatory obtains credit for abatement by investing in carbon abatement or sequestration activities in another member country. Under the proposed clean development mechanism, a signatory obtains abatement credit by investing in abatement or sequestration activities in a developing non-signatory country.

such as the failure to accommodate the possibility of unexpectedly high abatement costs. Design changes that reduce these costs might even be counterproductive. A corollary is that a successful IEA requires some kind of external punishment; Barrett (2003) (chapter 15) makes this case persuasively. Some have proposed reforming the World Trade Organization to permit the use of trade sanctions against countries that do not abide by a climate change IEA [cites here]. There appears to be little chance that the environmental tail will wag the trade dog, even if such an outcome were desirable. If an effective IEA really does require an external threat, the prospect of dealing successfully with the problem of climate change seems poor.

In our view, the pessimistic conclusion that effective IEAs require an external threat, and that they are unlikely to benefit from design changes, is exaggerated. That conclusion is a consequence of the assumption that the IEA makes the abatement decision conditioned on membership size, in order to maximize member's joint welfare. This assumption does not describe how IEAs actually behave. In one sense this assumption exaggerates IEAs' power, because clearly these are not capable of solving the collective action problem (although they might ameliorate it). In another sense, the assumption understates IEAs' power, because these are capable of prescribing contingent actions. The terms of an IEA are negotiated before, not after nations decide whether to sign.

We modify the standard model by replacing the assumption that signatories commit (only) to maximizing members' joint welfare, with the assumption that they can sign a simple binding contract. In our setting, with uncertain abatement costs, the IEA agreement is a contract that contains an escape clause. This contract consists of two parameters, a prescribed level of abatement and a cost of exercising the escape clause (a "fine") that exempts the signatory from the requirement to abate. Revenue from the escape clause payments are returned equally to all signatories, except for a transactions cost. In the first stage nations decide whether to join the IEA (the participation game). In the second stage (the abatement game) each signatory observes the outcome of the participation game (the number of signatories) and learns its abatement cost, which cannot be verified by courts. The signatory then decides whether to abate or to invoke the escape clause, taking as given other signatories' decision rules.

Kyoto does have a prescribed level of abatement – a feature that the U.S. criticized – and in that respect it does not conform to the standard model's description of an IEA. Our proposal differs from Kyoto by including the escape clause. This modification has two desirable effects. First, it protects signatories from unexpectedly high abatement costs, and thus answers one of

the U.S. objections. Second, unlike other cost-reducing reforms, such as trade in permits, the escape clause can increase equilibrium membership.[2]

It would be unreasonable to think that so simple a design change could solve the free-rider problem. We interpret the result as showing that a simple design change can substantially ameliorate the free-rider problem. This may appear to be a fairly non-controversial claim, but it is contrary to the IEA literature discussed above. That literature implies that design changes that reduce costs are futile, or even counterproductive. This conclusion emerges from a model that has become so widely used that it has taken on an air of inevitability.

The standard model, and our first set of results, uses a Nash equilibrium to the participation game. Modern games of coalition formation, including Chwe (1994), Mariotti (1997), Xue (1998) and Ray and Vohra (2001) are based on a more sophisticated interpretation of rationality, in which agents understand how their provisional decision to join or leave a coalition would affect other agents' participation decisions; nations are "farsighted". Diamantoudi and Sartzetakis (2002) adopt a similar notion of farsightedness to study IEAs, without establishing a precise relationship with the earlier theoretical literature. Eyckmans (2001) and de Zeeuw (2005) apply that definition to IEA models. Our description of farsighted nations builds directly on Chwe (1994).

Section 2 sets out our model. Section 3 analyzes the one-shot NE, and Section 4 compares our model with the standard model. Section 5 studies the non-cooperative participation game when nations are farsighted.

2 The Model

Each of N homogenous nations decides whether to join an IEA to reduce a global pollution. When nations make this decision the terms of the IEA are taken as given. The IEA specifies a target level of abatement, normalized to 1, and it contains an escape clause that allows a signatory not to abate if it pays a fine F. Abatement is a global public good, with constant marginal expected benefit $b > 0$. If m countries abate, all countries receive the expected benefit bm.

[2]In order to be able to study the effect of an escape clause in a simple setting, we ignore trade in emissions permits, an important feature of Kyoto. Trade in permits equalizes marginal abatement costs across countries, but *total* abatement costs still differ, so even with trade there is a role for the escape clause. Tradeable permits (with or without a price ceiling) "merely" reduce expected membership costs.

In the case of GHGs and a short-lived IEA, it is reasonable to treat b as a constant. Potential environmental damages are caused by the stock, not the flow of GHGs. During a short period of time (less than a decade), changes in the flow of GHGs will not lead to significant changes in the stock. Provided that expected marginal benefit is a continuous function of the stock, a change in the number of countries that abate has a negligible effect on the marginal benefit of abatement.[3] Hereafter we choose units of the value of abatement so that $b = 1$.

When nations decide whether to join the IEA, they do not know their true abatement costs. At this stage nations are identical; they all face the same probability distribution for costs. Nation i knows that its abatement cost θ_i, is a random variable drawn from $\Theta = \{\theta_L, \theta_H\}$, with $\theta_H > \theta_L$ and $p \in (0, 1)$ equal to the probability that $\theta_i = \theta_H$. The distributions of θ_i, $i = 1, \ldots, N$, are independent.

The IEA game has three stages. The fine F and the level of abatement (normalized to 1) are determined in stage 0. We do not model this choice, although we consider its welfare consequences. (The abatement level determines Θ and p.) The parameters F, Θ, and p are common knowledge. In stage one, nations play a *participation game* in which they decide whether to join the IEA. We study two types of equilibria to the participation game, the NE (Section 3) and an equilibrium based on farsightedness (Section 5). The outcome of this game is a partition of nations between signatories and non-signatories. Nations understand how their participation decision affects the final outcome in stage two. In stage two, each nation observes its own abatement cost θ, it knows whether it is a signatory, and it knows the total number of signatories. Based on this information, nations play a non-cooperative *abatement game*, each deciding whether to abate.

If M nations sign the IEA in the first stage and $M - m \geq 0$ of them invoke the escape clause in the second stage, revenue from the fine is $(M - m)F$. This revenue is shared equally among the M signatories (perhaps to provide a club good), except for a fraction $0 < 1 - \phi < 1$ that is lost to transactions costs. Each of the signatories receives a transfer of $\frac{M-m}{M}\phi F$.

[3]The first order approximation of damages equals a constant plus $b(dS)$, where dS is the change in the stock. Provided that the damage function is differentiable, this approximation is "adequate" if dS is very small – as is the case in our setting.

2.1 Stage two: the abatement game

We assume that the IEA requires an abatement level that exceeds the individually rational abatement even when $\theta = \theta_L$. This assumption is equivalent to

$$\theta_L > 1. \tag{1}$$

This inequality implies that in the abatement game, a non-signatory has a dominant strategy of not abating.

A signatory must abide by the terms of the IEA. A signatory's abatement decision depends on its cost realization $\theta \in \Theta$ and the number of signatories $M \in \mathcal{N} \equiv \{0, 1, \ldots, N\}$. The signatory's action set is $\{0, 1\}$ where 1 stands for abating and 0 stands for not abating. Its strategy is a mapping from $\Theta \times \mathcal{N}$ to $\{0, 1\}$. We consider only *symmetric pure strategy* Nash equilibria, hereafter referred to as simply NE.

There are three types of NE in the abatement game. In a type 0 NE, each signatory's strategy is not to abate for any cost realization; in a type 1 NE, each signatory's strategy is to abate only if its own cost is θ_L; and in a type 2 NE, each signatory's strategy is to abate for either cost realization. A nation that is indifferent between the two actions breaks the tie by abating. A non-signatory does not abate in any type of NE.

When there are M signatories, the probability that m of the $M-1$ other signatories have cost θ_L is given by the binomial formula

$$p_{m,M-1} \equiv \frac{(M-1)!}{m!\,(M-1-m)!}\,(1-p)^m\,p^{M-1-m}. \tag{2}$$

2.2 Types of NE

We identify the combinations of F and M that support each of the three types of NE. In view of the linearity of the model, each signatory's optimal decision depends on its own cost realization and on the *number* of other signatories, but not on the *actions* of other signatories. Conditional on M, signatories have a dominant strategy.[4] The net benefit of abating given costs θ_i is $1 - \theta_i$ (the national benefit of abatement minus the cost of abatement); the net benefit of not abating

[4]It is important that costs be non-verifiable, so that nations are unable to sign contracts that condition their abatement action on their cost realization. Since agents have dominant strategies in the abatement game, it does not matter if costs are private or public information.

is $-F + \frac{\phi F}{M}$ (the fine minus the rebate). These two are equal at $F = -M\frac{-1+\theta_i}{-M+\phi}$. Nation i will not abate given cost θ_L if and only if

$$F < F_1(M) \equiv \frac{\theta_L - 1}{1 - \phi/M}. \tag{3}$$

Nation i will abate given cost θ_H if and only if

$$F \geq F_2(M) \equiv \frac{\theta_H - 1}{1 - \phi/M}. \tag{4}$$

Since nations are symmetric and they have a dominant strategy, we have

Proposition 1 *The abatement game in stage two has a unique type 0 NE if and only if $F < F_1(M)$, a unique type 1 NE if and only if $F_1(M) \leq F < F_2(M)$, and a unique type 2 NE if and only if $F \geq F_2(M)$.*

Figure 1 graphs $F_1(M)$ and $F_2(M)$, which are decreasing and approach $\theta_L - 1$ and $\theta_H - 1$ respectively. The figure shows the regions of the different types of NE, conditional on M and F. For brevity, we will sometimes refer to a "type i IEA" to mean an IEA that results in a type i NE at the abatement stage, $i = 0, 1, 2$. The fact that the graphs of $F_1(M)$ and $F_2(M)$ are decreasing means that for a given level of F, an IEA member's incentive to abate (weakly) increases with the number of members. The reason for this relation is that each member's share of the revenue from the fine is $\frac{1}{M}$, so the net fine (after the rebate), $\frac{M-\phi}{M}F$, increases with the number of members. It is more expensive to exercise the escape clause in an IEA with more members. If there were no rebate ($\phi = 0$) the cost of exercising the fine, and therefore the cost of joining the IEA, would be independent of M.

2.3 Payoffs in NE

Let $\pi_{s,i}(M; F)$ and $\pi_{n,i}(M)$, $i = 0, 1, 2$, be, respectively, the expected payoffs of a signatory and a non-signatory in a type i IEA with M members and fine F. (s denotes "signatory" and n denotes "non-signatory".) Since no signatories abate in a type 0 NE, $\pi_{s,0} = -(1 - \phi)F$ and $\pi_{n,0} = 0 = \pi_{s,0} + G_0$, where $G_0 = (1 - \phi)F$.

In a type 1 NE, a signatory with low costs chooses to abate, and has an expected payoff of

$$u_{a,1}(\theta_L) \equiv \sum_{m=0}^{M-1} p_{m,M-1} \left\{ m + 1 - \theta_L + \frac{M - 1 - m}{M}\phi F \right\}. \tag{5}$$

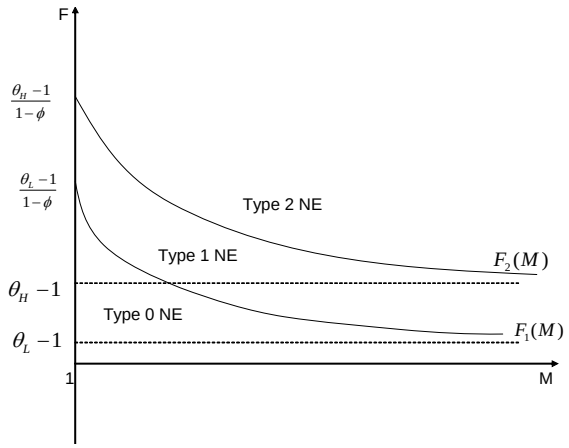


Figure 1: Three types of Nash Equilibria

The signatory with high cost chooses not to abate and has an expected payoff of

$$u_{na,1} \equiv \sum_{m=0}^{M-1} p_{m,M-1} \left\{ m - F + \frac{M-m}{M} \phi F \right\}. \tag{6}$$

Therefore, the unconditional expected payoff in a type 1 NE is

$$\pi_{s,1}(M;F) = \quad p u_{na,1} + (1-p) u_{a,1}(\theta_L) = M(1-p) - G_1(F), \tag{7}$$

where

$$G_1(F) = (1-p)\theta_L + Fp(1-\phi). \tag{8}$$

The expected payoff of a non-signatory is

$$\pi_{n,1}(M) = \quad \textstyle\sum_{m=0}^{M} p_{m,M} m = M(1-p). \tag{9}$$

Equations (7) and (9) have a simple explanation. In a type 1 equilibrium, the expected fraction of signatories that abate is $(1-p)$, resulting in an expected abatement benefit of $M(1-p)$. This value equals the expected payoff of a non-signatory (who never abates). A signatory's expected abatement cost is $(1-p)\theta_L$ and its expected fine payment net of reimbursements is $Fp(1-\phi)$.

For a type 2 IEA, the associated payoffs of signatories and non-signatories are

$$\pi_{s,2}(M) = M - \bar{\theta}, \tag{10}$$

and

$$\pi_{n,2}(M) = M = \pi_{s,2}(M) + G_2, \tag{11}$$

where $G_2 = \bar{\theta} = p\theta_H + (1-p)\,\theta_L$, the expected value of θ.

The payoff functions used above are indexed by i, the type of equilibrium, which is determined by M, F. We use $\pi_s\,(M, F)$ and $\pi_n\,(M, F)$ to denote the equilibrium payoff of a signatory and non-signatory, recognizing the endogeneity of the equilibrium type.

3 The participation game: Nash equilibrium

In this section we describe the NE to the participation game. We show that for an interval of fine F, a reduction in membership costs (smaller F) increases equilibrium membership size. We then discuss the welfare implications of different membership sizes.

3.1 The subgame perfect NE

Here we consider the NE to the participation game when the existence of the escape clause and the size of the fine are taken as given. In addition to the number of nations N, this model contains four parameters: the cost parameters θ_L and θ_H, the probability of a high cost p, and the transactions cost parameter ϕ. Even with this simple model, there are many possible combinations of parameter values, with different NE. Since a complete taxonomy would be uninteresting, we discuss the NE under a set of parameter values that are reasonable for the control of GHG. Figure 2 depicts this case; we use it to discuss informally the relation between F and the set of NE to the participation game. Appendix A provides a formal description of this correspondence and the proof.

Figure 2 reproduces Figure 1 and adds three curves; recall that F_1 and F_2 are the lower and upper boundaries, respectively, of the region where there is a type 1 equilibrium in the abatement game. $\tilde{F}\,(M)$ is the locus of points at which signatories in a type 1 IEA have zero payoff: $\pi_{s,1}(M; \tilde{F}(M)) = 0$. Payoffs are negative to the left of this line. Line $F_0(M)$, which we use in Section 3.2, is the locus of points at which signatories' payoffs are equal in type 1 and type 2 IEAs: $\pi_{s,1}(M; F(M)) = \pi_{s,2}(M)$. Below this line, signatories' payoffs are higher in a type 1 equilibrium. These functions are

$$\tilde{F}(M) \equiv (M - \theta_L)\,\frac{p-1}{p\,(\phi-1)}, \quad F_0(M) \equiv \frac{\theta_H - M}{1-\phi}.$$

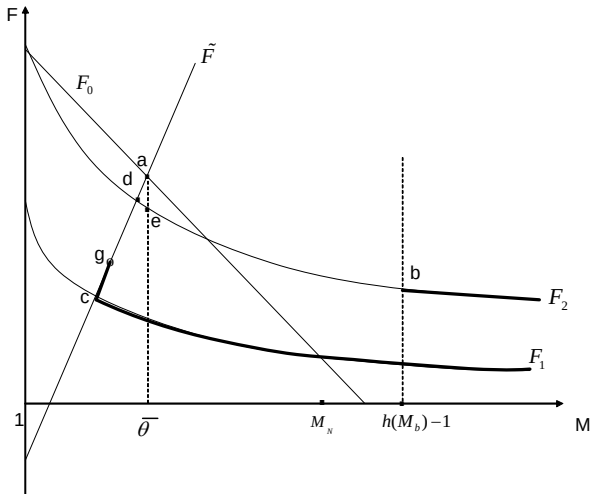


Figure 2: The Nash Equilibrium to the Participation Game

We use subscripts to denote the coordinate of a point; e.g., F_b is the vertical coordinate of point b and M_b is the horizontal coordinate. We say that a NE in the participation game is type i if the resulting NE in the abatement stage is type i, $i = 0, 1, 2$.

The equilibrium number of members must be a nonnegative integer. Define $h(x)$ to be the smallest integer not less than x. The formal presentation in Appendix A respects the integer constraint, but here, in order to keep the syntax manageable, we ignore this constraint. For example, if we state that a point x on the curve F_1 is a NE, we mean that when $F = F_x$ (the vertical coordinate of point x) then $h\left(F_1^{-1}(F_x)\right)$ rather than $F_1^{-1}(F_x)$ is a NE. With this understanding, the heavily shaded curves in Figure 2 show the NE correspondence for positive F. We discuss this figure, and then discuss the NE.

Define $M_b \equiv \frac{\bar{\theta}-1+p}{p}$, derived from $\pi_{s,2}(M_b) = \pi_{n,1}(M_b - 1)$: a nation is indifferent between being a signatory to a type 2 IEA of size M_b and a non-signatory to a type 1 IEA of size $M_b - 1$. Denote point b as the intersection between F_2 and the vertical line at $h(M_b) - 1$. If the size of a type 2 IEA (on or above F_2) is less than $h(M_b)$, a member would want to leave the IEA when this defection causes the abatement stage equilibrium to switch from type 2 to type 1. A simple calculation shows that point b always lies above F_0 as shown in Figure 2. Define M_N as the value that satisfies $F_1(M) = F_0(M)$. Appendix A shows that $M_N < M_b$, as Figure 2 illustrates. We can show that $\tilde{F}(M)$ and $F_0(M)$ cross at $M = \bar{\theta}$, represented by point a. Let e be the point when $M = \bar{\theta}$ crosses F_2. Recall that $\pi_{s,2}(\bar{\theta}) = 0$.

Figure 2 embodies several assumptions. The most important of these are that (i) the horizontal distance between curves F_2 and F_1 is greater than 2 at point e, and that (ii) $M_b - \bar{\theta} > 2$. Appendix A describes these assumptions and contains the necessary and sufficient conditions for them. Sufficient conditions are: (a) there is a non-negligible difference between high and low costs, (b) the probability of high abatement costs is less than 0.5, and (c) θ_L is at least 4. Conditions (a) and (b) are non-controversial. Given our normalization, condition (c) means that an IEA needs at least four members in order for abatement in the low cost state to improve the members' welfare. Since climate change requires substantial cooperation in order for abatement to improve welfare, condition (c) is reasonable.

From (i), if a signatory considers defecting from a candidate NE on F_2 below point e, it knows that the resulting IEA will be of type 1 rather than type 0. From (ii), for any candidate NE on $\tilde{F}$ consisting of fewer than $\bar{\theta}$ members, no non-signatory to a type 1 IEA wants to defect by joining the IEA: if it were to join, the membership would still be lower than M_b. (For $M < M_b$ the signatory's payoff in a type 2 IEA with M members is less than a non-signatory's payoff in a type 1 equilibrium with $M - 1$ members.)

Three facts about the equilibrium set are obvious. First, a membership size of 0 (not shown in Figure 2) is always a NE. Second, outcomes with negative payoffs for IEA members cannot be NE to the participation game. This fact eliminates many candidates. In the region below F_2, it eliminates all points to left of the upper envelope of curves F_1 and $\tilde{F}$ (i.e. below the curve dcF_1). In the region above F_2, it eliminates all points where $M < \bar{\theta}$. Third, in view of inequality (1) (which implies that it is never individually rational for a nation to abate) a member is deterred from leaving the IEA only if its defection would change the equilibrium at the abatement stage, e.g. from a type 2 to a type 1, or from a type 1 to a type 0. This fact means that only the "nearest integers" on or to the right of curves F_1, F_2, and $\tilde{F}$ are candidate NE. The second and third facts imply that the candidate NE include curve $\tilde{F}$ between points c and d, curve F_1 below point c, and curve F_2 below point e.

At points on F_1 below point c, signatories have a positive payoff. These points are NE in the participation stage, leading to a type 1 equilibrium in the abatement stage. At these points, a signatory knows that its defection would lead to a type 0 equilibrium in the abatement stage, and a 0 payoff for non-signatories. Non-signatories do not want to join the IEA because the result would still be a type 1 equilibrium. Other NE leading to type 1 abatement-stage equilibria consist of points between c and g on $\tilde{F}$. On this interval, signatories have a positive payoff. At

points on $\tilde{F}$ below g, defection by a signatory leads to a type 0 IEA, and losses for the defector. At points above g, defection by a non-signatory leads to a type 1 IEA, and gains to the defector. Thus, the only NE on $\tilde{F}$ are points between g and c.

Points on F_2 below point b are type 2 NE. At these points, members do not want to leave the IEA, since that would result in a type 1 equilibrium and a lower payoff. Points above b on the envelope aeb are not NE, even though members' payoffs are non-negative there. At these points, any member would want to defect, since it prefers to be a non-signatory in a type 1 equilibrium in the abatement stage. For $F > \max\{F_b, F_g\}$ there are no NE other than 0.

Figure 2 shows that smaller fines increase the equilibrium the size of the IEA when $F < F_c$ (for type 1 IEAs) and when $F < F_b$ (for type 2 IEAs). In a type 1 IEA, membership costs are increasing in F; in a type 2 IEA membership costs are independent of F. Thus, a reduction in the fine (weakly) increases equilibrium membership size, while decreasing membership cost.

The fact that IEA members obtain a rebate, and that the rebate decreases with the number of IEA members (making it more expensive to exercise the escape clause) is critical to the ability of the escape clause to increase equilibrium membership. If $\phi = 0$, so that firms receive no rebate, then the graphs of F_1 and F_2 are flat lines. In this case, a member's equilibrium action in the abatement stage is independent of the number of members. In that situation, nations have no incentive to join the IEA in the participation stage (because their decision has no effect on member's behavior), and the equilibrium size of the IEA is 0.

At the other extreme, if there were no transactions costs ($\phi = 1$) then members' equilibrium payoff is independent of F, but F still affects the equilibrium membership size. For $\phi = 1$ the lines $\tilde{F}$ and F_0 are vertical (at θ_L and θ_H, respectively), but Figure 2 is otherwise unchanged.

3.2 Welfare implications

Here we assume that nations are able to choose the fine in period 0 in order to maximize expected welfare. We denote the resulting level of welfare as the NE optimum, because it is chosen with the understanding of how the participation and the abatement games unfold. Since agents are homogenous before the realization of individual costs, there would be no reason to disagree on the fine. We assume that $N > \theta_L$, so that it is socially optimal to have a low cost nation abate. We compare the NE optimum with two benchmarks. The first benchmark is the full-information first best, the level of expected welfare if a social planner observes costs and is able to tell nations whether to abate. The second benchmark, the "constrained information

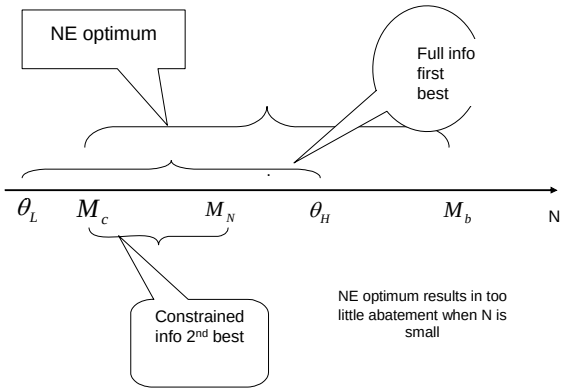


Figure 3: Range of N for which only low cost nations abate, under different equilibrium assumptions

second best", is the expected level of abatement if all nations are required to join the IEA, but abatement costs are private information.

Figure 3 shows the N axis for $N \geq \theta_L$. The brackets indicate the ranges of N for which the outcome is that only low cost nations abate, under the NE optimum and under the two benchmarks. It is straightforward to establish the order of the values on the N axis, but we omit the details. In the case of full information, the first best outcome requires that all nations abate in both states if and only if $N \geq \theta_H$. Thus, for $\theta_L \leq N < \theta_H$, only low cost nations abate under the full information first best outcome, as the middle bracket indicates.

From Figure 2, the smallest IEA that can be supported as a NE in the abatement stage is $M_c > \theta_L$. Thus, for $N < M_c$ the NE optimal fine is $F = 0$: the IEA does not form. In the constrained information second best, the social planner could instruct all nations to join the IEA. However, if $N < M_c$ any positive fine results in negative expected value, so again it is optimal to set $F = 0$.

From the definition of curve F_0, and the fact that a signatory's welfare in a type 2 IEA $\pi_{s,2}(M)$ is independent of F, we know a type 2 grand IEA leads to a higher expected welfare than a type 1 IEA if and only if $N \geq M_N$. Therefore, in the second best incomplete information scenario it is optimal to induce only low cost nations to abate when $M_c \leq N < M_b$, as the lower bracket in Figure 3 shows. Since $M_N < \theta_H$, private information expand the parameter space for which it is optimal to abate under both cost realizations. In this respect, the incentive compatibility constraint *at the abatement stage* leads to excessive abatement. This result is due

to the fact that the type 1 equilibrium requires that some nations incur a transactions cost F, causing the type 1 welfare (in the NE to the abatement stage) to be lower than in the first best outcome. In contrast, there are no transactions cost in a type 2 equilibrium.

However, our game includes not only the abatement stage incentive compatibility constraint, but also the constraint implied by non-cooperative behavior at the participation stage. The smallest NE in the participation stage that produces a type 2 equilibrium at the abatement stage is $M_b > \theta_H$. Therefore, if it is feasible to induce a type 2 equilibrium (by choice of F) it is always optimal to do so. If $N < M_b$, it is not feasible to induce a type 2 equilibrium.

In summary, if $N < M_c$ the optimal fine is zero. The incentive compatibility constraint is so tight that it is not optimal to require any nation to abate. If $M_c \leq N < \theta_H$, the optimal fine induces the socially optimal amount of abatement, but it does so by incurring a transactions cost. If $\theta_H \leq N < M_b$ the optimal NE results in too little abatement, relative to the first best, and there is a transactions cost. If $M_b \leq N$ the optimal fine achieves the first best.

4 Comparison with the "standard model"

The standard model assumes that the IEA maximizes members' joint welfare at the abatement stage. In our model, the signatories to an IEA are not able to solve the collective action problem. However, they are able to commit to following a simple contingent contract, to either abate or to pay to exercise an escape clause. Thus, nations have a different type of commitment ability, but it is not obviously greater or weaker relative to the standard model.

In a type 1 equilibrium, a nation that has a low abatement cost (and therefore chooses to abate) has a higher payoff than a high-cost nation (which decides to invoke the escape clause). The low-cost nation has an incentive to pressure non-abating signatories to abide by the IEA and pay the fine. In a type 0 equilibrium, all signatories have negative payoff of $-(1-\phi)F$.[5]

Thus, there are subgames in our model at which a signatory's (*ex post*) payoff is negative.[6] Some readers might object to this possibility, based on the claim that sovereign nations cannot bind themselves to contracts which, in some state of nature the nation would regret. We ac-

[5]We could modify the game by allowing the IEA to costlessly disband if all signatories agree to do so. That change causes $u_{na,0} = 0$, and the value of $F_1(M)$ in equation (3) is replaced by $\frac{\theta_L - b}{\phi - \phi/M}$. The change requires slightly more complicated notation, because it introduces an additional action (voting) at the abatement stage.

[6]This possibility also arises in the standard model. Consider the situation described in Section 4.1, where the IEA has to make a binary decision. Signatories with high costs might have negative payoffs.

cept that sovereignty is an important constraint on nations' ability to make binding contracts. Therefore, the magnitude of the signatory's payoff in the worst state of the world is relevant in assessing the plausibility of our proposal. However, nations are not able to *costlessly* abrogate – either unilaterally or in unison – agreements that they have signed. There is such a thing as reputation and punishment. If disbanding under unanimous agreement is an option that costs more than $(1-\phi)F$, the IEA would never disband. If unilateral withdrawal from the IEA costs more than $u_{na,1}$ (defined in equation (6)), unilateral defection does not occur.

We show that in the standard model a decrease in membership cost weakly reduces membership size and may reduce global welfare. The standard model assumes that the abatement levels specified in the IEA are determined *after* nations have made their participation decision. In order for this assumption to be consistent with our setting, we assume that in the standard model the abatement decision is a binary choice between one and zero, e.g. because of some technological constraint.

We first consider the simplest case where the IEA (which cannot verify cost realizations) sets an abatement level (0 or 1) for every signatory, without an escape clause. That is, the IEA decides whether or not to abate, independent of cost realizations, in order to maximize the expected welfare of the signatories. We then consider the situation in which the IEA is able to use an escape clause, and that (unlike in our model) it chooses the fine conditional on N, to maximize members' welfare. These two settings differ only in the policy menu available to the IEA, not in the timing of the decisions. Conditional on membership size, the IEA's payoff is (weakly) higher when it has the option of an escape clause. However, by reducing the membership cost, the escape clause lowers the equilibrium membership size and reduces global welfare. Finally, we compare the outcome in these models with those in our model.

4.1 The IEA chooses abatement level

Suppose after nations have decided whether to join the IEA, the IEA decides whether to abate. Conditional on M, the expected payoff to a signatory is $\Pi(M) = \max\left\{0, M-\bar{\theta}\right\}$. In the abatement stage, the IEA chooses to abate if and only if $M \geq \bar{\theta}$. In this case, the NE to the participation game is $M = h\left(\bar{\theta}\right)$. To confirm this, note that if there are $h\left(\bar{\theta}\right)$ members, each signatory's payoff is non-negative; no signatory would want to leave the IEA, because the resulting IEA would choose not to abate, leaving the defector with a zero payoff. No non-signatory wants to join, since in view of inequality (1), $h\left(\bar{\theta}\right) > h\left(\bar{\theta}\right) + 1 - \bar{\theta}$: the non-

signatory's payoff in the NE exceeds its payoff if it joins the IEA.

In this model, the membership cost equals $\bar{\theta}-1$. The level of membership, $h\left(\bar{\theta}\right)$, weakly increases with membership cost; $h\left(\bar{\theta}\right)$ is constant between integers, and jumps up by one unit as $\bar{\theta}$ passes through an integer value. The equilibrium global welfare of N nations is $\left(N-\bar{\theta}\right)h\left(\bar{\theta}\right)$. As $\bar{\theta}$ increases between integers welfare falls, but welfare has an upward jump as $\bar{\theta}$ passes through an integer value. (When N is an even integer, welfare is maximized at $\bar{\theta}=\frac{N}{2}$.) Relative to a grand IEA of N members, the fraction of potential welfare achieved in equilibrium is $\frac{h\left(\bar{\theta}\right)}{N}$. This example illustrates why the standard model leads to a pessimistic view of IEAs: they achieve a substantial portion of potential gains from cooperation only when $h(\bar{\theta})$ is high or when those potential gains are small. IEAs are effective only when they are unimportant.

This model assumes that when nations decide whether to join the IEA, they anticipate that the IEA will maximize members' joint welfare in the abatement stage. Members understand that their participation decision might have an effect on the IEA's action. If instead, the IEA makes the abatement decision *before* agents decide whether to join (as is the case for Kyoto), the equilibrium membership size is 0. In this case, there is nothing to offset nations' temptation to free-ride.[7] The assumption that the IEA abatement decision is made after the membership decision therefore increases the equilibrium size from zero to $h\left(\bar{\theta}\right)$.

4.2 The IEA chooses the fine

Suppose now that the IEA is able to use an escape clause with a fine, while leaving the abatement decisions to the signatories. As in our model, decisions in the abatement stage are made non-cooperatively.. In this variation of the standard model, however, the IEA chooses the fine F *after* the participation stage. If it is optimal for an IEA of size M to induce a type 1 equilibrium, it chooses the smallest fine that will achieve this, $F_1\left(M\right)$. If it is optimal to induce a type 2 equilibrium, the IEA sets $F \geq F_2(M)$. To induce a type 0 equilibrium, the IEA sets the fine at zero. Thus, the expected payoff of a member is

$$\hat{\Pi}(M) = \max\left\{0, \pi_{s,1}(M; F_1(M)), \pi_{s,2}(M)\right\}, \tag{12}$$

where $\pi_{s,1}$ and $\pi_{s,2}$ are given in (7) and (10). It is straightforward to show that for a sufficiently small M it is optimal to set $F=0$, and for sufficiently high M it is optimal to set $F \geq F_2(M)$.

[7] Kyoto solved this free-rider problem by stipulating that the agreement would not enter into force unless a minimum level of participation was achieved.

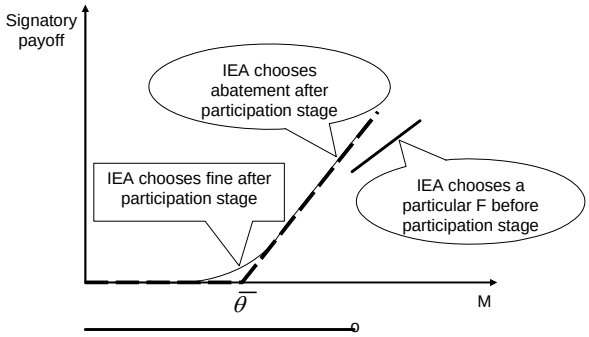


Figure 4: Signatory payoffs in different IEA games

For a range of intermediate values of M it is optimal to induce a type 1 equilibrium at the abatement stage. Clearly $\hat{\Pi}(M) \geq \Pi(M)$. Figure 4 compares the payoffs under the two policy instruments. The thick-dashed lines represent the expected payoff of a signatory when the IEA chooses the abatement level, and the thin solid curve represents the payoff when the IEA chooses the fine.

Let $\hat{M} = \sup\{M \mid \hat{\Pi}(M) = 0\}$. Following the same argument as in the previous case without the escape clause, we know that the equilibrium membership size is $h(\hat{M})$. Allowing the IEA to use a fine and escape clause, rather than requiring it to directly chose abatement, makes the IEA more efficient, and reduces membership costs, conditional on M. However, from (12), we know $\hat{M} < \bar{\theta}$, i.e., $h(\hat{M}) \leq h(\bar{\theta})$: a reduction in membership costs (weakly) reduces equilibrium membership size and may reduce equilibrium global welfare.[8]

Figure 4 also shows (the heavy solid line) the signatory's payoff in our model, where the IEA chooses the fine before the participation stage. In this example, the (possibly non-optimal)

[8]If $h\left(\hat{M}\right) = h\left(\bar{\theta}\right)$, membership size and global welfare is the same under the two policy instruments. A sufficient condition for $h\left(\hat{M}\right) < h\left(\bar{\theta}\right)$ is that $\hat{M} + 1 < \bar{\theta}$. When $\phi \approx 1$, the necessary and sufficient condition for the latter inequality is that $\theta_L + 1 < \bar{\theta}$. Suppose $h(\hat{M})$ leads to a type 1 equilibrium. Then the reduction in global welfare from switching to the more efficient instrument equals

$$\Delta \equiv \left(N - \bar{\theta}\right) h\left(\bar{\theta}\right) - \left((1-p)N - G_1\left(F_1\left(\hat{M}\right)\right)\right) h\left(\hat{M}\right).$$

For example, let $p = 0.1, \theta_L = 4, \theta_H = 8$, and $1 - \phi \approx 0$, so $G_1\left(F_1\left(\hat{M}\right)\right) \approx 3.6$. In this case, $h\left(\hat{M}\right) = 4$ and $h\left(\bar{\theta}\right) = 5$, so $\Delta \approx (N - 4.4)\,5 - (.9N - 3.6)\,4 = 1.4N - 7.6$. Provided that $N \geq 6$ (i.e., assuming that the IEA that chooses abatement can not obtain global cooperation), the switch to the more efficient policy instrument reduces global welfare.

fine which induces a type 1 NE.. The equilibrium to this participation game occurs at the point of discontinuity of the solid line, a level greater than $\bar{\theta}$. Both signatory and non-signatory payoffs are higher in this scenario, relative to the cases considered above.

4.3 A comparison

Table 1 compares the equilibrium IEA size for games with different timing and different policy instruments. The size of the IEA depends on both of these features. When the policy instrument is the abatement level, choosing this level before nations' participation decision decreases the IEA's size, and aggregate welfare. If the policy instrument is the escape clause with a fine, it is better to make the choice before the participation decision.

If the IEA must make its choice before the participation decision, a fine leads to a higher payoff. If the IEA must make it's choice after the participation decision, choosing abatement leads to a higher payoff. Of the four possibilities, both membership and aggregate welfare is highest when the IEA chooses a fine before the participation decision.

	IEA Policy Instrument	
Decision Timing	Abatement Level	Level of Fine
Before participation	$M^* = 0$	M^* can be large
After participation	$M^* = h(\bar{\theta}) \geq 2$ (small)	$M^* = h(\hat{M}) \leq h(\bar{\theta})$ (even smaller)

Table 1: Equilibrium IEA size in four different games

5 Farsighted stability in the participation game

The Nash equilibria in the previous section assume that in the participation game nations believe that: (i) if one nation deviates from equilibrium by withdrawing from or joining the IEA, other nations do not respond by changing their participation decisions, and (ii) each nation acts on its own, i.e., nations do not join or withdraw together in a coalition. Here we relax those assumptions.

Nations are likely to be more sophisticated, and more able to react to deviations, than the NE assumes. For example, a nation may perform a thought experiment to predict how its deviation from a particular candidate equilibrium would precipitate changes in other nations'

actions. The nation would compare the status quo payoff with the payoff under the *eventual* equilibrium following its own deviation and other nations' responses – not on the payoff that would result if no other nations responded. Such nations, using the terminology of Chwe (1994), are *farsighted*.

To understand the effects of farsightedness on the formation of IEAs, consider the IEA of size $M = h(\bar{\theta})$ when $F > F_a$ in Figure 2. In this IEA, each signatory's payoff is $\pi_{s,2}(h(\bar{\theta})) \geq 0$, where the inequality is strict unless $h(\bar{\theta}) = \bar{\theta}$. Suppose a signatory to the IEA withdraws. The immediate result of this deviation is an IEA with fewer than $\bar{\theta}$ members, and lying to the left of the curve $\tilde{F}$. In that outcome, each signatory's payoff is negative regardless of the type of the resulting IEA, so the remaining signatories would also withdraw, eventually leading to zero membership. Foreseeing the subsequent reactions of the other signatories, the first signatory will not withdraw, because doing so leads to a zero payoff instead of the non-negative payoff at $h(\bar{\theta})$. Thus, no signatory to the IEA of size $h\left(\bar{\theta}\right)$ wants to withdraw. We show that when nations are farsighted, this IEA is stable; in the previous section we saw that it is not a NE.

The second implicit NE assumption may or may not be reasonable, depending on whether nations can credibly coordinate *in the negotiation process* before the IEA is signed. For example, if a group of nations agree to join the IEA together, can they sign a binding agreement to guarantee that they will act as a group and no members will act differently? Although the negotiation process eventually produces a binding agreement (the IEA), binding agreements within the negotiation process before the IEA is formed may be harder to justify. Unlike the IEA, these pre-IEA agreements are at best informal.

If binding agreements are not possible, nations will act alone in making their participation decisions. But if binding agreements are possible, coalitional deviations have to be considered in studying the participation game. Continuing with the above example, if, through some exogenous processes, the current proposal is the trivial IEA with zero members, nations acting alone will not be able to form the IEA of size $h(\bar{\theta})$. However, when binding agreements are possible, a group of $h(\bar{\theta})$ nations want to move the IEA from size zero to size $h(\bar{\theta})$. In both cases, the nations can be farsighted.

Here we assume that the nations are farsighted. Depending on whether pre-IEA binding agreements are possible, we will analyze the negotiation game under different assumptions:

Assumption 1 (Unilateral Farsight) *Coalitional deviations are not possible: each nation acts on its own in deciding whether to join or to withdraw from the IEA.*

Assumption 2 (Coalitional Farsight) *Coalitional deviations are allowed.*

We analyze the participation game under Assumption 1 and calculate the associated stable set. We then show that a particular element of this set corresponds to the stable IEA under Assumption 2.

5.1 Unilateral farsighted stable set

The Nash equilibrium does not predict the kinds of IEAs that will form in the participation game when nations are farsighted. Chwe (1994)'s farsighted stable set (FSS) provides a reasonable model for this kind of behavior. We describe a variation of Chwe's definitions using Assumption 1.

In the participation game, let an outcome be a partition of the nations into signatories and non-signatories, and let Z be the set of outcomes. Consider two outcomes $a, b \in Z$. Denote $a \rightarrow_i b$ if nation i can move the outcome from a to b. For example, if i is a non-signatory, it can change the outcome by joining the IEA, making it one member larger. The preference ordering of nation i between two outcomes is given by $\prec_i$: $a \prec_i b$ if i prefers b to a. We define a dominance relation between two outcomes that allows each nation to act unilaterally, but not in coalitions.

Definition 1 (Chwe (1994)) *An outcome $a \in Z$ is* (unilaterally) indirectly dominated *by outcome $b \in Z$, denoted as $a \ll b$, if and only if there is a sequence of outcomes, $z_0, \ldots, z_m$ with $z_0 = a$ and $z_m = b$ and nations $0, \ldots, m-1$ such that $z_j \rightarrow_j z_{j+1}$ and $z_j \prec_j b$ for all $j = 0, \ldots, m-1$.*

That is, starting with outcome a, m nations makes sequential unilateral changes, generating a sequence of intermediate outcomes, $z_1 .... z_{m-1}$. Each nation (j) in the sequence prefers the final outcome (b) to the interim outcome that it faces (z_{j-1}). Thus, if $a \ll b$, there is *some* sequence of deviations from a that takes the outcome to b, and it is rational for each agent in that sequence to make the deviation.

The farsighted stable set (FSS) is essentially von Neumann and Morgenstern (1953)'s stable set armed with the indirect dominance relation. Due to the restriction to unilateral deviations in Assumption 1, we define a *unilateral* FSS.

Definition 2 (Chwe (1994)) *Given the set Z of outcomes and relation $\ll$, set $V \subseteq Z$ is a* unilateral farsighted stable set *(UFSS) of $(Z, \ll)$ if and only if*
(i) V is internally stable*: $\nexists a, b \in V$ such that $b \ll a$, and*
(ii) V is externally stable*: $\forall b \in Z \backslash V$, $\exists a \in V$ such that $b \ll a$.*

We say that an IEA with M members is "unilaterally farsighted stable" (or simply "stable" when there is no ambiguity) if and only if $M \in V$, the UFSS.

To understand the two requirements, note that if $a \ll b$ then a and b cannot both be internally stable, otherwise some sequence of players would cause a defection from a to b. Further, if b is outside the FSS, then there must be an element $a \in V$ that indirectly dominates b: if no such element a exists, then b would be stable. The FSS thus contains all the outcomes that are not indirectly dominated by other outcomes, and excludes all the outcomes that are indirectly dominated by some other outcomes.

As Chwe (1994) showed using the Condorcet Paradox, the UFSS does not exist when circular decisions arise. In our setting, a nation might withdraw from an IEA anticipating that another nation would join in its place; the new member would have the same incentive to withdraw, leading to a cycle of one nation withdrawing and another joining. Circular decisions are typical of coalition formation problems with farsight, and as we show in Appendix B.1, they also arise in our model for (M, F) such that a Nash equilibrium with a strictly positive number of signatories exists in the participation game. We assume that nations can find a way to "break the cycle;" for example, we can follow Mariotti (1997) and impose large negative payoffs when circular decisions arise.

Since the nations are assumed to be *ex ante* identical in the participation game, and since we have ruled out cyclical outcomes, we can identify each outcome by the size of its associated IEA, rather than by the identities of the nations. That is, $Z = \mathcal{N}$, and each nation is either a signatory or a non-signatory. This observation simplifies the determination of indirect dominance relation between two outcomes (or two IEAs).

Lemma 1 *Consider two IEAs of sizes $M, M' \in \mathcal{N}$ respectively.*
(i) Suppose $M > M'$. Then $M \ll M'$ if and only if $\pi_s(m; F) < \pi_n(M'; F)$ for all $m = M, M-1, \ldots, M'+1$.
(ii) Suppose $M < M'$. Then $M \ll M'$ if and only if $\pi_n(m; F) \leq \pi_s(M'; F)$ for all $m = M, M+1, \ldots, M'-1$.

The proof of the Lemma is a direct consequence of Definition 2 and is not presented. Since cyclical outcomes are ruled out, we only need to search "in one direction" in deciding the dominance relation. For example, when $M > M'$, M' indirectly dominates M if a signatory to the IEA of size M wants to withdraw, anticipating the subsequent withdrawal by other signatories until the IEA settles at size M'. In the process of moving from M to M', no non-signatories want to join the IEA, because otherwise circular decisions arise, resulting in large negative payoffs.

5.2 Finding the UFSS

The difficulty in finding the UFSS is that determining the stability of one IEA requires knowing other stable IEAs. Unless we know at least one element of the UFSS, it is not possible to determine the other elements. However, if we have identified the smallest element of the UFSS, a simple recursive procedure determines larger IEAs in the UFSS. This recursion uses the following:

Definition 3 *Given an IEA of size $M_0 < N$, the set $\mathcal{M}(M_0)$ generated by M_0 is a finite and strictly increasing sequence of integers, $\mathcal{M}(M_0) \equiv \{M^j(M_0), j = 1, 2, \ldots, k\}$, such that*

$$\begin{aligned} M^1 &= M_0, \\ M^j &= h(m^j), \quad \textit{where } m^j = \min\{m \in \mathcal{R} : \pi_s(m) = \pi_n(M^{j-1})\},\ j \geq 2 \\ M^j &\leq N, \quad j = 2, \ldots, k. \end{aligned} \tag{13}$$

The sequence $\mathcal{M}(M_0)$ depends on F, but we suppress that argument. Given an IEA of size M_0, the set $\mathcal{M}(M_0)$ is generated by a simple sequence of comparisons. Starting with $M^1 = M_0$, the next element M^2 is the smallest IEA such that a signatory's payoff in M^2 is no less than the non-signatory's payoff in M_0. Once we identify M^2, the next element M^3 is found through the same procedure. This process is to be repeated until the greatest possible element M^k is reached.[9]

We use Definition 3 to construct V by setting M_0 equal to the smallest element of V. We first describe two facts about V. First (as with NE), no equilibrium outcome can lie in a region where signatories have negative payoffs, i.e. the open set consisting of $M > 0$ and: (i) below

[9]The equation $\pi_s(m) = \pi_n(M^j)$ may have two solutions m_1 and m_2, where m_i is associated with a type i IEA. That is, it may occur that $\pi_{s,1}(m_1) = \pi_{s,2}(m_2) = \pi_n(M^j)$. Since $m_1 < m_2$, the procedure picks $h(m_1)$ instead of $h(m_2)$.

F_2 and to the left of the right envelope of F_1 and $\tilde{F}$, or (ii) less than $\bar{\theta}$ and on or above F_2. However, M_0 can lie outside or on the boundary of this region, or it can equal 0. As a result, V does not contain a type 0 IEA with positive membership. Second, we cannot exclude the possibility that V contains one or more type 1 IEAs followed by one or more type 2 IEAs. If this possibility occurs, then there is a single switch of IEA types, because the largest type 1 IEA lies below F_2 and the smallest type 2 IEA lies on or above F_2.

We identify V using the following result.

Proposition 2 *$\mathcal{M}(M_0) = V$ if and only the following three conditions hold:*
(i) When $M_0 = 0$, $M^2 - 1$ is not a type 0 IEA.
(ii) Either all positive M^j in V are the same type IEA; or there is a switch from a type 1 to a type 2 IEA, and the smallest type 2 IEA in V occurs at $M^j < M_b$.
(iii) When $M_0 > 0$, $\pi_s(M_0) \geq \pi_n(M)$ for all $M < M_0$.

Conditions (i) and (ii) of the proposition are used to guarantee internal stability of $\mathcal{M}(M_0)$, and condition (iii) is needed for external stability of $\mathcal{M}(M_0)$. To verify internal stability, note that by construction of $\mathcal{M}(M_0)$, an IEA of size M^{j+1} is not indirectly dominated by M^j or by smaller IEAs Showing that M^j is not indirectly dominated by M^{j+1} (or by larger IEAs) uses the first two conditions in the proposition. Recall from Lemma 1 that in order for $M^j \ll M^{j+1}$, we must have $M \ll M^{j+1}$ *for all* $M^j \leq M < M^{j+1} - 1$. Conditions (i) and (ii) guarantee that the sequence of inequalities is violated. From the two conditions, we know for all $j \geq 1$, either $M^{j+1} - 1$ and M^{j+1} are of the same type, or $M^{j+1} - 1$ is of type 1 and M^{j+1} is of type 2 with $M^{j+1} < M_b$. Inequality (1) and the definition of M_b imply that $M^{j+1} \ll M^{j+1} - 1$ in either case.

To verify external stability of this set, we note that all IEAs strictly between M^{j+1} and M^j are indirectly dominated by M^j because of the monotonicity in M of payoffs. Similarly, IEAs larger than M^k (defined as the largest element of $\mathcal{M}(M_0)$) are indirectly dominated by M^k. When $M_0 = 0$ there are no IEAs smaller than $M^1 = M_0$. When $M_0 > 0$, condition (iii) implies that IEAs smaller than M_0 are indirectly dominated by M_0.

Proposition 2 implies that $M^{j+1} - M^j > 1$.[10] Not all (in fact, "very few") integers are elements of V. Consequently, for arbitrary F it is not true in general that making nations

[10]This claim follows directly from Definition 3 when successive elements of V result in the same type IEA. When successive elements result in different type IEAs, the claim follows from condition (ii). If $M^{j+1} - M^j = 1$ and M^{j+1}, M^j are type 2 and type 1 IEAs, respectively, then condition (ii) is violated.

farsighted enables them to achieve global cooperation. Ray and Vohra (2001) obtain a similar result.

Proposition 2 enables us to find V by identifying its smallest element M_0, and then applying the recursive relation in equation (13). In particular, we *choose the smallest possible* M_0 in order to satisfy the three conditions. We start with $M_0 = 0$ and test whether conditions (i) and (ii) hold. If they hold, then the smallest element of V is zero. If they do not hold, then $M_0 \geq 1$ and we identify its value using conditions (ii) and (iii). To verify that a candidate $M_0 \geq 1$ is the smallest element of V we only need to verify that it is not indirectly dominated by smaller IEAs.

We illustrate this process using the example in Figure 5. As in the previous section, the equilibrium set (here, V) depends on the relative positions of the curves F_0, F_1, F_2, $\tilde{F}$ and M_b. Figure 5 uses the definitions and assumptions Figure 2; in addition, it assumes: (a) point c is above the line $F_2(N)$;[11] (b) the horizontal distance between $\tilde{F}$ and F_1 at $F = F_b$ is not less than one; and (c) the horizontal distance between $\bar{\theta}$ and F_1 at $F = F_d$ is not less than one. For this configuration of curves, we have:

Summary 1 *(i) If $F < F_1(N)$, the UFSS contains the single element of an IEA with zero membership.*
(ii) If $F \in [F_1(N), F_2(N))$, the UFSS is the set $\mathcal{M}(M_0)$, where $M_0 = h(F_1^{-1}(F))$.
(iii) If $F \in [F_2(N), F_b)$ where $F_b = F_2(h(M_b) - 1)$, the UFSS is the set $\mathcal{M}(M_0)$, where $M_0 = h(F_2^{-1}(F))$.
(iv) If $F \in [F_b, F_d)$, where F_d is the level of F where $\tilde{F}$ and F_2 cross, then the UFSS is the set $\mathcal{M}(M_0)$ where $M_0 = 0$. The second element of $\mathcal{M}(M_0)$ is $M^2 = h(\tilde{F}^{-1}(F))$.
(v) If $F \geq F_d$, the UFSS is the $\mathcal{M}(M_0)$ where $M_0 = 0$. The second element of $\mathcal{M}(M_0)$ is $M^2 = h(\bar{\theta})$.

Figure 5 graphs the first one or two elements of the UFSS, which are represented by the bold lines (ignoring the integer constraint). To see how Proposition (2) is used, consider first the case when $F \in [F_1(N), F_2(N))$. (The same reasoning applies to the case when $F \in [F_2(N), F_b)$.) Let M' be the IEA determined from the curve $F_1(\cdot)$: $M' = h(F_1^{-1}(F))$. We showed in the previous section that the IEA of size M' is a Nash equilibrium, so that $\pi_{s,1}(M') \geq \pi_{n,1}(M'-1)$.

[11] For $\phi \approx 1$, point c lies above $\theta_H - 1$ (a necessary condition for c to lie above $F_2(N)$) if and only if $\theta_H - \theta_L > 1$. This inequality is very likely to be satisfied for the problem of climate change, where there is a large difference between possible abatement costs.

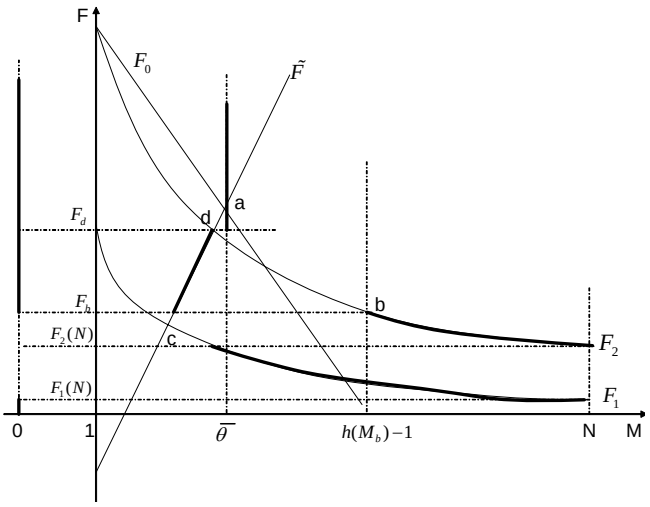


Figure 5: First elements of the UFSS

The inequality implies that $\pi_{s,1}(M') \geq \pi_{n,1}(M)$ for all $M \leq M' - 1$ since $\pi_{n,1}(\cdot)$ is increasing in M. Setting $M_0 = M' = h(F_1^{-1}(F))$ satisfies Condition (iii) of Proposition 2. Since IEAs of sizes higher than or equal to M' are all type 1, Condition (ii) is also satisfied for this value of M_0. Thus, M' is the smallest element of the UFSS.

When $F \in [F_b, F_d)$, there are two possible switches of IEA types: from type 0 to 1 (along curve F_1) and from 1 to 2 (along curve F_2). If $M_0 = 0$, the assumption that the horizontal distance between $\tilde{F}$ and F_1 is no less than one implies that condition (i) in Proposition 2 is satisfied. Further, condition (ii) is satisfied since the curve F_2 is to the left of M_b when $F > F_b$. Since 0 is the smallest possible IEA, we know $\mathcal{M}(0)$ is the UFSS. Similarly, when $F \geq F_d$, conditions (i) and (ii) are satisfied and thus $\mathcal{M}(0)$ is the UFSS.

5.3 The effects of unilateral farsight

Comparing Figure 2 and 5 shows that nations with farsight have greater ability to cooperate and are therefore "more likely" to form larger IEAs. While no abatement by any nation (zero sized IEA) is always a Nash equilibrium, it is *not* in V for certain values of F. In fact, if we ignore the effects of the integer constraint, whenever there is a Nash equilibrium with a positive IEA (e.g., when $F \in [F_1(N), F_c)$ and $F \in [F_2(N), F_b)$), this IEA also belongs to V. Further in these cases, the zero sized IEA, a Nash equilibrium, is *not* in V. For other values of F, while the zero sized IEA is the only NE, it is not the only element in V.

When some of the Nash equilibria do belong to V, they only represent the first or the smaller elements in V. The existence of larger IEAs in V means that farsighted nations may possibly cooperate and form a larger IEA. The concept of UFSS is silent on the negotiation procedure that leads to a particular IEA. Imposing more structure on the negotiation process may lead to finer predictions. For example, Ray and Vohra (2001) assumes a bargaining procedure with an exogenous order of movements. Under their procedure, we can show that the largest element in the UFSS will be proposed by the first mover and will be accepted by all other nations.

The definition of the UFSS, and the game in which it arises, does not involve actions at different points in time; the game is not written in extensive form. However, the UFSS does have the "flavor" of subgame perfection, as Xue (1998) noted. It is as if nations performed a thought experiment to predict the consequences of their actions. If we pursue the analogy of subgame perfection a bit further, the UFSS implies that IEAs can unravel, but they can not be built up. A nation can get the ball rolling by defecting from a stable IEA, but it can only get the ball rolling downhill. For example, suppose that we think of beginning at a particular status quo that falls just short of a stable IEA; that is, the size of the IEA is $M^{j+1} - 1$, possibly as the result of a signatory's defection from a stable IEA. Since $M^{j+1} \ll M^{j+1} - 1$, the IEA cannot be built up to the next stable element. However, beginning with this status quo, signatories do want to leave, causing the IEA to unravel to the next smallest stable element. "Rolling the ball uphill" requires coalitional deviation.

5.4 Coalitional farsighted stable set

Under Assumption 2, a group of nations may act together to deviate from the status quo. The unilateral indirect dominance relation Definition 1 can be extended to coalitional indirect dominance: the sequence of outcomes is generated by coalitional rather than unilateral deviations, and the preference relation at each step must hold for all members of the coalitions within the step. The coalitional farsighted stable set (CFSS) can be defined by modifying Definition 2 to replace unilateral with coalitional dominance relation.

Since unilateral deviations are still allowed in determining the CFSS, if IEA M' unilaterally indirectly dominates IEA M, M' also coalitionally indirectly dominates M'. Thus, IEAs not in the UFSS are not in the CFSS either: the CFSS is a subset of the UFSS. The next proposition derives the CFSS from the UFSS.

Proposition 3 *For any F, the CFSS is a singleton which is the largest element of the associated UFSS.*

If coalitional deviations are possible, non-signatories to a smaller IEA may want to join the IEA as a group, and thus enjoy the higher benefit of the larger IEA. In our model, allowing for coalitional deviations raises the incentives of groups of non-signatories to join the IEA, but does not affect the incentives of groups of signatories to withdraw from the IEA. The possibility of binding agreements in the negotiation stage can only be welfare improving in this setting.

6 Conclusion

In a non-cooperative setting (without side-payments), nations participate in IEAs in order to change the behavior of *other* nations. If an IEA chooses members' abatement levels before the participation decision, a nation has little or no leverage over other nations' actions, and therefore has little incentive to join an IEA. If the IEA chooses member's abatement after the participation decision, a nation has some leverage, and therefore has an incentive to join. However, IEAs typically set out the membership requirements before, not after, nations decide whether to join. The assumption that the IEA choice occurs after the participation decision is therefore questionable. In addition, that assumption implies that a reform that lowers abatement costs (e.g. trade in permits) also lowers equilibrium membership, and may reduce global welfare. The policy implication is that reforming an IEA offers little hope for making it more successful; instead, some kind of external threat, such as trade sanctions, would be needed in order to obtain cooperation. In our view, this policy implication is too pessimistic, and it is based on an implausible model of how IEAs are structured.

A re-designed Kyoto needs to accomplish (at least) two goals. It needs to address legitimate concerns that in view of the uncertainty about abatement costs, the cost of achieving a fixed target, may be prohibitive. It also needs to attract more members. The escape clause is attractive because it achieves both of these objectives, and is simple to implement.

The danger of this kind of result, based on mechanism design, is that it makes the problem of collective action appear too simple to solve. Even the best-designed agreement on climate change will require every other available support, including altruism, political courage, and side-payments.

There are a number of avenues for further research. We noted that the simplest "hybrid policy" (tradeable permits with a price ceiling) does not encourage participation. However, a modified version of that policy which auctions additional permits and returns revenue to IEA members might be effective. We assumed that nations' costs are uncorrelated, although in fact they are likely to be positively correlated. We also assumed that nations are homogenous at the participation stage, whereas in fact there is considerable heterogeneity even amongst OECD members. We intend to address these questions in future work.

A Nash equilibrium in the participation game: model details

In this appendix, we formally state and prove the results described in Section 3.1. Table 2 collects definitions of notations.

$h(x)$	The smallest integer no less than x
F_2	The locus above which signatories in a high cost state prefer to abate in a type 2 NE
F_1	The locus below which signatories in a low cost state prefer to prefer to pay the fine in a type 0 NE
$\tilde{F}$	The locus on which signatories have expected payoff of 0 in a type 1 NE
M_b	The value of M above which signatories have a higher payoff in a type 2 IEA than they would as non-signatories in a type 1 IEA.
F_0	The locus above which signatories' expected payment is higher in a type 2 than a type 1 NE

Table 2: Definitions and notation

Figure 2 embodies three parametric assumptions.

Assumption 3 *Point 'a' lies above the curve F_2.*

Assumption 4 *The horizontal distance between curves F_2 and F_1 is greater than 2 at point e.*

Assumption 5 $M_b - \bar{\theta} > 2$ *(equivalently, $\bar{\theta} > \frac{p+1}{1-p}$).*

These conditions are appropriate for a model that describes the problem of forming an IEA to control GHGs. (i) A sufficient condition for Assumption 3 is that transactions costs are positive but small. (ii) Even if nations were certain that abatement costs are low, an agreement would have to contain at least several members in order for them to benefit from abatement.[12] In addition, there is a non-negligible difference between high and low abatement costs. These conditions are sufficient for Assumption 4. (iii) Finally, the probability of high abatement costs is moderate or small (e.g., less than 0.5) so that Assumption 5 is satisfied.

Assumption 2 implies that if, at the participation stage, a signatory considers defecting from a candidate NE on F_2 below point e (i.e., for an IEA larger than $\bar{\theta}$), then the signatory knows

[12]That is, θ_L must be "moderately large", e.g. $\theta_L \geq 4$. Given our normalization, $\theta_L = 4$ means that in the low cost state, at least four nations would have to abate in order for their joint welfare to be higher than if they did not abate. As is clear from the lemmas below, this sufficient condition is very strong; the horizontal distance between the two graphs, at point b, can be greater than 2 even if this condition does not hold.

that the resulting outcome at the abatement stage will be a type 1 NE rather than a type 0 NE. Assumption 3 insures that for any candidate NE on $\tilde{F}$ consisting of fewer than $\bar{\theta}$ members, no non-signatory wants to defect by joining the IEA. (If it were to join the IEA, the membership would still be lower than M_b, the critical value below which a nation prefers being a non-signatory to an IEA that results in a type 1 NE in the abatement stage, rather than a signatory to an IEA that results in a type 2 equilibrium.)

We first show that $M_b > M_N$. By inspection of Figure 2, this inequality implies that point b lies above the graph of F_0.

Lemma 2 $M_b > M_N$.

Proof. Since $F_0 - F_1$ is a decreasing function of M for $M > 1$, and $F_0 - F_1 = 0$ at M_N, the lemma is true iff $F_0 - F_1 < 0$ at M_b. We have

$$F_0 - F_1 = \frac{-M - M\theta_H + M\theta_L + \phi\theta_H + M^2 - M\phi\theta_L}{(\phi - 1)(M - \phi)}.$$

This expression is negative iff the numerator is positive. Evaluating the numerator at $M = M_b$ and simplifying yields

$$\frac{1}{p^2}(\theta_L - 1)\left[p + \theta_L + p\theta_H - p\theta_L - p\phi\theta_L - p^2\phi\theta_H + p^2\phi\theta_L - 1\right],$$

so we require the term in square brackets to be positive. This term equals

$$\begin{aligned}(1 - \phi p)\,\bar{\theta} - (1 - p) &= (1 - p + p - \phi p)\,\bar{\theta} - (1 - p) \\ &= (1 - p)\left(\bar{\theta} - 1\right) + p(1 - \phi)\,\bar{\theta} > 0.\end{aligned}$$

■

Assumption (3) states that the intersection of $\tilde{F}$ and F_0, denoted point a, lies above the curve F_2. This assumption is equivalent to

$$\frac{\phi - p}{1 - p} > \frac{\theta_L}{\theta_H}. \tag{14}$$

This inequality holds if the transaction cost is small (ϕ close to 1) and/or if there is a substantial cost difference in the two states.

Our characterization of the NE of the participation game requires that the horizontal distance between F_2 and F_1 be greater than 2 for relevant values of F. We provide the necessary and sufficient condition for Assumption (4), and then show that this condition implies that the two graphs are "far enough apart".

We begin with the following

Lemma 3 *The horizontal distance between F_2 and F_1 is a decreasing function of F.*

Proof. Using the definitions in section 2.2, we have $F_2 - M\frac{-1+\theta_H}{-M+\phi}$, so the inverse of this function is $M = -F_2\frac{\phi}{-F_2-1+\theta_H}$. Also, $F_1 = -\left(-1+\theta_L\right)\frac{M}{-M+\phi}$, so the inverse of this function is $M = -F_1\frac{\phi}{-F_1-1+\theta_L}$. The horizontal distance between the two functions is

$$D \equiv F\phi\frac{-\theta_L+\theta_H}{\left(-F-1+\theta_H\right)\left(-F-1+\theta_L\right)}.$$

The derivative of D is

$$\frac{dD}{dF} = -\phi\left(-\theta_L+\theta_H\right)\frac{F^2-1+\theta_L+\theta_H-\theta_H\theta_L}{\left(F+1-\theta_H\right)^2\left(F+1-\theta_L\right)^2}$$

The sign of this derivative equals the negative of the sign of $F^2-1+\theta_L+\theta_H-\theta_H\theta_L$, so we need to show that this expression is positive. Use the fact that $F > \theta_H - 1$, which implies that it is sufficient to show that $\left(\theta_H-1\right)^2+\theta_L-1 > \theta_H\left(\theta_L-1\right)$, or $\left(\theta_H-1\right)^2 > \left(\theta_H-1\right)\left(\theta_L-1\right)$, or $\left(\theta_H-1\right) > \left(\theta_L-1\right)$. This inequality is true because $\theta_H > \theta_L$. ■

To state the next result we use the following definitions:

$$\begin{aligned}\alpha &\equiv \left(\theta_L-\theta_H\right)^3 < 0\\ \beta &\equiv -2\left(\theta_L-1.5\right)\left(\theta_L-\theta_H\right)^2\\ \gamma &\equiv \left(3\theta_L-\theta_L^2\right)\theta_H + \left(\theta_L^3-3\theta_L^2+2\theta_L-2\right).\end{aligned} \tag{15}$$

The next lemma shows that Assumption (4) is equivalent to the following inequality:

$$R \equiv \alpha p^2+\beta p+\gamma < 0. \tag{16}$$

Lemma 4 *(i) $F_2^{-1}(F_e) - F_1^{-1}(F_e) - 2 > 0 \iff R < 0$. (ii) A sufficient condition for $R < 0$ (when $p \geq 0$) is that $\beta < 0$ and $\gamma < 0$. Both of these inequalities are satisfied if*

$$\theta_L > 3 \text{ and } \theta_H > \theta_L + \frac{2\left(\theta_L-1\right)}{\theta_L(\theta_L-3)}. \tag{17}$$

Proof. *(Part i) Using the definition of D we have*

$$D-2 = \frac{-\left(4F-2\theta_L-2\theta_H-2F\theta_L-2F\theta_H+2\theta_L\theta_H+2F^2+F\theta_L\phi-F\theta_H\phi+2\right)}{\left(F-\theta_L+1\right)\left(F-\theta_H+1\right)}.$$

The denominator of this expression is positive, so $D > 2$ iff the numerator is positive. In view of Lemma (3), this inequality requires that the numerator is positive evaluated at $F =$

$-M_e\frac{-1+\theta_H}{-M_e+\phi}$ *(where* $M_e = \bar{\theta}$*). Evaluating the numerator at this point and simplifying gives the expression*

$$-\phi\frac{K}{\left(-\bar{\theta}+\phi\right)^2},\ \textit{with}\ K \equiv \left(2(\theta_L-1)+\bar{\theta}(\theta_H-\theta_L)\right)\phi+\bar{\theta}\left(\bar{\theta}-2\right)\left(\theta_L-\theta_H\right).$$

Since $-\frac{\phi}{\left(-\bar{\theta}+\phi\right)^2} < 0$ *we need to show that* $K < 0$*. Note that* K *is an increasing function of* ϕ*. Therefore we need to establish that* K *evaluated at* $\phi = 1$ *is negative. Denote this value as* L*:*

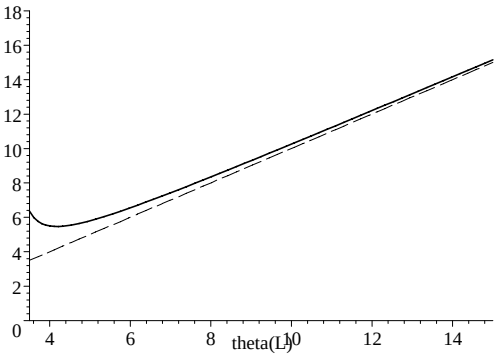
$$L = \left(2(\theta_L-1)+\bar{\theta}(\theta_H-\theta_L)\right)\phi+\bar{\theta}\left(\bar{\theta}-2\right)\left(\theta_L-\theta_H\right).$$

We write this expression as a function of p *using* $\bar{\theta} = p\theta_H + (1-p)\theta_L$*, using the definitions in equation* (15)*, to obtain the expression* R *given in equation* (16)*. To establish part (ii) note that* R *is concave in* p*, and at* $p = 0$*,* R *is decreasing if* $\theta_L > 1.5$ *and* $R = \gamma$*. Therefore, a sufficient condition for* $R < 0$ *for* $p \geq 0$ *is* $\theta_L > 1.5$ *and* $\gamma < 0$*. Suppose that* $\theta_L > 3$*. Then* $\gamma < 0$ *if and only if*

$$\theta_H > \theta_L + \frac{2\left(\theta_L-1\right)}{\theta_L\left(\theta_L-3\right)}.$$

■

Figure (**??**) shows the graph of $\theta_L + \frac{2(\theta_L-1)}{\theta_L(\theta_L-3)}$ and the (dashed) line where $\theta_H = \theta_L$. For $\theta_L > 4$, $R < 0$ for all p and for nearly all $\theta_H > \theta_L$. Given our normalization, $\theta_L = 4$ means that in the low cost state, at least four nations would have to abate in order for their joint welfare to be higher than if they did not abate.



The graph of $\theta_L + \frac{2(\theta_L-1)}{\theta_L(\theta_L-3)}$ (solid) and the 45 degree line (dashed)

The following corollary gives a necessary and sufficient condition for the horizontal distance between F_2 and F_1 to be greater than 2 for values of F less than F_e.

Corollary 1 *$F_2^{-1}(F) - F_1^{-1}(F) - 2 > 0$ for $F \in (\theta_H - 1, F_e)$ for all $0 < \phi < 1$ if and only if $R < 0$.*

Proof. The proof is immediate from the previous two lemmas. ■

We now formally state and prove the characterization of the NE to the participation game.[13]

Proposition 4 *We adopt Assumptions (3), (4), and (5). The IEA uses an escape clause with fine F that is taken as given at the participation stage.*
(i) For $N \geq F_2^{-1}(F_b)$, and for $F \in [F_2(N), F_b]$ there exists a NE to the participation game consisting of $h(F_2^{-1}(F))$ members. The resulting abatement-stage NE is type 2.
(ii) The smallest IEA leading to a type 2 abatement-stage NE consists of M_b members, induced by fine F_b.
(iii) For $N \geq F_1^{-1}(F_c)$, and for $F \in \left[F_1^{-1}(N), F_c\right]$ there exists a NE to the participation game consisting of $h(F_1^{-1}(F))$ members. This NE induces a type 1 equilibrium in the abatement stage.
(iv) Define F_k to satisfy $h\left(\tilde{F}^{-1}(F_k)\right) - F_1^{-1}(F_k) = 1$; define $F_q = \sup\left\{F \mid h\left(\tilde{F}^{-1}(F)\right) \leq F_2^{-1}(F)\right\}$; finally define $F_g = \min\{F_k, F_q\}$. It must be case that $F_c < F_g \leq F_d$. For $F_c \leq F \leq F_g$ there is a NE with $h\left(\tilde{F}^{-1}(F)\right)$ members. This NE induces a type 1 equilibrium in the abatement stage. For $F > F_g$ there is no NE to the participation game that induces a type 1 equilibrium in the abatement game.
(v) If F can be chosen at stage 0, it is feasible to induce a type 2 equilibrium at the abatement stage iff $N \geq M_b$. If it is feasible to induce a type 2 equilibrium, it is optimal to do so.

Proof. (Proposition 2) We begin by explaining the meaning of $M_b = \frac{\bar{\theta}-1+p}{p}$ and $F_2(M_b)$, the coordinates of point b in Figure 2. At these values, a signatory in a type 2 equilibrium has the same payoff that it would obtain if it left the IEA and became a non-signatory in a type 1

[13] If nations could costlessly disband the IEA, there would be additional NE to the participation game. For example, for $F \geq F_2(\bar{\theta})$, $M = \bar{\theta}$ is a NE. For F between F_c and the horizontal coordinate of the intersection between $\tilde{F}$ and F_2, $\tilde{F}^{-1}(F)$ is a NE, leading to a type 1 equilibirum in the abatment stage.

IEA:

$$\pi_{s,2}(M) \left\{ \begin{array}{c} < \\ = \\ > \end{array} \right\} \pi_{n,1}(M-1)$$
$$\Longleftrightarrow \tag{18}$$
$$M \left\{ \begin{array}{c} > \\ = \\ < \end{array} \right\} M_b$$

For points on the curve F_2 below point b, a signatory in a type 2 equilibrium would not want to leave the IEA if that defection induced a type 1 equilibrium; for points on F_2 above b, a signatory would want to defect if the result was a type 1 equilibrium.

Since $M_b > \bar{\theta}$, $F_2(M_b) < F_e$; therefore, by Corollary (1) the horizontal distance between F_2 and F_1 is greater than 2:

$$F_2^{-1}(F) - F_1^{-1}(F) - 2 > 0 \text{ for } F \in (\theta_H - 1, F_2(M_b)]. \tag{19}$$

We now prove the claims in Proposition 2.

(i) For $F \in \left[F_2^{-1}(N), F_b\right]$ consider the candidate equilibrium consisting of $h(F_2^{-1}(F))$ members. If a member of the IEA defects, the resulting equilibrium to the abatement game is type 1, in view of Corollary 1. The defector's payoff is lower, in view of equation (18). No non-signatory wants to defect from the candidate by joining the IEA, because $\pi_{s,2}(M+1) < \pi_{n,2}(M)$. Therefore, the candidate is a NE.

(ii) For $F > F_b$ we need to consider two possibilities. Consider first $F \in (F_b, F_e)$. Clearly $M > h\left(F_2^{-1}(F)\right)$ is not an equilibrium: a member would want to defect by leaving the IEA, since the resulting IEA would still induce a type 2 equilibrium in the abatement game. Similarly, $M = h\left(F_2^{-1}(F)\right)$ is not an equilibrium: by equation (18), a member would want to leave the IEA, inducing a type 1 equilibrium in the abatement game. Next, consider $F \geq F_e$. Over this range of F, it is easy to see that the only candidate equilibrium is $h\left(\bar{\theta}\right)$. However, this cannot be an equilibrium, since defection by a member would induce either a type 1 or a type 2 equilibrium in the abatement game (depending on the magnitude of F). By equation (18), a signatory who leaves the IEA (becoming a non-signatory) has a higher payoff than at the candidate equilibrium.

(iii) For $F \in \left[F_1^{-1}(N), F_c\right]$, consider a candidate NE at $M = h(F_1^{-1})$. Signatories' payoffs are positive at $h(F_1(M))$ because this point is to the right of $\tilde{F}$ (except at the endpoint

F_c where the payoff is 0). If any signatory were to defect by leaving the IEA, the resulting NE in the abatement game is type 0, where a non-signatory obtains a 0 payoff. Therefore, no signatory wants to defect.

We now need to show that non-signatories do not want to defect from the candidate equilibrium by joining the IEA. Since $h\left(F_1^{-1}(F)\right)+1 < F_1^{-1}(F)+2 < F_2^{-1}(F)$ by inequality (19)) the defection induces a type 1 equilibrium in the abatement stage. The defector's payoff is lower at the new point than at the candidate, because $\pi_{s,1}(M+1;F) < \pi_{n,1}(M)$.

(iv) First note that if $F > F_q$ the only candidate NE to the participation game that could result in a type 1 equilibrium in the abatement game, is $M = h\left(\tilde{F}^{-1}(F)\right)$, since smaller values would result in negative payoffs for signatories, and larger values would not be immune from defection by signatories. However for $F > F_q$ the candidate $M = h\left(\tilde{F}^{-1}(F)\right)$ results in a type 2 equilibrium in the abatement stage. Therefore, NE to the participation game that lead to type 1 equilibria must have fines $F \leq F_q$.

Next consider candidates $M = h\left(\tilde{F}^{-1}(F)\right)$ for $F > F_k$. A signatory would want to defect from this candidate, since the resulting abatement stage equilibrium would still be type 1. Therefore, NE to the participation game that lead to type 1 equilibria must have fines $F \leq F_k$.

Thus, for $F \leq F_g$ the candidate $M = h\left(\tilde{F}^{-1}(F)\right)$ is consistent, in that it leads to a type 1 equilibrium, and it is immune from defection by signatories. Therefore we need only show that this candidate is immune from defection by a non-signatory. By virtue of Assumption (5), if a non-signatory defects by joining the IEA, the resulting abatement stage equilibrium is still type 1. Thus, the defecting non-signatory has a lower payoff. Therefore, the candidate is a NE to the participation game.

(v) When all countries are in the IEA, aggregate welfare equals the joint welfare of IEA members. Define M_N to satisfy $F_0(M_N) = F_1(M_N)$. On F_0, signatories' payoffs are the same in a type 1 or a type 2 equilibrium consisting of all nations. Therefore, at M_N:

$$\pi_{s,2}(M_N) = \pi_{s,1}(M_N; F_1^{-1}(M_N)).$$

Recall that $\pi_{s,2}(M)$ is independent of F. For $M < M_N$ the point $\left(M; F_1^{-1}(M)\right)$ lies below the line F_0, so at that point $\pi_{s,2}(M) < \pi_{s,1}(M; F_1^{-1}(M))$. Therefore, for $M < M_N$ aggregate welfare is higher in a type 1 equilibrium consisting of all nations, than in a type 2 equilibrium consisting of all nations. The argument is reversed when $M > M_N$.

By part (ii) above, the smallest IEA that results in a type 2 NE in the abatement stage consists of M_b members. By Lemma (2), this value is greater than M_N, the value above which it is optimal to induce a type 2 equilibrium. ■

B Farsighted stable sets: model details

In this section, we provide the model details for Section 5.

B.1 Circular decisions under farsightedness

Consider a Nash equilibrium IEA of the participation game identified in Section 2, and suppose the IEA's size is M. Being a NE implies that $\pi_s(M;F) \geq \pi_n(M-1,F)$. Suppose a signatory, say nation i, withdraws from the IEA, and consider the reaction of a non-signatory, say nation j. Since $\pi_s(M;F) \geq \pi_n(M-1,F)$, nation j has incentive to join the IEA, and if it joins, i's payoff becomes $\pi_n(M;F) > \pi_s(M;F)$. Anticipating j's reaction, i thus has incentive to withdraw: it can become a free-rider since j will join in its place. But this argument can go on forever, since every signatory has incentive to withdraw in order to become a free-rider.

B.2 Proof of results

Proposition 2. To demonstrate "only if" we merely show that if any one of the conditions are note satisfied, then the set $\mathcal{M}(M_0)$ is either not internally or not externally stable. This claim is straightforward, and we do not provide the details. The proof demonstrates the "if" part of the proposition, following the outline given in the paragraph below the statement of the Proposition. Step 1 uses conditions (i) and (ii) to establish that $\mathcal{M}(M_0)$ is an internally stable set, and Step 2 uses condition (iii) to confirm its external stability.

Step 1 (Internal Stability): Payoffs are monotonic in M. In addition, in order to move from an IEA of size M^j to an IEA of size M^{j+s} with $s > 1$ it is necessary to "move through" an IEA of size M^{j+1}. Therefore, the fact that M^{j+1} does not indirectly dominate M^j implies that larger IEAs also do not indirectly dominate M^j. Similarly, the fact that M^j does not indirectly dominate M^{j+1} implies that smaller IEAs also do not dominate M^{j+1}. These facts allow us to demonstrate internal stability by showing that neither of the IEAs M^j nor M^{j+1} indirectly dominate each other.

No element of $\mathcal{M}(M_0)$ can indirectly dominate a larger element of the set. For example to move from M^{j+1} to M^j, one signatory has to begin the process by leaving the IEA. The "first deviator's" payoff is no higher (except for knife-edge cases, strictly lower) when it becomes a non-signatory at M^j instead of remaining a signatory at M^{j+1}. (For the knife-edge case, recall our assumption that in the case of a tie, a nation prefers to abate.)

To complete the argument for internal stability, we need only show that no element of $\mathcal{M}(M_0)$ can indirectly dominate a smaller element of the set. We do this by showing that M^{j+1} does not indirectly dominate M^j.

First consider the case where M^j and M^{j+1} are both positive and both of the same type. Recall from Lemma $(1(ii))$ that in order for $M^j \ll M^{j+1}$, it must be true that $\pi_n(m) \leq \pi_s(M^{j+1})$ *for all* $m = M^j, M^j + 1, \ldots, M^{j+1} - 1$. Thus, for this step, all we need to establish is that this inequality does *not* hold for some m. We establish this inequality for the case of $m = M^{j+1} - 1$.

Recall that $\pi_{s,i}(1) < \pi_{n,i}(0)$, $i = 0, 1, 2$; a nation never wants to be the sole member of an IEA. Equations (7) - (11) imply that $\partial \pi_s(M, i)/\partial M = \partial \pi_n(M, i)/\partial M$. The two conditions above imply that, *if IEAs of sizes* M *and* $M - 1$ *are of the same type*,

$$\pi_{s,i}(M) < \pi_{n,i}(M - 1), \quad \text{or} \quad M \ll M - 1, \quad M = 1, \ldots, N. \tag{20}$$

If M^j and M^{j+1} are of the same type, $M^{j+1} - 1$ and M^j are of the same type as well, implying that $M^{j+1} \ll M^{j+1} - 1$.

Next consider the case where M^j is a type 1 IEA and M^{j+1} is a type 2 IEA. (We know that there can be no type 1 IEAs larger than the smallest type 2 IEA because the curve F_2 lies above F_1.) By condition (ii), $M^{j+1} < M_b$. By the definition of M_b, a nation prefers to be a non-signatory to an IEA of size $M^{j+1} - 1$ rather than a signatory to an IEA of size M^{j+1}, so again $M^{j+1} \ll M^{j+1} - 1$.

Finally, consider the case where $M_0 = 0$, so that $\pi_n(M_0) = 0$. If it were the case that the IEA with $M^2 - 1$ were a type 0 equilibrium, then a non-signatory would want to join that IEA, because joining increases its payoff from 0 to a non-negative level. In that case, M^1 indirectly dominates M^2, violating internal stability. However, if the IEAs with $M^2 - 1$ and M^2 are both the same type, $M^2 \ll M^2 - 1$. The "last signatory" does not want to join, so M^2 does not indirectly dominate M^1. Also, if M^2 is a type 2 IEA and $M^j - 1$ is type 1, then by virtue of condition (ii) we again have $M^2 \ll M^2 - 1$.

Step 2: (External stability) We need to show that each element in $\mathcal{N}$ in the complement of $\mathcal{M}(M_0)$ (i.e. $\mathcal{N}/\mathcal{M}(M_0)$) is indirectly dominated by some element of $\mathcal{M}(M_0)$. The set $\mathcal{N}/\mathcal{M}(M_0)$ is the union of two sets, IEAs that are smaller than, or larger than M_0. Denote these as $A = \{M \mid M < M_0, M \in \mathcal{N}/\mathcal{M}(M_0)\}$ and $B = \{M \mid M > M_0, M \in \mathcal{N}/\mathcal{M}(M_0)\}$.

Consider set A. When $M_0 = 0$, $A = \varnothing$, so for this subset we need only consider $M_0 > 0$. In this case, condition (iii) states that IEAs smaller than M_0 are indirectly dominated by the IEA of size M_0.

Now consider set B. We show that M^j indirectly dominates IEAs with sizes between M^j and M^{j+1} for $j + 1 \leq k$ (Recall that k is the index of the largest element of $\mathcal{M}(M_0)$.) That is, $M \ll M^j$ for all $M = M^j + 1, \ldots, M^{j+1} - 1$. In addition, for $j = k$, $M \ll M^j$ for all $M = M^j + 1, \ldots, N$. We provide details only for the case of $j < k$; the proof is similar when $j = k$.

>From (13), we know $\pi_s(m^{j+1}) = \pi_n(M^j)$. We need to consider two cases: where M^j and M^{j+1} are the same type of IEA, and were they are different types. Suppose first that IEAs of sizes M^j and M^{j+1} are of the same type i, i.e., $\pi_{s,i}(m^{j+1}) = \pi_{n,i}(M^j)$. Since $\pi_{s,i}(\cdot)$ is strictly increasing in M, the equation means that $\pi_{s,i}(M^{j+1}-1) < \pi_{n,i}(M^j)$, which in turn implies that $\pi_{s,i}(M) < \pi_{n,i}(M^j)$, for all $M = M^j + 1, \ldots, M^{j+1} - 1$. Since all these IEAs are of the same type i, we know $\pi_s(M) < \pi_n(M^j)$ and thus $M \ll M^j$ for all $M = M^j + 1, \ldots, M^{j+1} - 1$.

Suppose instead that IEAs of sizes M^j and M^{j+1} are of different types. Here there are two possibilities. Either (i) $M^j = 0$ and M^{j+1} is a type 1 or type 2 IEA, or (ii) M^{j+1} is a type 2 and and M^j is a type 1 IEA. (As explained in the text, there can be no positive elements of the stable set that are type 0.)

First consider the possibility $M^j = 0$, which occurs when $j = 1$ and $M_0 = 0$. In this case, $\pi_s(M) < 0$ for $1 \leq M < M^2$, so $M \ll M^j = 0$ for all $M = 1, 2, \ldots, M^{j+1}-1$. Next consider the case where M^{j+1} is a type 2 and and M^j is a type 1 IEA. Let $M' \leq M^{j+1}$ be such that the IEA of size $M' - 1$ is of type 1 but that of M' is of type 2. For IEAs between M' and M^{j+1}, Because $\pi_{s,2}(M^j - 1) < \pi_n(M^j)$, we know $\pi_{s,2}(M) < \pi_n(M^j)$ for all $M \in [M', M^{j+1} - 1]$. That is, $M \ll M^j$ for all $M \in [M', M^{j+1} - 1]$. For IEAs between M^j and $M' - 1$ we know from (13) that $\pi_{s,1}(M' - 1) < \pi_s(M^j)$; if this inequality did not hold, $M' - 1$ instead of M^{j+1} would have been the next element in $\mathcal{M}(M_0)$ after M^j. Again, since $\pi_{s,1}(\cdot)$ is increasing, we know $\pi_{s,1}(M) < \pi_s(M^j)$ for all $M \in [M^j + 1, M' - 1]$. Therefore, $M \ll M^j$ for all $M \in [M^j + 1, M' - 1]$. ■

Summary 1. (i) If $F < F_1(N)$, the IEA is of type 0 and its signatory earns negative payoffs. Signatories to an IEA of any positive size have incentive to withdraw, i.e., $M \ll 0$ for all $M > 0$. In this case, the UFSS has only one element $M = 0$.

(ii) Let $M' = h(F_1^{-1}(F))$. Recall that the IEA of size M' is a Nash equilibrium, i.e., $\pi_{s,1}(M') \geq \pi_{n,1}(M' - 1)$, implying that $\pi_{s,1}(M') \geq \pi_{n,1}(M)$ for all $M \leq M' - 1$ or $M \ll M'$. Since IEAs of size $M \geq M'$ are of the same type 1, Corollary **??** implies that M' is not indirectly dominated by any $M > M'$. Thus, M' is the smallest farsighted stable set, or $M_0 = M'$.

(iii) Suppose $F \in [F_2(N), F_b)$. The proof is the same as the case of (ii) since the IEA of size $M' = h(F_2^{-1}(F))$ is also a Nash equilibrium, and IEAs of sizes $M \geq M'$ are of the same type.

(iv) Suppose $F \in [F_b, F_d)$. To show that $M_0 = 0$, we only need to show that M_0 is not indirectly dominated by any $M > 0$. But we know from Figure 5 (and from Assumption 5) that there are two possible switches of IEA types: from type 0 to type 1 along curve F_1, which is to the left of curve $\tilde{F}$, and from type 1 to type 2 along curve F_2, which is to the left of M_b. Thus, the conditions in Proposition 2(ii) are satisfied, and $M_0 = 0$ is not indirectly dominated by $M > 0$ from Corollary 2.

(v) Suppose $F \geq F_d$. The proof is similar to case (iv): $M_0 = 0$ since the conditions in Proposition 2(ii) are satisfied for all three possible switches of IEA types. ■

Proposition 3. Consider the set $V = \mathcal{M}(M_0)$ with the largest element being M^k. >From (13), we know

$$\pi_s(M^k) \geq \pi_n(M^{k-1}) > \pi_n(M^{k-2}) > \ldots > \pi_n(M^1). \tag{21}$$

Consequently, at any IEA M^j, $j < k$, a group of $M^k - M^j$ non-signatories have incentive to join the IEA together, and earn $\pi_s(M^k)$ instead of $\pi_n(M^j)$. That is, M^k coalitionally indirectly dominates all other elements in the set $\mathcal{M}(M_0)$. ■

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