Dynamic Models for International Environmental Agreements

Michèle Breton, Lucia Sbragia
and Georges Zaccour

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Michèle Breton, *GERAD, CREF and HEC Montréal*
Lucia Sbragia, *GERAD and HEC Montréal*
Georges Zaccour, *GERAD and Chair in Game Theory & Management HEC Montréal*

Corso Magenta, 63, 20123 Milano (I), web site: www.feem.it, e-mail: working.papers@feem.it

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Summary

In this paper we develop a model to analyze, in a dynamic framework, how countries join international environmental agreements (IEAs). In the model, where countries suffer from the same environmental damage as a result of the total global emissions, a non-signatory country decides its emissions by maximizing its own welfare, whereas a signatory country decides its emissions by maximizing the aggregate welfare of all signatory countries. Signatory countries are assumed to be able to punish the non-signatories at a cost. When countries decide on their pollution emissions they account for the evolution of the pollution over time. Moreover, we propose a mechanism to describe how countries reach a stable IEA. The model is able to capture situations with partial cooperation in an IEA stable over time. It also captures situations where all countries participate in a stable agreement, or situations where no stable agreement is feasible. When more than one possibility coexists, the long-term outcome of the game depends on the initial conditions (i.e. the size of the initial group of signatory countries and the pollution level).

Keywords: International Environmental Agreements, Non ‑ Cooperative Dynamic Game, Coalition Stability

JEL Classification: C73, Q53

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Address for correspondence:

Michèle Breton
HEC Montréal
3000, chemin de la Côte-Sainte-Catherine
H3T 2A7 Montréal (Québec)
Canada
Phone: (514) 340 6490
Fax: (514) 340 6432
E-mail: michele.breton@hec.ca

1 Introduction

Environmental problems often share the feature of being international, that is, the welfare of a country depends not only on its own policy, but also on those of other countries. Examples of these problems are acid rains, pollution emissions, exploitation of the fishing grounds or rain forests. In the case of pollution emissions, air pollutants mix in the atmosphere and additions to the concentrations of these gases depend on the global total emissions. Countries have realized that these kinds of problems have to be solved on a global basis and that international environmental agreements (IEAs) are the only solutions.

The participation of countries in an international agreement to improve the quality of the environment is a complex question for two main reasons. First, countries are sovereign and their participation to international agreements is voluntary. There is no supra-national authority that forces countries to participate to an agreement, as well as there is no international environmental judicial system powerful enough to guarantee compliance to an IEA [17, 36, 19]. Second, each country may have an incentive to free-ride. In fact, while the costs for reducing emissions are carried out exclusively by the country that is taking action, the benefits of a reduction in emissions are shared by all countries, so that each country has the incentive to wait for the others to reduce their emissions. This problem is commonly known as "The Tragedy of the Commons" [22].

Because of these interactions, global environmental problems can be modeled in a game theoretic framework. The literature based on this approach has developed following two streams: the cooperative and the non-cooperative approach. In this paper, we adopt the non-cooperative point of view; the main concept, in this case, is that players cannot make binding agreements and they act as rivals and in their own best interest,[1] so that successful agreements must be *self-enforcing* [1].The conditions for an agreement to be self-enforcing are profitability, which ensures that the accession to the agreement is individually rational for a country, and stability, which ensures that the group of signatory countries is an equilibrium.

The main body of literature on non-cooperative games and self-enforcing agreements uses a static framework to describe the problem of pollution emissions, that is, the environmental damage is assumed to depend on the flow of emissions. In this literature following [1], two conditions define an equilibrium: internal stability, which implies that no member has an incentive to leave the agreement, and external stability, which implies that no non-member has an incentive to join the agreement. Behind these concepts, there is the idea that governments can re-optimize their choice, but in static models, this is only hypothetical, because since the game will not be played again, there is no adjustment towards a stable solution and no change of state. In this framework, several stages in which specific decisions have to be made can be considered; a typical example is a two-stage game, where countries decide wether or not to become a member of an IEA in the first stage (membership game), and decide on their emissions in the second stage (emissions game).

Many static models using this stability concept have reached the conclusion that successful cooperation among a large number of countries is difficult to obtain, and that the size of the membership of a stable IEA is inversely related to the relative importance of the environmental damage. In order to explain the greater participation observed in reality, like for exam-

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[1] Cooperative game theory assumes that players realize that, if they act as a group and coordinate their actions, they can obtain mutual benefits. A particular agreement is the result of questions about the circumstances under which the agreement can be established, what can be achieved as a group, and the ways in which the benefits of the cooperation are redistributed among the participants [14, 36].

ple in the Montreal Protocol,[2] static models have incorporated several ideas to increase the propensity to cooperate. Some of them are: Stackelberg leadership of signatories [2, 13, 34], transfers [10, 23], reputation effects [23, 24, 8], issue linkages [6, 7, 3, 25, 11, 12, 28], including a minimum participation clause [9], and considering modest emission reduction targets [20].

Although any model abstracts from reality, static games applied to pollution emissions and IEAs may be criticized on two important aspects. One aspect is the stock externality: transboundary environmental damage is usually related to the accumulation (stock) of pollution, rather than to the emissions (flow). The second aspect is that countries can revise their decisions of being or not member of an agreement at different points in time, especially if the environmental damage is changing over time.

In the literature considering the dynamics of the pollution stock, the concepts of renegotiation-proof or dynamically consistent agreements may be conceptually linked to internal and external stability conditions, in the context of repeated and dynamic games respectively. Part of this literature develops differential games that compare different solution concepts without addressing the membership problem (see for instance [27, 30, 15, 16] and [32]). Papers considering the membership decision include [33, 21], and [31]. In [33], the membership game is played once and forever and, on the basis of this result, signatory and non-signatory countries decide their emissions by solving an infinite-horizon differential game in both open-loop and feedback strategies. Thus, the dynamics of the pollution stock only affects the emissions strategies but not the IEA membership. In [21], a transfer scheme is proposed in a dynamic game such that full cooperation is maintained over time. In this case, the dynamics of the stock pollutant is included in the membership decision, but the transfer scheme is able to ensure full cooperation so that the size of the IEA membership does not change over time. Finally in [31] the formation and stability of IEAs over time is studied in a difference game with dynamic pollution stock. In each period, countries solve both an emission game and a membership game so that the number of signatories changes over time with the stock of pollution. The authors assume an upper bound on non-signatory emissions. They also suppose that, in each period, signatories are randomly selected, so that the stability concept is the equality of the welfare of signatories and non-signatories.[3] The result is the existence of a unique steady-state of pollution stock to which corresponds a steady-state for the size of a stable IEA. As in the static case, the size of the self-enforcing IEA is negatively related to the importance of the damage costs.

In this paper, we recognize that countries can joint or quit an agreement over time and that it takes time to reach a stable IEA, so that we propose a possible mechanism which could describe how this happens. We choose a discrete time setting because, even if pollution evolves continuously over time, decisions from countries whether to enter or leave an IEA are rather made at discrete moments.

The agreement we model in this paper includes two aspects. The first one is that a signatory country agrees to decide its emissions level by maximizing the aggregate welfare of the coalition. Instead, a non-signatory country decides its emissions level by maximizing its individual welfare. In each case, countries use the total discounted welfare over an infinite horizon, taking into account the evolution of the pollution stock. The second aspect is that a signatory country agrees to punish non-signatory countries. In particular, we assume that the punishment is a function of the number of signatory countries, as in Hoel and Schneider [23], but also of the level of the accumulated pollution. This non-environmental cost suffered

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[2] The Montreal Protocol on Substances that Deplete the Ozone Layer signed in 1987 at present counts 191 nations.

[3] This means that the incentive for a signatory to abide by its agreement is not addressed in the model.

by non-signatories can be interpreted as a trade sanction (e.g. a carbon tax), or a social norm, which becomes stronger with increasing levels of pollution and environmental damage. Including some sort of punishment in an IEA as a tool to increase and sustain cooperation is not uncommon [4, 3]. Indeed, the Montreal Protocol, among the other measures to boost participation to the agreement, includes trade sanctions against non-members (banning trade between signatories and non-signatories).

Moreover, since a general punishment or, more specifically, a trade sanction is not without adverse consequences, we also include another element in the model that has not been addressed to the best of our knowledge in the context of IEA to reduce pollution emissions, that is, a cost suffered by signatory countries for punishing the non-signatories (as in [35] and [5] in the fishery context). We assume this cost to be proportional to the punishment.

Finally, we propose an evolutionary process that may describe how countries reach over time a stable IEA. This process is able to depict the stickiness and delays that may characterize this convergence. This idea of gradually achieving stability finds its justification in practice: often, an IEA is promoted and signed by a first group of founding countries (for some reason more sensitive to the environmental problem) and it is then joined over time by other countries.[4] An example is the Montreal Protocol which, after being ratified by a first group of countries, was joined by new members every year.

In particular, we adopt a replicator dynamics in discrete-time which provides evolutionary pressures in favor of group obtaining the highest payoff. Following the spirit of evolutionary games, the group that performs better is joined by a fraction of new agents. The adjustment speed at which countries switch to the superior strategy is related to the difference in welfare, and it reflects the "psychological" or "physical" cost of changing behavior. The evolutionary process ends in an IEA which is stable over time and at the steady-state pollution stock. It is worthwhile noticing that in that process, the evolution of players' welfare over time depends not only on the dynamics of emissions and pollution, but also on the evolution of the different groups' composition.

Our model is able to capture different long-run situations: that no stable agreement is reached, that all countries joint the agreement, and the (more realistic) result in which some countries are in, and others are out, of a stable IEA.

The paper is organized as follows. Section 2 presents the model and the general dynamics that governs the evolution of pollution stock. In Section 3, we propose and solve a dynamic game in which countries optimize their welfare over an infinite horizon by taking into account the evolution of the pollution stock. Section 4 introduces stability concepts and the replicator dynamics for the number of signatory countries. Section 5 presents numerical illustrations and sensitivity analysis. Finally, Section 6 concludes the paper.

2 The Model

Let us consider N identical countries. A fraction s of them, identified as "signatory countries", decides to join an international environmental agreement, according to which their production activity is decided by maximizing the aggregate welfare of the coalition. We denote S the set of signatory countries. The remaining fraction $(1-s)$, identified as "non-signatory countries" or "defectors", acts individually, that is each of them decides its production activity by maximizing its individual welfare, and we denote D the set of defectors.

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[4] Of course, it may also happen that a member country decides to abandon the agreement.

Each country has a production activity that generates benefits but also pollution. Let us indicate with e_{jt} the emissions generated by the production of country j in time period t. We suppose that the net revenues (i.e., gross revenues minus costs) derived from country j's production activity in a given period are increasing concave functions of its emissions, and given by the quadratic function

$$R(e_{jt}) = e_{jt}\left(b - \frac{1}{2}e_{jt}\right).$$

Countries suffer an environmental damage arising from (global) pollution, which is assumed linear[5] and given by

$$D(P_t) = dP_t,$$

where $d > 0$ is the constant marginal damage and P_t is the stock of pollution at time t.

As part of the agreement, we assume that each signatory country has to punish a non-signatory for its irresponsible behavior ([23]). Moreover, we suppose that this punishment is directly proportional to the level of pollution, reflecting an environmental concern of signatories increasing with pollution stock, so that the non-environmental cost incurred by a defector as punishment is given by

$$\phi(s, P_t) = \alpha N s P_t.$$

This sanction can be interpreted as a limited trade with a non-signatory country, or a carbon-tax imposed on its exports. In the following we assume that $\alpha < d$, that is, the punishment inflicted on a non-member country from an individual signatory is small with respect to the damage it suffers from pollution.

As punishing a country has some negative effect on signatory countries, we suppose that punishing has itself a cost, which is proportional to the punishment αP_t imposed to the $N(1-s)$ non-signatory countries,[6] so that each signatory incurs in a non-environmental cost given by

$$\omega(s, P_t) = \gamma N(1-s)P_t,$$

where one would normally expect $\gamma < \alpha$.[7] As a consequence, the welfare of a signatory country $j \in S$ in time period t is given by

$$W_t^S(e_{jt}, P_t, s) = e_{jt}\left(b - \frac{e_{jt}}{2}\right) - dP_t - \gamma N(1-s)P_t,$$

whereas the welfare of a non-signatory $j \in D$ is given by

$$W_j^D(e_{jt}, P_t, s) = e_{jt}\left(b - \frac{e_{jt}}{2}\right) - dP_t - \alpha N s P_t.$$

In the sequel, we will use the following convenient abbreviated notation

$$\begin{aligned} c_S &\equiv d + \gamma N(1-s) \\ c_D &\equiv d + \alpha N s \end{aligned}$$

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[5] This simplification is not uncommon (see for example [23, 20] and is supported by some empirical estimations (see [26]).

[6] The marginal cost of punishing is assumed to be independent from the number of signatory countries. This is the case for example for a trade sanction: the cost on a member's welfare depends only on the number of countries to which it applies the sanctions.

[7] Notice that the results are not affected if this is not the case.

to represent the marginal (environmental and non-environmental) impacts of pollution on the welfare of signatory and non-signatory countries respectively (which are however not constants, but linear functions of s). Notice that the difference in marginal costs $c_S - c_D$ is a linear function of s which is positive for $s < \frac{\gamma}{\alpha+\gamma}$ and negative for $s > \frac{\gamma}{\alpha+\gamma}$.

Finally, the evolution over time of the pollution stock is assumed to be governed by the discrete time equation

$$P_t = P_{t-1}(1-\delta) + \sum_{i \in S} e_{it} + \sum_{k \in D} e_{kt} \tag{1}$$

where $\delta \in (0,1)$ is the natural decay, $\sum_{i \in S} e_{it}$ is the total emissions of signatory countries and $\sum_{k \in D} e_{kt}$ is the total emissions of non-signatories both at time period t.

3 A dynamic game of emissions

In this section, we solve the dynamic emissions game. We assume that, for a given fixed number of signatories, countries optimize their welfare by taking into account the evolution of the stock of pollution. The total discounted welfare of players is maximized over an infinite horizon, where β is the one-period discount factor assumed common to all players. The welfare maximization problem for a signatory country $j \in S$ is thus given by

$$\begin{aligned} \max_{(e_j), j \in S} W^S &= \sum_{j \in S} \sum_{t=0}^{\infty} \beta^t \left(e_{jt} \left(b - \frac{e_{jt}}{2} \right) - P_t c_S \right) \\ \text{s.t.} & \\ P_t &= P_{t-1}(1-\delta) + \sum_{i \in S} e_{it} + \sum_{k \in D} e_{kt}, \quad P_0 \text{ given}, \end{aligned} \tag{2}$$

where e_{jt} is the emissions of country j during period t and e_j denotes the sequence of emissions $\{e_{jt}\}_{t=0,\dots\infty}$. In the same way, the welfare maximization problem for a defector country $j \in D$ is

$$\max_{e_j} W^D = \sum_{t=0}^{\infty} \beta^t \left(e_{jt} \left(b - \frac{e_{jt}}{2} \right) - P_t c_D \right),$$

subject to (2).

In order to characterize the optimal reaction strategies of players and the dynamic equilibrium, we use a dynamic programming formulation where the state variable is P, that is the level of pollution of the preceding time period. We solve for a Nash equilibrium in stationary feedback strategies between the group of signatories, acting as a single player, and the non-signatories, acting as $N(1-s)$ individual players, where $Ns \in [1, N-1]$. We call κ the constant representing the combined effect of the discount factor and the natural pollution decay,[8] that is

$$\kappa \equiv \frac{1}{1-\beta(1-\delta)} \geq 1.$$

We first compute the optimal reaction of the set of signatory countries to a given stationary strategy vector for the defectors, denoting $E^D(P)$ the resulting total emissions of non-signatory countries as a function of P. For each signatory country the value function

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[8] A value of $\kappa = 1$ corresponds to myopic limiting cases, with either $\beta = 0$ (no value for the future) or $\delta = 1$ (no stock accumulation).

$V^S(P;E^D)$ represents the optimal total welfare of a signatory country given $E^D(P)$, and it satisfies

$$\begin{aligned} V^S(P;E^D) &= \max_e \Big\{ e\left(b - \frac{e}{2}\right) - \left(P(1-\delta) + Nse + E^D(P)\right) c_S \\ &\quad + \beta V^S\left(P(1-\delta) + Nse + E^D(P); E^D\right)\Big\}. \end{aligned} \tag{3}$$

Proposition 1 *The value function of a signatory country is linear in P. The optimal reaction of signatory countries is independent of the level of pollution and the strategy of the defectors, and it is given by*

$$e^S = b - Ns\kappa c_S, \tag{4}$$

assuming $b > Ns\kappa c_S$.

Proof. Assume that $V^S(P;E^D) = k^S - m^S P$. Then, first order sufficient conditions yield

$$e^S = b - Ns\left(m^S\beta + c_S\right),$$

which achieves the maximum in (3) and which does not depend on P or $E^D(P)$. Replacing e^S in (3) we obtain an expression linear in P that verifies our assumption. It is now straightforward to get by identification

$$\begin{aligned} m^S &= c_S\kappa(1-\delta) \\ k^S &= Ns\kappa c_S\frac{Ns\kappa c_S - 2b}{2(1-\beta)} + \frac{b^2}{2(1-\beta)} - \frac{\kappa E^D(P)\, c_S}{(1-\beta)}. \end{aligned}$$

The optimal emissions of a signatory country are therefore

$$e^S = b - Ns\kappa c_S.$$

■

Notice that the emissions of signatory countries endogenize the damage of the entire coalition and they are convex in s. It is then immediate to compute the total emissions of signatory countries as $E^S = Ns(b - Ns\kappa c_S)$.

In the same way, we now express the optimal reaction of a defector to a given stationary strategy vector of the other countries, denoting by $E^d(P)$ the total emissions of all other non-signatory countries as a function of P, and by E^S the total emissions of the signatory countries. The value function V^D of a defector country represents the optimal total welfare of a defector given P, $E^d(P)$ and E^S, and it satisfies

$$\begin{aligned} V^D(P;E^S,E^d) &= \Big\{\max_e e\left(b - \frac{e}{2}\right) - \Big(P(1-\delta) + E^S + e + E^d(P)\Big) c_D \\ &\quad + \beta V^D\Big(P(1-\delta) + E^S + e + E^d(P); E^S, E^d\Big)\Big\}. \end{aligned} \tag{5}$$

Proposition 2 *The value function for a defector country is linear in P. The optimal reaction of non-member countries is independent of the level of pollution and the strategy of the other players, and it is given by*

$$e^D = b - \kappa c_D, \tag{6}$$

assuming $b > \kappa c_D$.

Proof. Assume that $V^D(P; E^S, E^d) = k^D - m^D P$. Then, first order sufficient conditions yield

$$e^D = b - c_D - m^D \beta.$$

Substituting e^D in (5) we obtain a linear function of P and

$$\begin{aligned} m^D &= c_D \kappa (1-\delta) \\ k^D &= \frac{b^2 - \kappa c_D \left(2b - \kappa c_D + 2\left(E^S + E^d(P)\right)\right)}{2(1-\beta)}, \end{aligned}$$

so that the optimal emissions for a defector country are

$$e^D = b - \kappa c_D.$$

■

Notice that the optimal emissions[9] of a defector are linear decreasing in s, independent of P and of the strategies of the other players. It is then immediate to compute the total emissions of the other defector countries as $E^d = (N - Ns - 1)(b - \kappa c_D)$.

Combining these results, the equilibrium strategy pair for both kinds of players is given by $\left(e^S, e^D\right)$ and the equilibrium total emissions are

$$E(s) \equiv N\left(b - \kappa\left(c_D(1-s) + Ns^2 c_S\right)\right).$$

Notice that the consequence of assuming a constant marginal environmental damage is that the optimal emissions of countries are independent of each other (orthogonal free-riding), but they are still linked because they are both functions of s.

It is straightforward to verify in the same way that the full defection equilibrium, where all players maximize their individual welfare, that is:

$$\max_{e_j} W^D = \sum_{t=0}^{\infty} \beta^t \left(e_{jt}\left(b - \frac{e_{jt}}{2}\right) - P_t d\right),$$

subject to (2) can be obtained by setting s either to 0 in (5); Similarly the cooperative solution, where all players agree to maximize their aggregate welfare, that is:

$$\max_{(e_j)} W^S = \sum_{j=1}^{N} \sum_{t=0}^{\infty} \beta^t \left(e_{jt}\left(b - \frac{e_{jt}}{2}\right) - P_t d\right)$$

subject to to (2) can be obtained by setting s to 1 in (3). We extend the domain of the value functions in the obvious way: when $s = 0$, V^D represents the total discounted welfare and e^D the equilibrium strategy of the players when there is no coalition, and when $s = 1$, V^S represents the total discounted welfare and e^S the optimal strategy of the players under full cooperation.

Replacing (4) and (6) in (1), the dynamics of the pollution stock becomes

$$P_t = P_{t-1}(1-\delta) + N\left(b - \kappa\left(c_D(1-s) + Ns^2 c_S\right)\right). \tag{7}$$

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[9] Emissions of a defector are larger than those of a signatory for $Ns \in [1, N-1]$ iif $\frac{\gamma}{\gamma+\alpha} > \frac{1}{N}$.

For a given s, the steady-state of the pollution stock is

$$P^*(s) = \frac{NE(s)}{\delta}, \tag{8}$$

and the individual current (one-period) welfares and total discounted welfares of a signatory and non-signatory country when the pollution stock is P are respectively

$$w^S(s,P) = \frac{b^2 - N^2\kappa^2 c_S^2 s^2}{2} - c_S\left(P\left(1-\delta\right) + E(s)\right) \tag{9}$$

$$w^D(s,P) = \frac{b^2 - \kappa^2 c_D^2}{2} - c_D\left(P\left(1-\delta\right) + E(s)\right) \tag{10}$$

$$V^S(s,P) = \frac{b^2 - N^2\kappa^2 c_S^2 s^2}{2\left(1-\beta\right)} - \kappa c_S\left(P\left(1-\delta\right) + \frac{E(s)}{\left(1-\beta\right)}\right) \tag{11}$$

$$V^D(s,P) = \frac{b^2 - \kappa^2 c_D^2}{2\left(1-\beta\right)} - \kappa c_D\left(P\left(1-\delta\right) + \frac{E(s)}{1-\beta}\right). \tag{12}$$

4 Evolution and stability of IEAs

We now state conditions characterizing a stable coalition for a given level of pollution stock, using two alternative stability concepts representing different degrees of rationality. We then propose a discrete-time replicator dynamics for the proportion of signatories that will allow players to reach a stable IEA in the long run.

4.1 Limited rationality

The limited rationality equilibrium concept requires the equality of signatories' and non-signatories' welfares. This concept is used in [31], where the authors justify it by saying that, in each period, there is a random process for determining which countries become signatories. In our case, it can be explained by bounded rationality of the players: when current welfares are equal, players observe that the members of the other group do not fare better, and they are not tempted to switch. Under this assumption, the necessary condition for an IEA with $Ns \in [1, N-1]$ signatories to be stable when the stock of pollution is $\bar{P}$ is obtained by equating (9) and (10)[10] so that we get

$$\bar{P}\left(1-\delta\right) + E(s) = \frac{\kappa^2\left(c_D - Nsc_S\right)\left(c_D + Nsc_S\right)}{2\left(c_S - c_D\right)}. \tag{13}$$

It is interesting to note that for $Ns \in [1, N-1]$, the pollution stock $\bar{P}\left(1-\delta\right) + E(s)$ where that condition is satisfied is positive when $c_S < c_D < Nsc_S$. As a consequence, if it exists, a stable IEA necessarily has $s \geq \frac{\gamma}{\gamma+\alpha}$, and defectors emitting more than signatories. Notice also that at the steady-state pollution, $\bar{P} = P^*(s)$, equality of current welfares implies equality of total discounted welfares.

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[10] If we rather require equality of total discounted welfares at $\bar{P}$, the stability condition becomes $\bar{P}\left(1-\delta\right)\left(1-\beta\right) + E(s) = \frac{\kappa(c_D - Nsc_S)(c_D + Nsc_S)}{2(c_S - c_D)}$.

4.2 Unilateral deviation and foresight

The second equilibrium concept is a dynamic version of the one introduced by [1] and widely used in static games. It assumes that each player is able to compare his welfare with what he would achieve if he unilaterally switched group. In a dynamic context where the players' criterion is total discounted welfare, the conditions for internal and external stability become respectively

$$\begin{aligned} V^S(s,P) &\geq V^D(\frac{Ns-1}{N},P) \\ V^S(\frac{Ns+1}{N},P) &< V^D(s,P). \end{aligned}$$

Since these two conditions are continuous in s, it is easy to show that a necessary condition for stability of an IEA with $\lceil Ns \rceil$ signatories when the stock of pollution is $\bar{P}$ is given by:

$$\begin{aligned} \bar{P}\left(1-\beta\right)\left(1-\delta\right) &= \kappa\frac{N^2s^2c_S^2-\left(c_D-\alpha\right)^2\left(2N\left(1-s\right)+1\right)}{2\left(c_S-c_D+\alpha\right)} \\ &\quad -\kappa\frac{Nc_Sc_D\left(1-s\right)+\left(c_S+\gamma\right)\left(c_D-\alpha\right)\left(Ns-1\right)^2}{\left(c_S-c_D+\alpha\right)}-Nb. \end{aligned} \tag{14}$$

4.3 Dynamics

As the pollution stock changes over time, the number of signatories required for a stable IEA also changes. One could assume, as in [31] for instance, that in each period, the number of signatories satisfies the stability condition (13) or (14) at P_t; in practice, this would require at each time period either an exogenous intervention or some time-consuming negociation process.

Instead, we introduce a mechanism that describes how countries may gradually reach a stable IEA. Define

$$\sigma^L(s_t,P_t)=\frac{w^S(s_t,P_t)}{s_tw^S(s_t,P_t)+(1-s_t)w^D(s_t,P_t)}. \tag{15}$$

where $w^S(s_t,P_t)$ and $w^D(s_t,P_t)$ are given by (9) and (10) and assumed non-negative.[11] Let us assume that the proportion of signatory countries evolves over time following the discrete time replicator dynamics[12]

$$s_{t+1}=\begin{cases} \sigma^L(s_t,P_t) & \text{if } \sigma^L(s_t,P_t)\in(0,1) \\ 0 & \text{if } \sigma^L(s_t,P_t)\leq 0 \\ 1 & \text{if } \sigma^L(s_t,P_t)\geq 1 \end{cases} \tag{16}$$

The denominator of (15) represents a weighted average of the welfares observed in period t, where the weights are given by the current proportions of the two types of countries.

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[11] It is straightforward to adapt the adjustment mechanism if the welfare of one or both groups of players is negative.

[12] The replicator dynamics in continuous time is commonly used in the context of common pool resource games and, in particular, in the fisheries to describe the evolution of a population of agents where two behaviors can be adopted [[35, 29, 18]for instance]. In [37], the replicator dynamics is used to model participation and compliance of firms to voluntary environmental agreements.

Whenever the current welfare obtained from one type of behavior is higher than the other, a fraction of countries will switch behavior and join the group that is performing better. This equation captures the notion that a strategy yielding profits above *(below)* the average increases *(decreases)* in share in the population[13] and that the "speed" of change depends on the relative welfare inequalities. This update mechanism ensures that the change in shares is a gradual process, showing that there might be some delays or inertia for countries to readjust their behavior, due for instance to an intangible or political cost of switching.

In this case, (7) and (15)-(16) give rise to a two-dimensional dynamic system that describes the evolution, over time, of the stock of pollution and proportion of signatories. It is easy to check that a steady-state (s^*, P^*) of this dynamic system satisfies the stability conditions for an IEA at $\bar{P} = P^*(s^*)$ where we assume countries with limited rationality.

Similarly, an update mechanism that reaches a stable IEA under the unilateral deviation criterion is:

$$\sigma^U(s_t, P_t) = s_t \frac{V^S(s_t, P_t)}{s_t V^S(s_t, P_t) + (1 - s_t) V^D(s_t - \frac{1}{N}, P_t)} \tag{17}$$

$$s_{t+1} = \begin{cases} \sigma^U(s_t, P_t) & \text{if } \sigma^U(s_t, P_t) \in \left(\frac{1}{N}, 1\right) \\ 1 & \text{if } \sigma^U(s_t, P_t) \geq 1 \\ 0 & \text{if } \sigma^U(s_t, P_t) \leq \frac{1}{N}. \end{cases} \tag{18}$$

Now, the two-dimensional dynamic system (7) and (17)-(18) describes the evolution over time of both the stock of pollution and the proportion of signatories. Players reach a stable IEA by comparing "current" total discounted welfares when staying in or leaving unilaterally a coalition, that is, without taking into account the dynamics of s.

5 Steady-state and sensitivity analysis

We now study the dynamics of the pollution and of countries' shares under the two types of behavior. In particular, we are interested in finding whether or not full cooperation, coexistence of cooperators and defectors, or no cooperation at all are possible outcomes of this model, and under what conditions they eventually occur. In our numerical simulations, we use parameter values that give rise to positive individual emissions. The results obtained under the two stability concepts are qualitatively similar.

When they exist, equilibrium steady-state values of the stock of pollution and the proportion of signatory countries are indexed by υ and we denote $\xi_\upsilon = (s_\upsilon, P_\upsilon)$ an equilibrium steady-state of the dynamic system (7)–(15) or (7)–(17).

We first notice that the boundary equilibria ξ_n, corresponding to $s_n = 0$, and ξ_c, corresponding to $s_c = 1$, may be reached by the dynamic system. These are given by

$$\begin{aligned} \xi_n &= \left(0, \frac{N(b - \kappa d)}{\delta}\right) \\ \xi_c &= \left(1, \frac{N(b - \kappa d N)}{\delta}\right), \end{aligned}$$

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[13] This idea is not uncommon in economics. For example, when new strategies or technologies are introduced on the market, firms will tend to imitate the most successful ones, or the ones that yields a 'satisficing' level of profits. Here, we assume that governments follow the same kind of behavior.

where $P_n > P_c$. The dynamic system may also reach inner steady-states corresponding to IEAs with partial cooperation.

5.1 Partial cooperation

According to the value of the parameters, 0, 1 or 2 coexisting inner steady-states may appear corresponding to situations where the necessary condition for stability is satisfied at the steady-state pollution. These are defined by the intersections of $P^*(s)$ with $\bar{P}(s)$. When two inner steady-states exist, the one with the lower percentage of signatory countries, denoted ξ_l, is a saddle point[14] and the one with the higher percentage of signatory countries, denoted ξ_h, is a stable node, corresponding to a stable IEA with partial cooperation. Figures 1–3 illustrate in the (s, P) plane three representative examples, and how these situations may appear when the values of parameters α and γ are changed. These examples are generated under the limited rationality criterion. The unilateral deviation hypothesis generate stable IEAs with a slightly higher level of cooperation, and with slightly wider basins of attraction.

Figure 1 illustrates the impact of an increase in the punishment α. In Figure 1a (with $\alpha = 0.000295$), functions P^* and $\bar{P}$ do not intersect: there is no value of s such that the stability criterion is satisfied at the steady-state pollution stock. From any initial conditions (s_0, P_0), the replicator dynamics converges to $s = 0$, that is, no feasible agreement is possible. In Figure 1b (with $\alpha = 0.000305$), if the initial group of signatory countries is large enough (that is, if the initial conditions are in the blue area), then the steady-state ξ_h is reached, corresponding to a stable IEA with partial cooperation. An interesting observation is that the minimum size of the initial number of signatories which leads to the inner steady-state is decreasing with the initial pollution stock (see Figure 2 for a zoom-in).

In general, an increase of α decreases both $P^*(s)$ and $\bar{P}(s)$; it determines a higher level of cooperation and a lower level of pollution at the steady-state, and it enlarges the basin of initial states generating trajectories converging to ξ_h. In Figure 1c (with $\alpha = 0.000337$), there is no interior value of s yielding a stable IEA at the steady-state. Starting from any initial condition in the green area, the system converges to ξ_c. Further increases in the punishment do not have any effect on the long run values of the dynamic variables, but they make the full cooperation more robust (i.e. supported by a greater number of initial states).

Figure 3 illustrates the impact of decreasing γ, starting from the case depicted in Figure 1a (with $\gamma = 0.0002$). A decrease in γ decreases both P^* and $\bar{P}$. In Figure 3a (with $\gamma = 0.00017$), an inner steady-state with partial cooperation appears. Further decreases in γ have positive effects on the long run values of the dynamic variables (higher cooperation and lower pollution stock), and especially on the basin of the stable steady-state (Figure 3b). This means that if the mandatory punishment foreseen by the agreement is not too expensive, the initial group of founding countries does not need to be very large to lead to a stable agreement. The reduction of the cost for punising may or may not generate full cooperation depending on the value of the other parameters (this is discussed further in Section 5.2).

Sensitivity analysis shows that, with respect to other parameters, increasing the profitability of emissions (parameter b) has a positive impact on the number of signatories at the steady state, as well as on the set of initial states generating trajectories converging to partial or full cooperation, however at the expense of a higher steady-state pollution stock. More interestingly, an increase of the marginal environmental cost (parameter d) impacts negatively the

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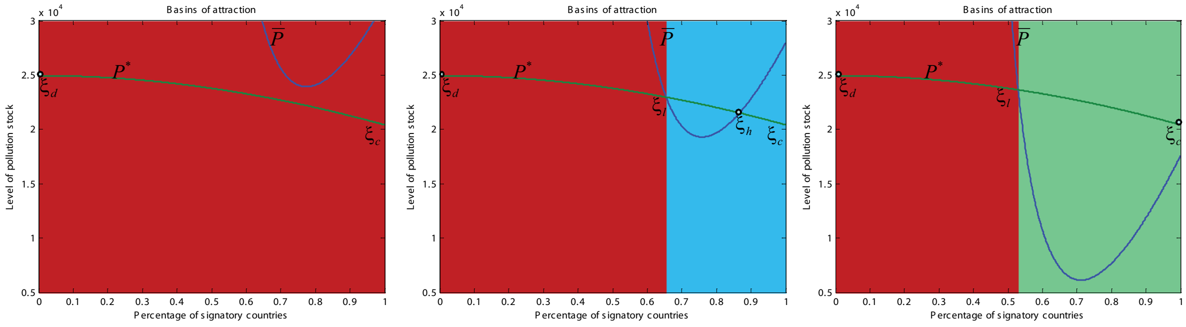
[14] Under the unilateral deviation criterion, entry and exit conditions are not satisfied at a saddle point. Under the limited rationality criterion, welfares are equal at a saddle point, but this steady-state is not stable.



a b c

Figure 1: Impact of increasing punishment. The parameter values are: $N = 100$, $b = 200$, $d = 0.3$, $\gamma = 0.0002$, $\delta = 0.8$, $\beta = 0.9$. In (a), $\alpha = 0.000295$; in (b), $\alpha = 0.000305$; in (c), $\alpha = 0.000337$. The red area represents the set of initial conditions of s and P generating trajectories converging to the fully non-cooperative outcome. The blue area represents the set of initial conditions of s and P generating trajectories converging to the partial cooperation outcome. The green area represents the set of initial conditions of s and P generating trajectories converging to the full cooperative outcome.

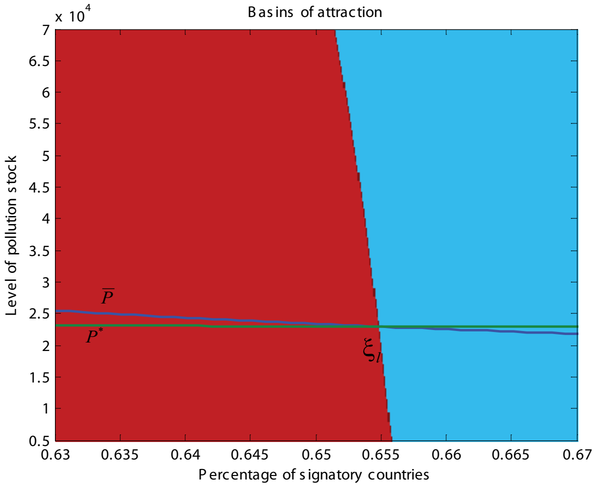
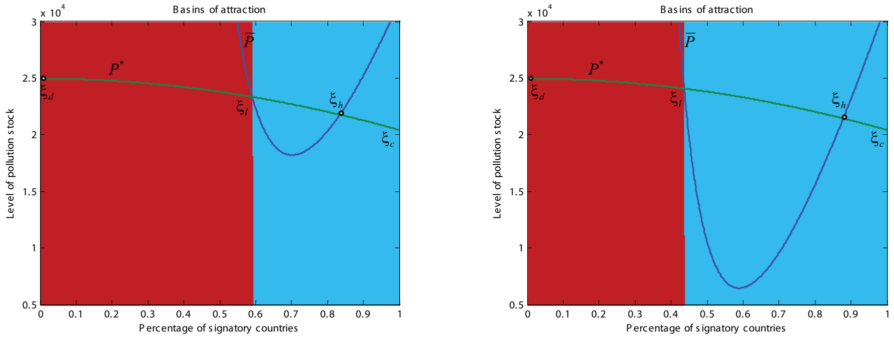


Figure 2: Zoom in on the basin of attraction.

size of the steady state coalition as well as the size of the basin of attraction leading to it. This result is consistent with what has been observed in static games: when the potential gain from cooperation is large, the membership of an IEA is likely to be small. This can be explained by the incentive to free-ride, implying that a stable IEA is the smallest one where emitting less is welfare-enhancing.

Figure 4 represents various trajectories for the pollution stock and the number of signatory countries over time, in the case depicted in Figure 1b, where an inner steady-state exists. Depending on the initial conditions, trajectories converge either to a situation with no cooperation, or to a stable IEA. The way this stable solution is reached also depends on the initial condition. Possible evolutions in the space (s, P) are illustrated in Figure 5. Notice



a

b

Figure 3: Impact of decreasing cost for punishment. The parameter values are: $N = 100$, $b = 200$, $d = 0.3$, $\alpha = 0.000295$, $\delta = 0.8$, $\beta = 0.9$. In (a), $\gamma = 0.00017$; in (b), $\gamma = 0.00013$. The red area represents the set of initial conditions of s and P generating trajectories converging to the fully non-cooperative outcome. The blue area represents the set of initial conditions of s and Pgenerating trajectories converging to the partial cooperation outcome.

how evolutionary pressure increases s above $\bar{P}$ (where signatories fare better) and decreases s otherwise.

5.2 No Cost for Punishing

We now consider the special case when enforcing a sanction does not entail any cost (as in [23]). In this case, the marginal cost of pollution of a non-signatory country is always higher than that of a signatory country, and a non-signatory emits more than a signatory for $s > \frac{d}{N(d-\alpha)}$. For both stability criteria considered, function $\bar{P}$ is increasing on $\left[\frac{1}{N}, \frac{N-1}{N}\right]$ and negative for $s \leq \frac{1}{N}$. As a consequence, if punishing has no adverse consequences on coalition members' welfare, then there is at most one inner equilibrium with coexistence of defectors and signatories. Moreover, the system never admits as a solution the case of complete defection, but the dynamics converge either to an inner steady state with partial cooperation, or to a situation with full cooperation.

5.3 No punishment

An interesting question is how the dynamic model performs when there is no punishment $(\alpha = \gamma = 0)$. In this case, the difference between current welfares is given by

$$w^S(s,P) - w^D(s,P) = -\frac{1}{2} d^2 \kappa^2 \left(Ns - 1\right)\left(Ns + 1\right)$$

and it is straightforward to verify that, for $Ns \geq 1$and any level of pollution stock, the welfare of signatories is always smaller than that of the non-signatories. As a consequence, under the limited rationality criterion, no stable coalition can be attained.

On the other hand, under the unilateral deviation criterion, the exit condition

$$\begin{aligned} V^S(s,P) &\geq V^D\left(\frac{Ns-1}{N}, P\right) \\ \text{reduces to } \left(Ns-3\right)\left(Ns-1\right) &\leq 0, \end{aligned}$$

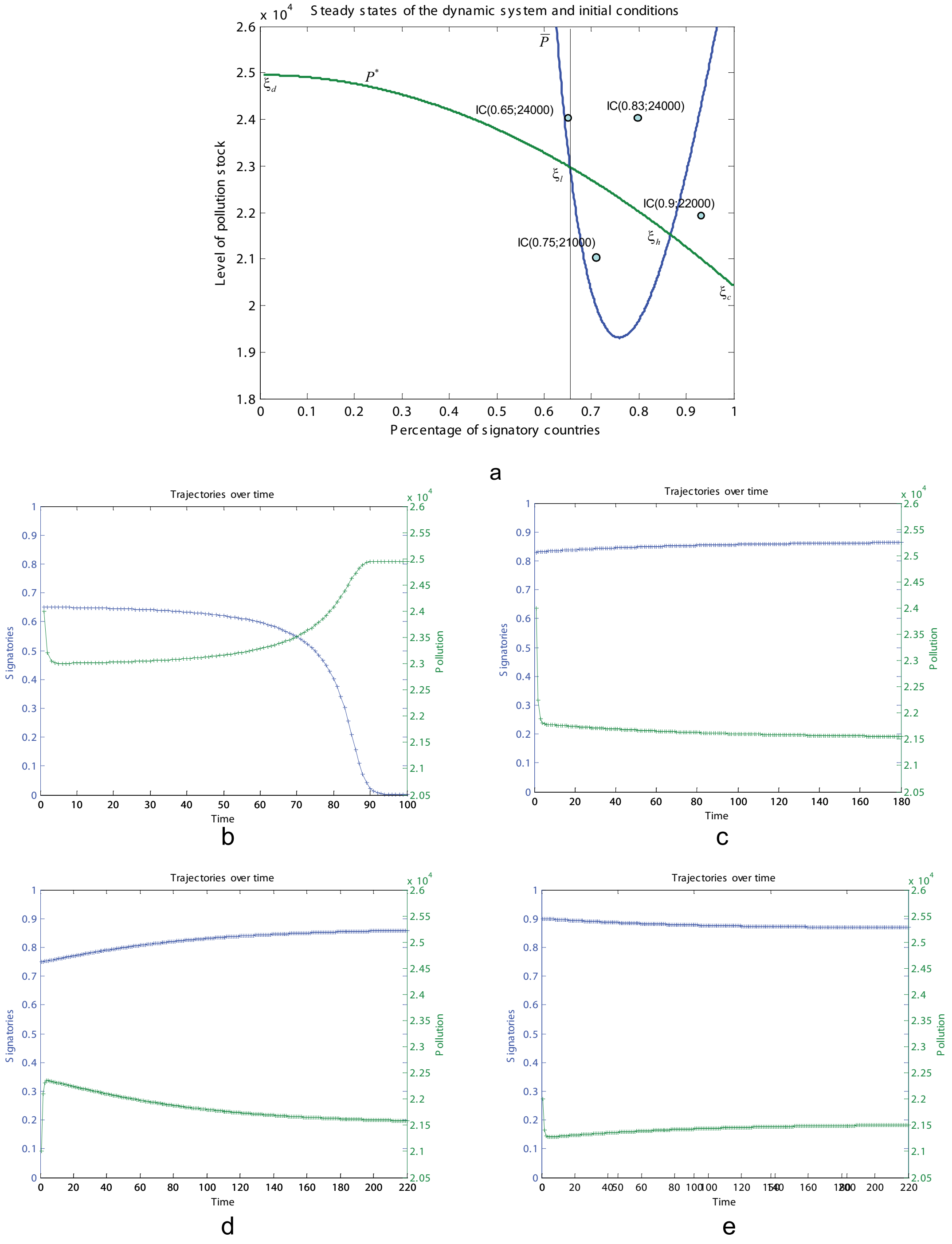


Figure 4: Trajectories corresponding to various initial conditions. Parameters are as in Figure 1b. In panel b, the number of signatories converge to 0. In panels c, d and e, trajectories converge to the same inner steady-state, but following different paths depending on the initial conditions.

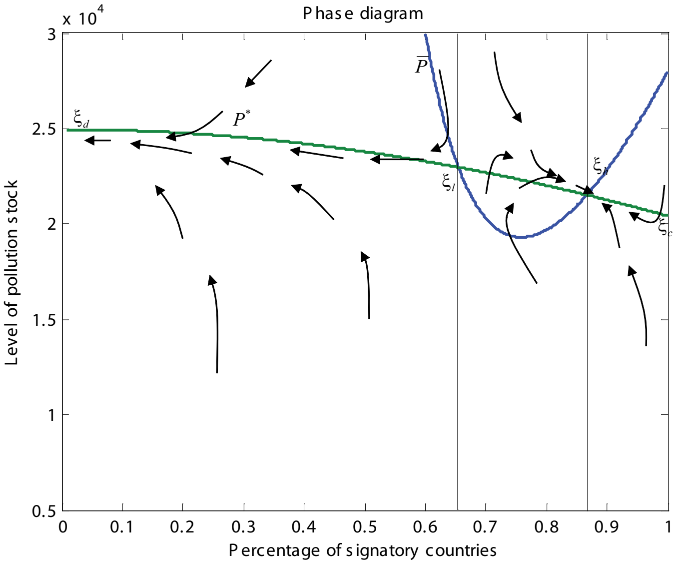


Figure 5: Evolution of s and P.

while the entry condition

$$\begin{aligned} V^S(\frac{Ns+1}{N}, P) &< V^D(s,P) \\ \text{reduces to } Ns &> 2. \end{aligned}$$

As a consequence, for any level of pollution, the only stable IEA involves 3 members, which corresponds to the result obtained for static games.

5.4 Endogeneous punishment

In the above analysis, we assumed that the punishment level agreed on by the signatories was exogenous. Recognizing that the best outcome is full cooperation, it is however possible for the initial group of signatories to compute a value for α such that full cooperation is realised in the long run. In this case, we assume that $\gamma = \tau\alpha$ (the cost is proportional to the level of punishment). If players use the unilateral deviation criterion to decide on their membership, the smallest level α for which full cooperation is achieved at the steady state satisfies (14) at $\bar{P} = \frac{b-Nd\kappa}{\delta}$ and $s = 1$, or equivalently solves

$$\begin{aligned} \alpha^2\kappa^2\delta\left(N-1\right)\left(2\tau\left(N-1\right)+1\right) & \\ +2\alpha\left(-Nb+d\kappa\left(\kappa\delta\left(\tau-2\right)\left(N-1\right)+N^2\right)\right) & \\ +d^2\kappa^2\delta\left(N-3\right) &= 0. \end{aligned}$$

For instance, with the parameter values used in Figure 1 with $\tau = 0.67$, one obtains $\alpha^* = 3.16938 \times 10^{-4}$.

If players use the limited rationality criterion, the smallest level of α for which full cooperation is achieved at the steady-state satisfies (13) at $\bar{P} = \frac{b-Nd\kappa}{\delta}$ and $s = 1$, that is, solves

$$N^2\kappa^2\delta\alpha^2 - 2\alpha N\left(-Nb+d\kappa\left(N^2-\kappa\delta\right)\right) - d^2\kappa^2\delta\left(N-1\right)\left(N+1\right) = 0.$$

For instance, with the parameter values used in Figure 1, one obtains $\alpha^* = 3.2759 \times 10^{-4}$. As expected, with respect to the unilateral deviation criterion, a higher level of punishment is required under limited rationality to achieve the same level of cooperation.

6 Conclusions

In this paper, we dealt with the problem of stability of international environmental agreements concerning pollution emissions. Stock externalities were included, as well as the possibility for countries to abide by the agreement or to defect at any time. We considered an agreement that includes a provision for signatory countries to punish non-signatory countries, even if sanctioning the defectors entails a cost. We developed a model in which countries optimize their welfare over an infinite horizon, taking into account the evolution of the stock of pollution. In defining a stable coalition, we applied the well known internal and external stability conditions ([1]) but also a less sophisticated equilibrium concept that only requires the equality of the current welfares obtained by signatory and non-signatory countries. We found that the equilibrium concept based on the unilateral deviation hypothesis generates stable IEAs with a higher level of cooperation than the ones based on less sophisticated agents. Finally, we proposed an evolutionary mechanism that might be used to reach a stable IEA over time. This idea finds its validation in the real practice where conception and "growth" of an IEA are experienced. A motivating example is the Montreal Protocol, to which many countries joined over the last 20 years since its ratification, showing that IEAs with high participation do occur, and that membership in the agreement may change over time.

The main results of our numerical simulations can be summarized as follows. The outcome with no country joining the IEA is always a solution, but, provided sanctions are strong enough and/or cost for punishing is not too high, this outcome coexists with either a partial cooperation solution or full cooperation. When two outcomes coexists, initial conditions are determinant: if the initial coalition is not large enough for a given initial level of the pollution stock, then the equilibrium solution is full defection. The basin boundary can be interpreted as a minimum participation clause, where the minimum number of members is affected by the level of punishment included in the agreement and/or by its cost. However, the higher the initial level of pollution, the less initial signatory countries are needed to converge to a stable agreement, indicating that it is easier to endogenously bring other countries in the IEA when the stock of pollution is high. Finally, as in the static models, the number of signatories in a stable IEA is negatively related to the environmental cost or, equivalently, to the benefits of cooperation.

To complete the analysis, we considered the special case when enforcing a sanction doesn't entail any cost. In this case, full defection can never be observed; the only possible outcome, independent of the initial conditions but depending on the value of the parameters, is either partial or full cooperation. We also considered another special case excluding punishment and we found that stable coalitions with large number of players cannot be implemented, irrespective of the pollution stock. Finally, we observed that a punishment level ensuring that full cooperation will be reached in the long run can be easily obtained.

Our assumption of linear environmental damage makes the problem tractable, since the strategies of the players become independent of the state and of the other players' actions. A linear damage may be interpreted as a marginal approximation of the damage function by the players. A further development is to consider a non-linear environmental damage, which will require a numerical approach to solve for equilibrium outcomes.

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