The case of two self-enforcing international agreements for environmental protection

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Abstract

The non-cooperative game theoretical models of self-enforcing international environmental agreements (IEAs) that employ the cartel stability concept of d'Aspremont et al. (1983) frequently use the assumption that countries can sign a single agreement only. We modify the assumption by considering two self-enforcing IEAs. By developing further a model of Barrett (1994a) on a single self-enforcing IEA, we demonstrate that there are many similarities between one and two self-enforcing IEAs. But in the case of few countries and high environmental damage we show that two self-enforcing IEA works far better than one self-enforcing IEA in terms of both welfare and environmental equality

Keywords: self-enforcing international environmental agreements, non-cooperative game theory, stability, nonlinear optimization.

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JEL: C61, C72, H41

1 Introduction

The formation and implementation of International Environmental Agreements (IEA) is the topic of a broad economic literature. A significant part of the literature uses game theory as a tool to understand the formation mechanism of IEAs. There are two main directions of literature

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on IEAs (for a review of current literature see Finus 2003; Carraro/Siniscalco 1998; Ioannidis/Papandreou/Sartzetakis 2000; Carraro/Eyckmans/Finus 2005). The first direction utilizes the concepts of cooperative game theory in order to model the formation of IEAs. This is a rather optimistic view and it shows that an IEA signed by all countries is stable provided that utility is transferable and side payments are adequate (Chander/Tulkens 1995, 1997). The second direction uses the concepts of non-cooperative game theory to model the formation of IEAs. At the first level, the link between the economic activity and physical environment is established in order to generate the economical-ecological model. This link is established through a social welfare function. The social welfare function is represented as the difference between the profit from pollution and the environmental damage. Following this approach, countries play a two stage-game. In the first stage, each country decides to join or not the IEA. In the second stage, every country decides on emissions. The emission game is solved first followed by equilibrium coalition. The main body of literature examining the formation of IEA within a two stage framework uses a certain set of assumptions. We mention below only the essential ones:

- Decisions are simultaneous in both stages.
- Countries are presented with single agreements.
- When defecting form coalition, a country assumes that all other countries remain in the coalition (it is a consequence of employed stability concept of d'Aspremont et al (1983) that allows only singleton movements and myopia).
- Within the coalition, players play cooperatively while the coalition and single countries compete in a non cooperative way among them.

Non-cooperative game theory draws a pessimistic picture of the prospect of successful cooperation between countries. It claims that a large coalition of signatories is hardly stable, and that the free-rider incentive is strong. The model explains the problems of international cooperation in the attendance of environmental spillovers, but cannot explain IEAs with high membership such as the Montreal Protocol. This calls for a modification of the standard assumptions. We mention in the following paragraphs some of the possible modifications.

Maybe the most important development is the work on coalition theory of Ray and Vohra (1994), Yi and Shin (1995) Yi (1997) and Bloch (1995, 1996, 1997). They allow many coalitions to be formed, although they employ different rule of forming coalitions. Ray and Vohra (1994) analyse Equilibrium Binding Agreements, (a game in which coalitions can only break up into smaller coalitions) Bloch (1996) shows that the infinite-horizon Coalitional Unanimity game (game in which a coalition is formed if and only if all members agree to form it) yields a unique subgame perfect equilibrium coalitions structure. Yi and Shin (1995) examine an Open Membership Coalitional game (in which nonmembers can join a coalition without the permission of existing members). Yi (1997) shows that in the Open Membership Coalitional game the grand coalition can be an equilibrium outcome for *positive externalities*. But for *positive externalities* in Coalitional Unanimity game, the grand coalition will be rarely an equilibrium. He shows also that for the same game, the grand coalition can rarely be an equilibrium outcome for *negative externalities* due to free-rider problems.

A sequential choice of emission levels means there is a Stackelberg leader (a coalition of signatories), who takes into account the optimal choice of non-signatories that behave as Stackelberg followers (Barrett 1994a and 1997a). Participants have an advantage towards non-participants as they chose they emissions level based on reaction function of non-participants.

Ecchia/Mariotti (1998) distinguish two problems in standard model of self-enforcing IEA. In the basic model, countries are presumed to behave myopically by disregarding other countries' reaction when they make their choices. They modify this assumption by introducing *the notion of farsightedness*. If countries are farsighted, that is they can foresee other countries' reaction to their choices and incorporate them into their decisions, a new notion of stability has to be established. They demonstrate that if the idea of farsightedness is placed into the model, the likelihood of larger coalition increases.

Within the framework of asymmetric welfare functions, *transfers* can help to increase membership and success of IEAs (Botteon/Carraro 1997, Carraro/Siniscalco 1993 and Barrett 1997b).

Jeppesen/Andersen (1998) demonstrate that if some countries are committed to cooperation concerning their abatement implies that this group of countries presuppose a leader role in forming the coalition. The leading role allows them to evaluate potential aggregate benefits from increasing the coalition and device side payments to countries that have follower role in order to attain optimum membership.

Hoel/Schneider (1997) integrate *a non-environmental cost function* from not signing the IEA which they call "non-material payoff". They find that, even in the absence of side payments the number of signatories is not very small.

Barrett (1997b) uses a partial equilibrium model to observe the effectiveness of trade sanctions in signing an IEA. He considers only trade goods that are linked to environmental problems. He explains that if the public good agreement IEA is linked to a club agreement, such as a trade agreement, the membership in IEAs can be raised. *Issue linkage* entails that countries can only benefit from the club good agreement if they also become a member of an IEA. Botteon/Carraro (1998), Carraro/Siniscalco (1997), Breton/Soubeyran (1998) and Katsoulacos (1997) give similar conclusions.

Carraro/Marchiori/Oreffice (2001) make obvious that the implementation of *a minimum participation clause* can help to improve the success of IEAs. Such a clause implies that a treaty only enters into force if a certain number of signatories have approved it. The minimum participation clauses in almost all IEAs in the past.

Endres (1996 and 1997) shows that the bargaining outcome under the inefficient uniform emission reduction quota regime may be better-quality from an ecological and economic point of view than an efficient uniform tax rate in a two-country model. Endres/Finus (2002) Finus/Rundshagen (1998b), Finus/Rundshagen (1998a) demonstrate that an inefficient emission reduction under the quota regime is rewarded by higher stability and higher membership.

This paper uses non-cooperative game theory in order to develop further a model from Barrett (1994a). Being aware of the recent work on coalition theory of Ray and Vohra (1994), Yi and Shin (1995) and Bloch (1996, 1997) we think that modelling two self-enforcing IEA (employing the stability concept of d'Aspremont et al. (1983)) can bring a better understanding of improving capacity of IEA's. We are less concerned with developing a general theory of coalition formation. Rather, we present and apply a method for computing the maximum size of two coalition. The loss in generality is compensated by a gain in practically. The main contribution of this paper is the discussion on the *possibility of improving capability (size and emission reduction) of two self-enforcing IEA compared to one self-enforcing IEA* by modelling the IEA as a one-shot game. Another contribution is *a different formulation (as nonlinear optimization problem) of finding* α *(*αN *= the number of signatories)* in extended Barrett's model. Although our work is less general than that of Yi and Shin, Bloch etc, we are able to compute the coalition sizes and optimal abatement levels. We would like to stress that we reinforce the conclusions of Asheim et. al (2006) and Carraro (2000) by following a different method, that is nonlinear optimization.

In section two we describe the Barrett's model on one-self enforcing IEA and formulate it differently as a nonlinear optimization problem. In the third section we present our model for two-self enforcing IEA and introduce a essential part of our simulations. In section four we give our conclusions and further suggestions. In the Appendix we present a full description of our simulation.

2 Barrett's model

For an IEA to be *self-enforcing* means that no single nonsignatory has an incentive to join an IEA (*External Stability*) and no single signatory has an incentive to withdraw from the agreements (*Internal Stability*). Furthermore, the coalition *has to be profitable*, that is the coalition members pay-off is greater than their pay-off in Nash equilibrium. The IEA have to be designed so that they are *self-enforcing* because of nonexistence of a supranational authority that can implement and enforce the agreements. The striking result of Barrett's research is that *a self-enforcing IEA* can be signed by large number of countries only when the difference between full cooperative and noncooperative payoffs is small. When this difference is large, *self-enforcing IEA* would be signed only by a small number of countries.

The model imposes some important assumptions which are:

- all countries are identical
- each country's net benefit function is known and known to be known by all countries
- pollution abatement is the only policy instrument
- abatement levels are instantly and costlessly observable
- the pollutant does not accumulate in the environment
- cost functions are independent of one another

The abatement benefits function $B_i(Q)$, the abatement cost function $C_i(q_i)$ and the profit function π of country i are defined as:

$$B_i(Q) = b(aQ - Q^2/2)/N \tag{1}$$

$$C_i(q_i) = cq_i^2/2 \tag{2}$$

$$\pi_i = B_i(Q) - C_i(q_i) \tag{3}$$

$a \in R^+$,$b \in R^+$ and $c \in R^+$ parameters,
q_i amount of abatement of country i,
Q global abatement $Q = \sum_{i=1}^{N} q_i$,
N number of identical countries, each of them emits a pollutant.

The marginal abatement benefit and cost of country i are linear, b is the slope of marginal benefit and c is the slope of marginal cost.

The full cooperative outcome is found by maximizing global net benefits $\Pi = \sum_{i=1}^{N} \pi_i$ with respect to Q. The *full cooperative abatement levels* are:

$$Q_c = aN/(N + \gamma) \tag{4}$$

$$q_c = a/(N + \gamma) \tag{5}$$

Q_c global abatement, q_c individual's country abatement, $\gamma = c/b$.

Noncooperative outcome is found by maximizing country net benefits π with respect to q_i. The *noncooperative abatement levels* are:

$$Q_0 = a/(1+\gamma) \tag{6}$$

$$q_0 = a/N(1+\gamma) \tag{7}$$

Q_0 global abatement, q_0 individual's country abatement.

It is obvious that $Q_c > Q_0$.

2.1 One self-enforcing IEA

Let's suppose we have αN countries that sign the IEA (signatories) forming a coalition and $(1-\alpha)N$ countries that do not sign the agreements (nonsignatories). In the first stage the coalition of signatories (C_s) try to maximize their net-benefits, the coalition behaves like Stackelberg leader (Barrett 1994a and 1997a). In the second stage every nonsignatory try to maximize his own benefit (after observing the behavior of signatories), they behave like Stackelberg followers. Modelling C_s as a cooperative game, *the Nash bargaining solution will require that each country undertake the same level of abatement*. This implies that if Q_s is the total abatement of signatories and q_s is the single signatory abatement then $Q_s = \alpha N q_s$. Let Q_n be the total abatement of nonsignatories and q_n be the single nonsignatory abatement. As countries are identical *the Nash equilibrium requires that q_n are identical* thus $Q_n = (1-\alpha)Nq_n$. The reaction function of nonsignatories is given by:

$$Q_n(\alpha, Q_s) = (1-\alpha)(a - Q_s)/(\gamma + 1 - \alpha) \tag{8}$$

In order to find $Q_s(\alpha)$ the following nonlinear optimization problem need to be solved:

$$Max(\Pi_s) \quad s.t \quad (8) \tag{9}$$

where Π_s the total benefit of signatories, π_s a single benefit of a signatory, $\Pi_s = \sum \pi_s$.

The solution is:

$$Q_n^*(\alpha) = a\alpha^2 N\gamma/[(\gamma+1-\alpha)^2 + \alpha^2 N\gamma] \tag{10}$$

By substituting (10) to (8) it follows that:

$$Q_s^*(\alpha) = a(1-\alpha)(\gamma+1-\alpha)/[(\gamma+1-\alpha)^2 + \alpha^2 N\gamma] \tag{11}$$

Let's define the *self-enforcing (SE) IEA*. We recall a concept developed for analysis of cartels stability (d'Aspremont et al. 1983). Let's assume we have αN signatories:

Definition 2.1 *An IEA is self-enforcing if and only if it satisfies the following conditions:*

$$\pi_s(\alpha) \geq \pi_n(\alpha - 1/N) \text{ and } \pi_n(\alpha) \geq \pi_s(\alpha + 1/N).$$

$$[IEA \quad is \quad SE] \Longleftrightarrow [\pi_s(\alpha) \geq \pi_n(\alpha - 1/N) \wedge \pi_n(\alpha) \geq \pi_s(\alpha + 1/N)] \tag{12}$$

If (12) is satisfied, than no signatory wants to withdraw from the IEA. It will reduce costs, but it will reduce benefits even more. This aspect of stability is known as *Internal Stability*. Similarly no nonsignatory wants to join the IEA. It will rise benefits, but it will rise costs even more. This aspect of stability is known as *External Stability*. For both cases *any movement of any country (joining or withdrawing from IEA) will reduce its profit*.

Table 1: Analysis of one self-enforcing IEA for different α

α	q_s	q_n	π_s	π_n	Q	Π
0	-	8.6	-	725.5	85.7	7255.1
0.1	1.4	9.2	732.0	721.5	84.6	7225.8
0.2	3.3	9.7	729.2	718.9	83.9	7209.7
0.3	5.5	9.6	726.9	719.2	84.0	7214.8
0.4	7.8	9.0	725.6	723.2	85.0	7241.5
0.5*	9.7*	7.7*	725.8*	730.0*	87.1*	7279.1*
0.6	10.9	6.2	727.4	737.4	89.7	7313.8
0.7	11.3	4.5	729.9	743.2	92.5	7338.7
0.8	11.1	3.1	732.7	746.9	94.9	7355.0
0.9	10.6	1.9	735.3	748.8	96.9	7366.9
1	9.8	-	737.7	-	98.4	7377.0

We introduce an example in order to make it clear. Let $a = 100, b = 1.5, c = 0.25$; and define global net benefits (profits) $\Pi(\alpha) = \alpha N\pi_s + (1-\alpha)N\pi_n$. Table(1) shows the net benefit (profit) and abatement levels for representative country i of signatories (C_s) as well as for representative country i of nonsignatories (C_n) for each possible α. It also shows the global net benefits Π and the global abatement level Q. Figure(1) gives a graphical relation between the profit of a single country of signatories and nonsignatories and alpha. From Table(1) and Figure(1) it is clear that the self-enforcing IEA conditions (12) are satisfied for $\alpha = 0.5$.

The example explains how to find the number of countries that can form a self-enforcing IEA. In other words, how to find α, then *only αN countries can form a self-enforcing IEA*. A very simple algorithm (i = number of signatories) can be:

Table 2: A simple algorithm for finding α for one self-enforcing IEA

$for \quad i = 1 \quad to \quad N$
if $\quad [\pi_s(\alpha) \geq \pi_n(\alpha - 1/N) \wedge \pi_n(\alpha) \geq \pi_s(\alpha + 1/N)]$
save α.

Please note that for our function's specification we have only one α. We introduce a new formulation of our problem. We formulate it *as nonlinear optimization one*, because this formulation can be used to solve the problem of *two self-enforcing IEA*.

Max(α)

$$s.t \quad [\pi_s(\alpha) \geq \pi_n(\alpha - 1/N) \wedge \pi_n(\alpha) \geq \pi_s(\alpha + 1/N)] \tag{13}$$

The problem van be formulated as minimization one[1].

[1] αN usually will not be an integer number, but we round down, then find the new $\alpha = rounddown(\alpha N)/N$. (Please note that *if we solve our problem as maximization one and round down we get usually the same solution if we solve it as minimization one and round up*). Using Matlab Optimization Toolbox, minimization proved to be

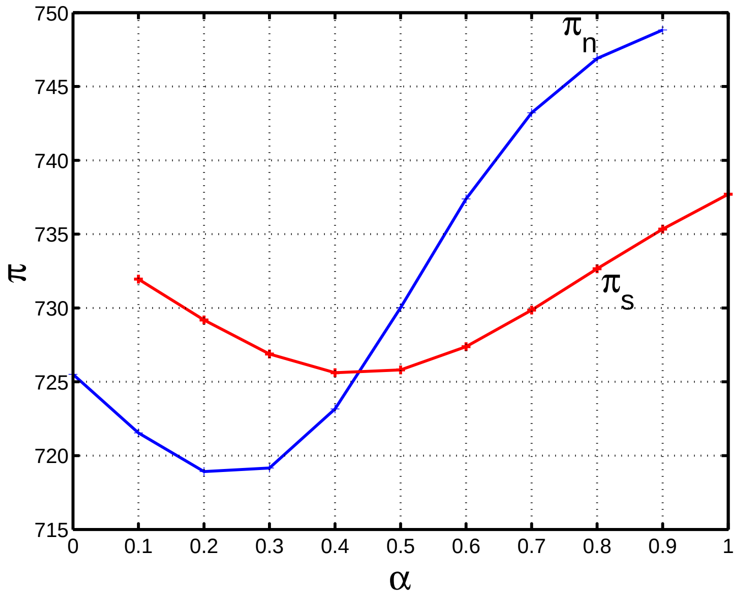

Figure 1: Stability analysis of IEA

3 Two self-enforcing IEA

In the case of two self-enforcing agreements we have two coalition of signatories; the first coalition (C_{s1}) with $\alpha_1 N$ countries, and the second one (C_{s2}) with $\alpha_2 N$ countries, and $(1-\alpha_1-\alpha_2)N$ nonsignatories (C_n). Firstly the coalition of signatories (C_{s1}) (*it is the Stackelberg leader*[2]) and the second coalition of signatories (C_{s2}) (*the Stackelberg follower for* C_{s1}) are formed; they try to maximize their net-benefits (every coalition knows the number of countries in the other coalition). After observing the choice of signatories, every nonsignatory (*Stackelberg followers for* C_{s1} *and* C_{s2}) maximize its own net benefit by taking the abatement level of signatories coalition and other nonsignatories as given. Let Q_{s1} be the total abatement of C_{s1}, q_{s1} be the single signatory abatement of C_{s1}; let Q_{s2} be the total abatement of C_{s2}, q_{s2} be the single signatory abatement of C_{s2}; let Q_n be the total abatement of C_n, q_n be the single signatory abatement of C_n. The same arguments as before imply that $Q_{s1} = \alpha_1 q_{s1} N$, $Q_{s2} = \alpha_2 q_{s2} N$, $Q_n = (1-\alpha_1-\alpha_2)q_n N$.

more robust. In our experience the starting point can be slightly problematic, but as we know that $\alpha \in [0,1]$ it is easily overcome.

[2]Note that this sequentially game can be easily changed by taking the Stackelberg leader C_{s2}. Or by taking both of C_{s1}, C_{s2} as Stackelbergs leaders playing between each-other a simultaneous Nash-Cournot equilibrium.

Let's summarize the notation that we use in this section:

$\alpha \ = \alpha_1 + \alpha_2$,
$Q = Q_s + Q_n$,
Q total abatement level,
Q_s total abatement level of two coalition of signatories,
Q_n total abatement level of nonsignatories,
$Q_s = Q_{s1} + Q_{s2}$,
Q_{s1} total abatement level of first coalition,
Q_{s2} total abatement level of second coalition,
π_{s1} the profit of a country of first coalition of signatories,
$\Pi_{s1} = \sum_1^{\alpha_1 N} \pi_i = \alpha_1 N \pi_{s1}$ the total profit of first coalition of signatories,
q_{s1} the abatement level of a country of first coalition of signatories,
π_{s2} the profit of a country of first coalition of signatories,
$\Pi_{s2} = \sum_1^{\alpha_2 N} \pi_i = \alpha_2 N \pi_{s2}$ the total profit of second coalition of signatories,
q_{s2} the abatement level of a country of first coalition of signatories,
π_n the profit of a country of nonsignatories,
q_n the abatement level of a country of nonsignatories.

As we have the same cost and benefit function of country i, we have the same profit function, which is given for the first and the second coalition of signatories and for nonsignatories by:

$\pi_{s1} = b(aQ - Q^2/2)/N - cq_{s1}^2/2$

$\pi_{s2} = b(aQ - Q^2/2)/N - cq_{s2}^2/2$

$\pi_n = b(aQ - Q^2/2)/N - cq_n^2/2$

The reaction function of nonsignatories is similarly found by maximizing the profit of a single nonsignatory π_n:

$$Q_n(\alpha_1, \alpha_2, Q_{s1}, Q_{s2}) = (1-\alpha)(a - Q_s)/(\gamma + 1 - \alpha) \tag{14}$$

Note that above we have $Q_n = f(\alpha_1, \alpha_2, Q_{s1}, Q_{s2})$, so the Q_n is not independent variable anymore. In order to find $Q_{s2} = f(\alpha_1, \alpha_2, Q_{s1})$, we need to solve the following optimization problem:

$$Max[\Pi_{s2} = b(aQ - Q^2/2) - c\,Q_{s2}^2/(2\alpha_2 N)] \quad s.t \quad (14) \tag{15}$$

Note that the above optimization problem can be transformed to a nonconstrained one by replacing the equation (14) to objective function Π_{s2}. As $d^2\Pi_{s2}/dQ_{s2}^2 < 0$ then by $d\Pi_{s2}/dQ_{s2} = 0 \Rightarrow Q_{s2} = f(\alpha_1, \alpha_2, Q_{s1})$. We do not write explicitly $Q_{s2} = f(\alpha_1, \alpha_2, Q_{s1})$ because of the lengthy analytical formula, but note that Q_{s2} is expressed by means of other variables. In order to find $Q_{s1} = f(\alpha_1, \alpha_2)$, we need to solve the similar optimization problem:

$Max[\Pi_{s1} = b(aQ - Q^2/2) - c\,Q_{s1}^2/(2\alpha_1 N)]$

$$s.t \quad Q_n(\alpha_1, \alpha_2, Q_{s1}) = (1-\alpha)(a - Q_s)/(\gamma + 1 - \alpha), \quad Q_{s2} = f(Q_{s1}) \tag{16}$$

Note that the above optimization problem can be transformed to a nonconstrained one by replacing the constrains to objective function Π_{s1}. As $d^2\Pi_{s1}/dQ_{s1}^2 < 0$ then by $d\Pi_{s1}/dQ_{s1} = 0 \Rightarrow Q_{s1} = f(\alpha_1, \alpha_2)$. As we have $Q_{s1} = f(\alpha_1, \alpha_2)$, we replace it in $Q_{s2} = f(Q_{s1})$ and have $Q_{s2} = f(\alpha_1, \alpha_2)$. We replace both of them in (14) then we get $Q_n = f(\alpha_1, \alpha_2)$. Finally we have all $\pi_{s2}, \Pi_{s2}, \pi_{s1}, \Pi_{s1}, \pi_n, \Pi_n$ as $f(\alpha_1, \alpha_2)$.

In order to find α_1 and α_2 we need to formulate a different optimization problem. We need the condition in (12) to be satisfied between three groups of countries, the coalition one of signatories, (C_{s1}), the coalition two of signatories, (C_{s2}) and the nonsignatories, (C_n) in order to have *intercoalition stability*. ***The intercoalition stability*** means a stable relations between C_{s2} and C_n, C_{s1} and C_{s2} as well as C_{s1} and C_{s2}.

Definition 3.1 We have **intercoalition stability** if and only if the following conditions (17),(18) and (19) are satisfied:

$$[\pi_{s1}(\alpha_1, \alpha_2) \geq \pi_n(\alpha_1 - 1/N, \alpha_2) \wedge \pi_n(\alpha_1, \alpha_2) \geq \pi_{s1}(\alpha_1 + 1/N, \alpha_2)] \tag{17}$$

$$[\pi_{s2}(\alpha_1, \alpha_2) \geq \pi_n(\alpha_1, \alpha_2 - 1/N) \wedge \pi_n(\alpha_1, \alpha_2) \geq \pi_{s1}(\alpha_1, \alpha_2 + 1/N)] \tag{18}$$

$$[\pi_{s2}(\alpha_1, \alpha_2) \geq \pi_{s1}(\alpha_1 + 1/N, \alpha_2 - 1/N) \wedge \pi_{s1}(\alpha_1, \alpha_2) \geq \pi_{s2}(\alpha_1 - 1/N, \alpha_2 + 1/N)] \tag{19}$$

It is important to note that *the conditions (17),(18) and (19) together describe all possible changes among C_{s1},C_{s2} and C_n if only one country is changing its position. It is clear that any change in any country position reduce its profit. In other words they guarantee stability among two coalitions and nonsignatories, so they guarantee* ***intercoalition stability***.

Now we are ready to formulate the nonlinear optimization problem that helps us to find α_1 and α_2.

$Max(\alpha_1 + \alpha_2)$

s.t

$[\pi_{s1}(\alpha_1, \alpha_2) \geq \pi_n(\alpha_1 - 1/N, \alpha_2) \wedge \pi_n(\alpha_1, \alpha_2) \geq \pi_{s1}(\alpha_1 + 1/N, \alpha_2)]$

$[\pi_{s2}(\alpha_1, \alpha_2) \geq \pi_n(\alpha_1, \alpha_2 - 1/N) \wedge \pi_n(\alpha_1, \alpha_2) \geq \pi_{s1}(\alpha_1, \alpha_2 + 1/N)]$

$[\pi_{s2}(\alpha_1, \alpha_2) \geq \pi_{s1}(\alpha_1 + 1/N, \alpha_2 - 1/N) \wedge \pi_{s1}(\alpha_1, \alpha_2) \geq \pi_{s2}(\alpha_1 - 1/N, \alpha_2 + 1/N)]$

The constrains of above optimization problem are just the conditions (17),(18) and (19). We use the MATLAB Optimization Toolbox to solve the above optimization problem.

As one would expect the starting point and rounding are cumbersome [3].

[3] The starting point is slightly problematic but with the help of algorithm in Table (2) we can find a starting point for α_2. As the interval of α_1 is small, it is not difficult to find the second starting point. As with the case of one self-enforcing IEA, $\alpha_1 N$ and $\alpha_2 N$ will usually not be integer numbers, so we only can round both of them down and find the new $\alpha_1 = rounddown(\alpha_1 N)/N$ and $\alpha_2 = rounddown(\alpha_2 N)/N$. After rounding down we expect still the six constrains to be satisfied (for one self-enforcing IEA there were only two constrains). Our numerical experience advice us *to solve the problem often as a minimization one in stead of maximization.* (Please note that *if we solve our problem as a maximization one and round up we get usually the same solution if we solve it as a minimization one and round down*). We do this because the result of optimization $\alpha_1 N$ and $\alpha_2 N$ are not integer and *rounding them up works almost always better then rounding them down and it is almost always successful.* In the case that

Let introduce an example in order to make clear our proceeding. The values of parameters are: a = 100, b = 1.5, c = 0.25, N = 10. The solution of our nonlinear optimization problem is, $\alpha_1 = 0.54, \quad \alpha_2 = 0.22$. After we round down, we have $\alpha_1 = 0.5, \quad \alpha_2 = 0.2$, note that after rounding down our constrains (17), (18) and (19) are still satisfied. This can not happen always! As $q_{s1}, \ q_{s2}, \ q_n, \ \pi_{s1}, \ \pi_{s2}, \ \pi_n$ are function of only α_1 and α_2 we know all of them. As profit functions depend on α_1 and α_2 we use also a 3-dimensional visualization. Note that we introduce graphics for real nonnegative α, but the α's that makes sense to our problem satisfy that αN is a natural number.

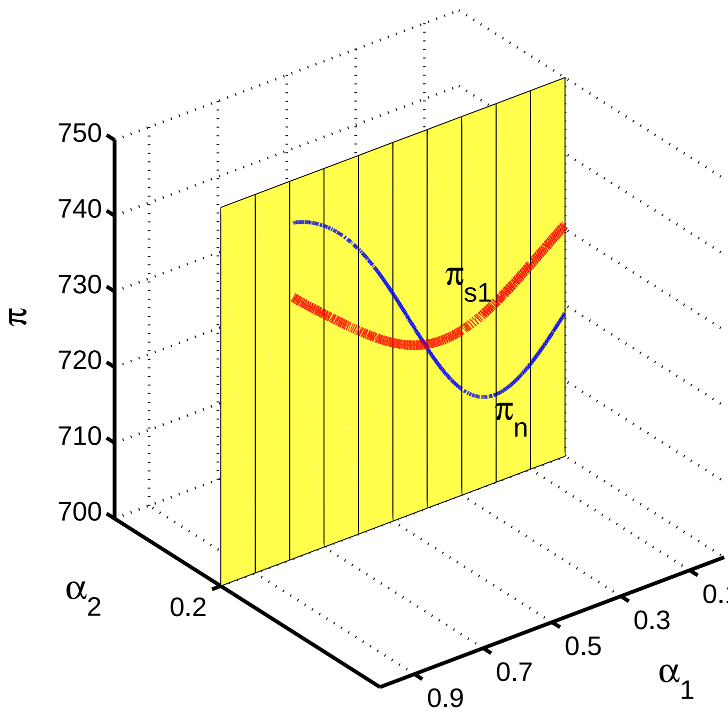

Figure 2: Graphical analysis of stability between first coalition and nonsignatories

In the Figure (2) we introduce graphically the relation between π_{s1}, the profit of a country of first coalition and π_n, the profit of a single nonsignatory. In the plane $\alpha_2 = 0.2$ (the size of second coalition is constant) parallel to YZ-plane, we see the π_{s1}, π_n only as function of α_1. In the Figures (3) we see the plane $\alpha_2 = 0.2$ only in 2 dimension. Note that any movement of a country of C_{s1} to C_n or in the opposite direction reduces the profit of country that moves.

The Figures (4) and (5) are similar to Figures (2) and (3) but we introduce graphically the relation between π_{s2}, the profit of a country of first coalition and π_n, the profit of a single nonsigna-

rounding up does not give a solution, we follow another way. In the first step we solve four nonlinear optimization problem that have the same constrains as above, but the objective function is different. The four different objective functions are Min(α_1), Min(α_2) and Max(α_1), Max(α_2). As we solve the maximization problem we know the intervals, which α_1 and α_2 that satisfy the conditions (17),(18) and (19), belong. The $\alpha_1 \in [\alpha_1^{min}, \alpha_1^{max}]$ and $\alpha_2 \in [\alpha_2^{min}, \alpha_2^{max}]$. The minimal values $\alpha_1^{min}, \alpha_2^{min}$ come from solving the nonlinear minimization problems and the maximization values $\alpha_1^{max}, \alpha_2^{max}$ from solving the nonlinear maximization problems. As we know this intervals, (which usually are small) a relatively simple combinatorial work to find all possible (α_1),(α_2) for which $\alpha_1 N$ and $\alpha_2 N$ are integer. If none of them satisfies the conditions (17),(18) and (19) then we can say there is no local solution to our problem !

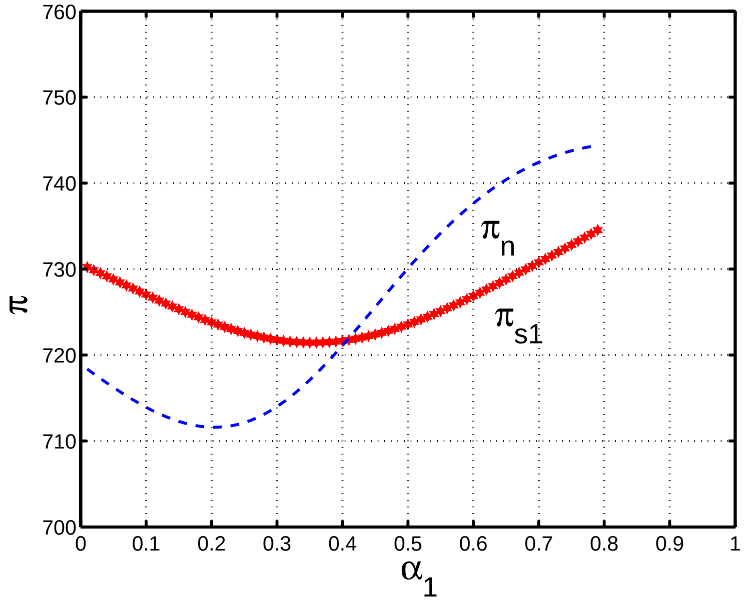

Figure 3: Graphical analysis of stability between first coalition and nonsignatories

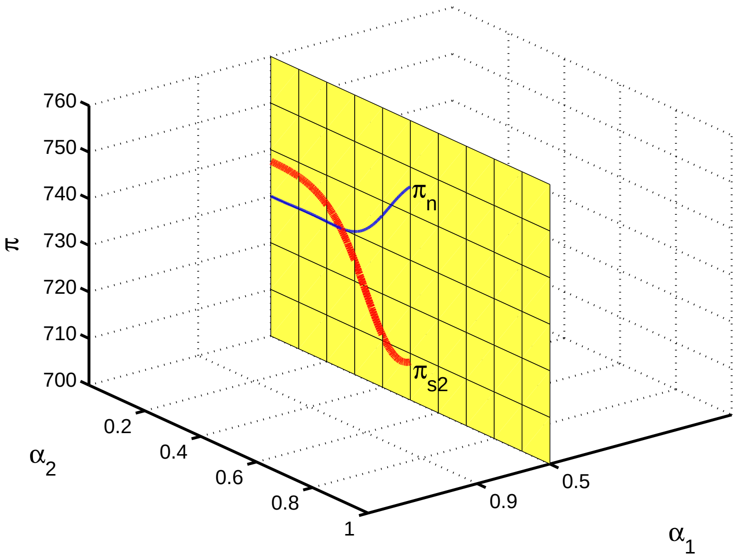

Figure 4: Graphical analysis of stability between second coalition and nonsignatories

tory. The graphical relation is clear in the plane $\alpha_2 = 0.5$ (the size of first coalition is constant) parallel to XZ-plane.

In the Figure (6) we present graphically the relation between π_{s1}, the profit of a country of first coalition and π_{s2}, the profit of a country of second coalition. In the plane $\alpha_1 + \alpha_2 = 0.7$ (the number of nonsignatories is constant) parallel to Z-axes, we see the π_{s1}, π_{s2} as function of

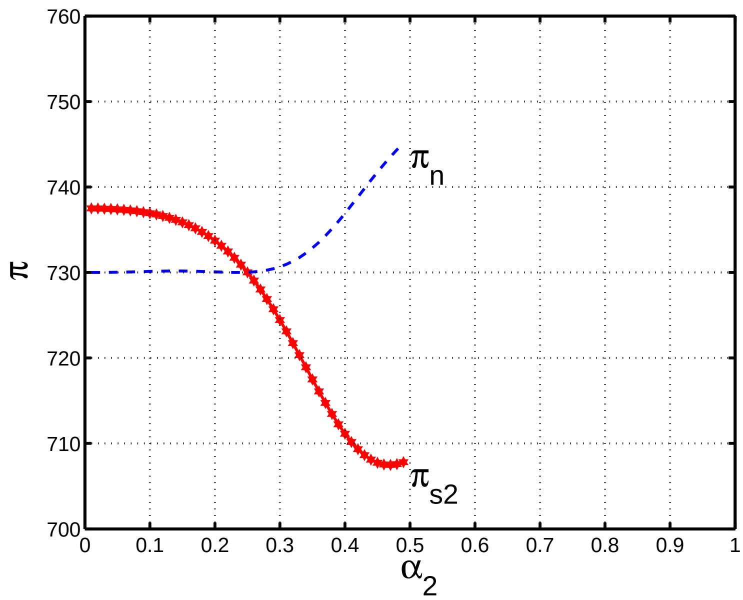

Figure 5: Graphical analysis of stability between second coalition and nonsignatories

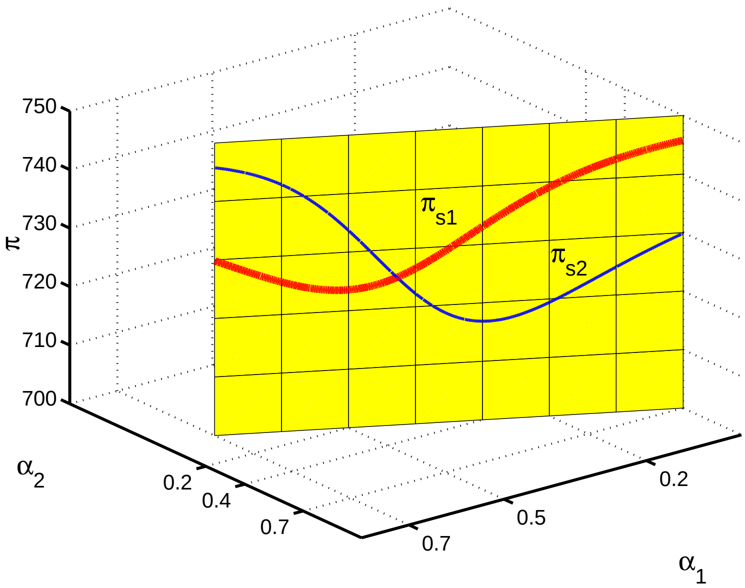

Figure 6: Graphical analysis of stability between first and second coalition

α_1 and α_2. We must chose the plane $\alpha_1 + \alpha_2 = 0.7$ because in this plane is located our solution $\alpha_1 = 0.5, \quad \alpha_2 = 0.2$. In the Figure (7) we see the plane $\alpha_1 + \alpha_2 = 0.7$ in 2 dimension. In the upper part of Figure (7) we put the values of α_2 too. Note that as before any movement of single signatory of C_{s1} to C_{s2} or in the opposite direction reduces the profit of country that moves.

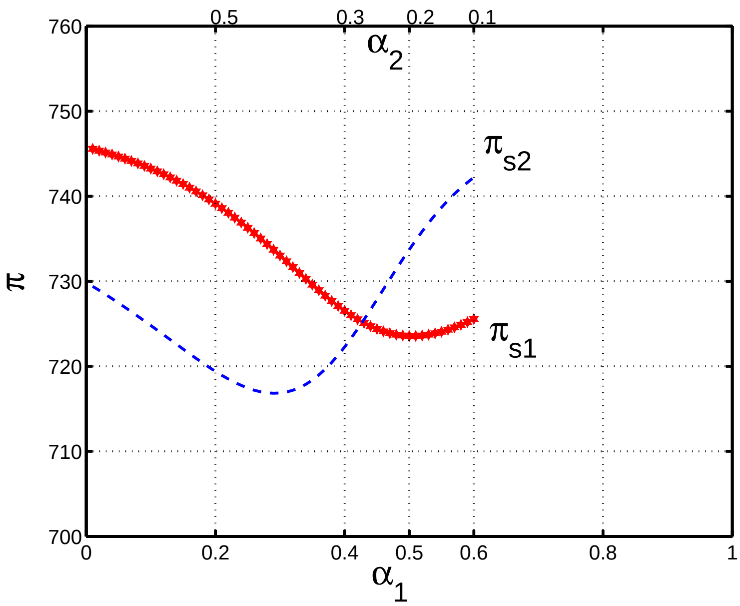

Figure 7: Graphical analysis of stability between first and second coalition

3.1 Simulations

We present in this section the essential part of our simulations and we postpone the detailed description of them in Appendix. Firstly let's define:

the global profit, no coalition $\Pi_{\alpha=0} = N\pi_n = \Pi_n$.
the global profit, grand coalition $\Pi_{\alpha=1} = N\pi_s = \Pi_s$.
the global profit, one coalition $\Pi_{\alpha_1} = \alpha_1 N\pi_{s1} + (1-\alpha_1)N\pi_n = \Pi_{s1} + \Pi_n$.
the global profit, two coalitions
$\Pi_{(\alpha_1,\alpha_2)} = \alpha_1 N\pi_{s1} + \alpha_2 N\pi_{s2} + (1-\alpha_1-\alpha_2)N\pi_n = \Pi_{s1} + \Pi_{s2} + \Pi_n$.

the global abatement, no coalition $Q_{\alpha=0} = Nq_n = Q_n$.
the global abatement, grand coalition $Q_{\alpha=1} = Nq_s = Q_s$.
the global abatement, one coalition $Q_{\alpha_1} = \alpha_1 Nq_{s1} + (1-\alpha_1)Nq_n = Q_{s1} + Q_n$.
the global abatement, two coalitions
$Q_{(\alpha_1,\alpha_2)} = \alpha_1 Nq_{s1} + \alpha_2 Nq_{s2} + (1-\alpha_1-\alpha_2)Nq_n = Q_{s1} + Q_{s2} + Q_n$.

the fraction of fully cooperative welfare
for one coalition:
$(\Pi_{\alpha_1} - \Pi_{\alpha=0})/(\Pi_{\alpha=1} - \Pi_{\alpha=0})$.
for two coalitions:
$(\Pi_{(\alpha_1,\alpha_2)} - \Pi_{\alpha=0})/(\Pi_{\alpha=1} - \Pi_{\alpha=0})$.

the fraction of fully cooperative abatement
for one coalition:
$(Q_{\alpha_1} - Q_{\alpha=0})/(Q_{\alpha=1} - Q_{\alpha=0})$.

for two coalitions:
$(Q_{(\alpha_1,\alpha_2)} - Q_{\alpha=0})/(Q_{\alpha=1} - Q_{\alpha=0})$.

the fraction of countries in one coalition α_1.
the fraction of countries in two coalitions $(\alpha_1 + \alpha_2)$.

The Figures (8), (9), and (10) use the data from Tables (3), (10) in Appendix. The set of parameters are: a = 100, N = 10 and we vary $\gamma = c/b$. It is clear from that the fraction of fully cooperative welfare, the fraction of fully cooperative abatement and the fraction of countries in two coalition increase if we increase $\gamma = c/b$ for two self-enforcing agreements (two coalition) compared to one self-enforcing agreements (one coalition). When γ is small, one coalition is better than two coalitions.

The Figures (11), (12), and (13) use the data form Tables (7) and (8) in Appendix. The set of parameters are: a = 100, c = 0.25, b = 1.5 so $\gamma = c/b = 0.167$; a = 100, c = 0.3, b = 1.5, $\gamma = c/b = 0.833$; a = 100, c = 150, b = 25, $\gamma = c/b = 6$ and we vary N (total number of countries). From the figures we derive the conclusion that if the damage cost is relative big (γ large), and if the number of countries is small then two coalitions improve the welfare and abatement level significantly compared to one coalition. In all cases a higher N implies less additional welfare and abatement due to the second coalition. So, a second coalition is more effective with a small number of countries than with a large number.

4 Conclusions

The paper investigates the size and the improving capability of two self-enforcing IEA. An IEA is self-enforcing when no country wants to withdraw and no country wants to join the IEA. As we employ a simplified model the results must be interpreted with caution. Although our work is less general than that of Yi and Shin, Bloch etc, we are able to compute the coalition sizes and optimal abatement levels.

The paper shows the results of Barrett on one self-enforcing IEA are partly true for two self-enforcing international IEAs too; when the coalitions of signatories are big, the difference (in welfare and environmental quality) between the two self-enforcing IEA and one self-enforcing IEA (as well as noncooperative behavior) is small, two self-enforcing IEA can even reduce the welfare and environment quality; only when the coalitions of signatories are small, the two self-enforcing IEA can bring improvements compared to the case of one self-enforcing IEA.

A striking result is that when the cost of pollution abatement is high and the total number of countries is small, then two self-enforcing IEA can significantly improve welfare and environmental equality compared to one-self enforcing IEA. So the model shows that in continental pollution problems where the above conditions are met, two self-enforcing IEA's can be preferred to a single coalition.

As always further research is needed in asymmetry between countries, independence cost function, issue linkage, repeated games, uncertainty or limited information.

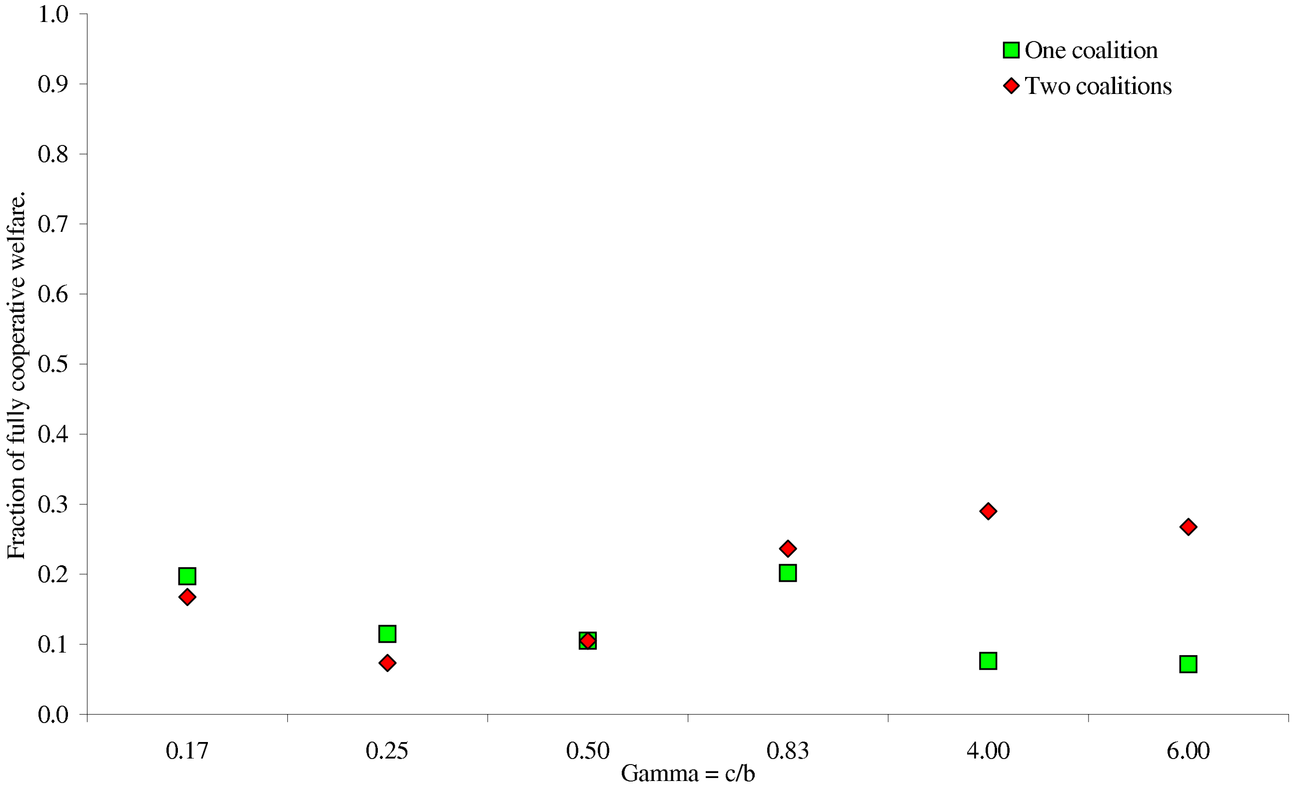

Figure 8: Profit Π as function of γ ($= c/b$) for one and two self-enforcing IEA.

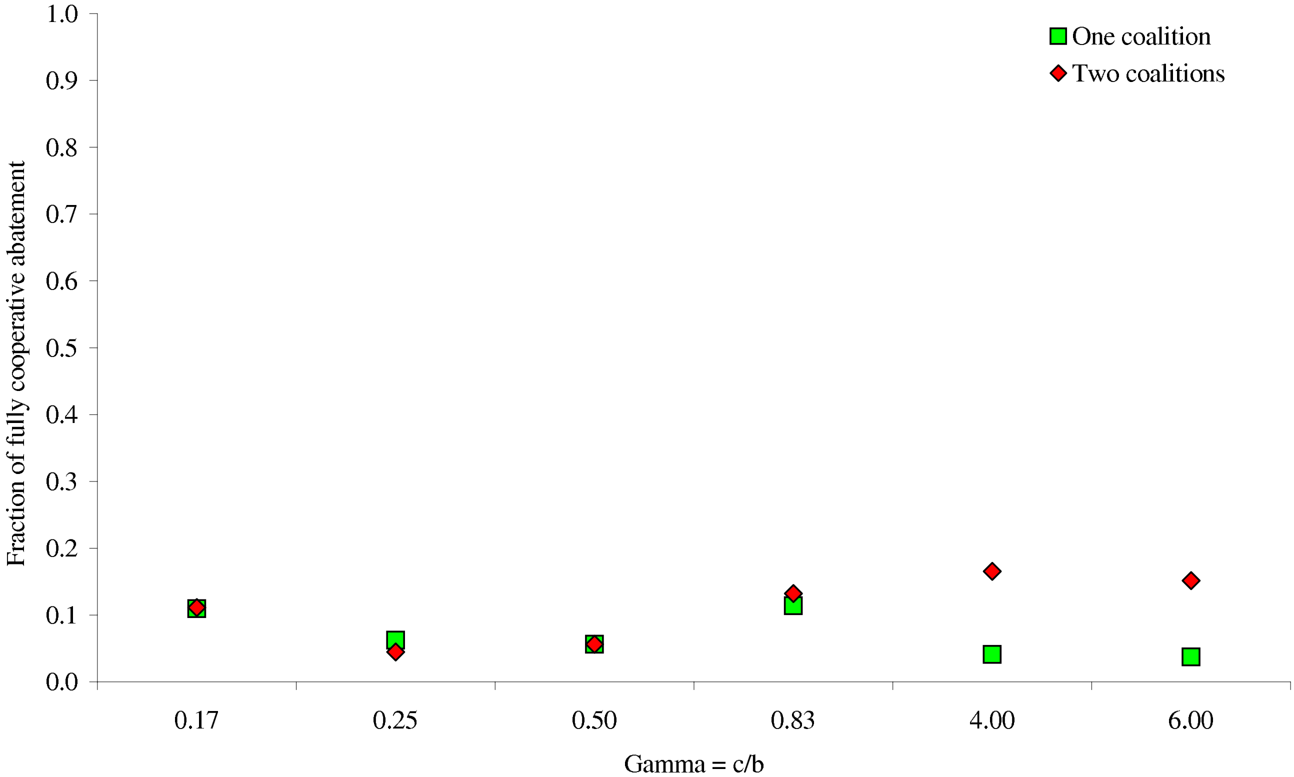

Figure 9: Abatement Q as function of γ ($= c/b$) for one and two self-enforcing IEA.

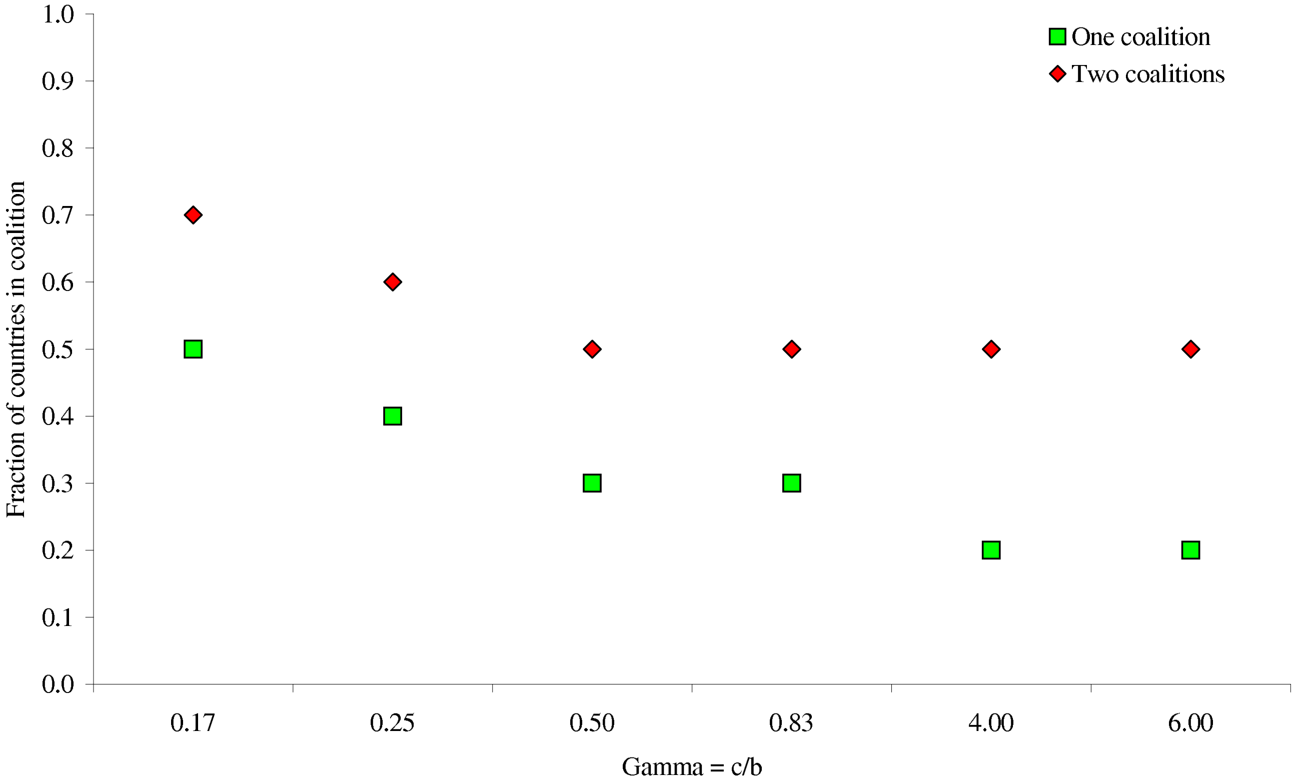

Figure 10: Coalition size as function of γ ($= c/b$) for one and two self-enforcing IEA.

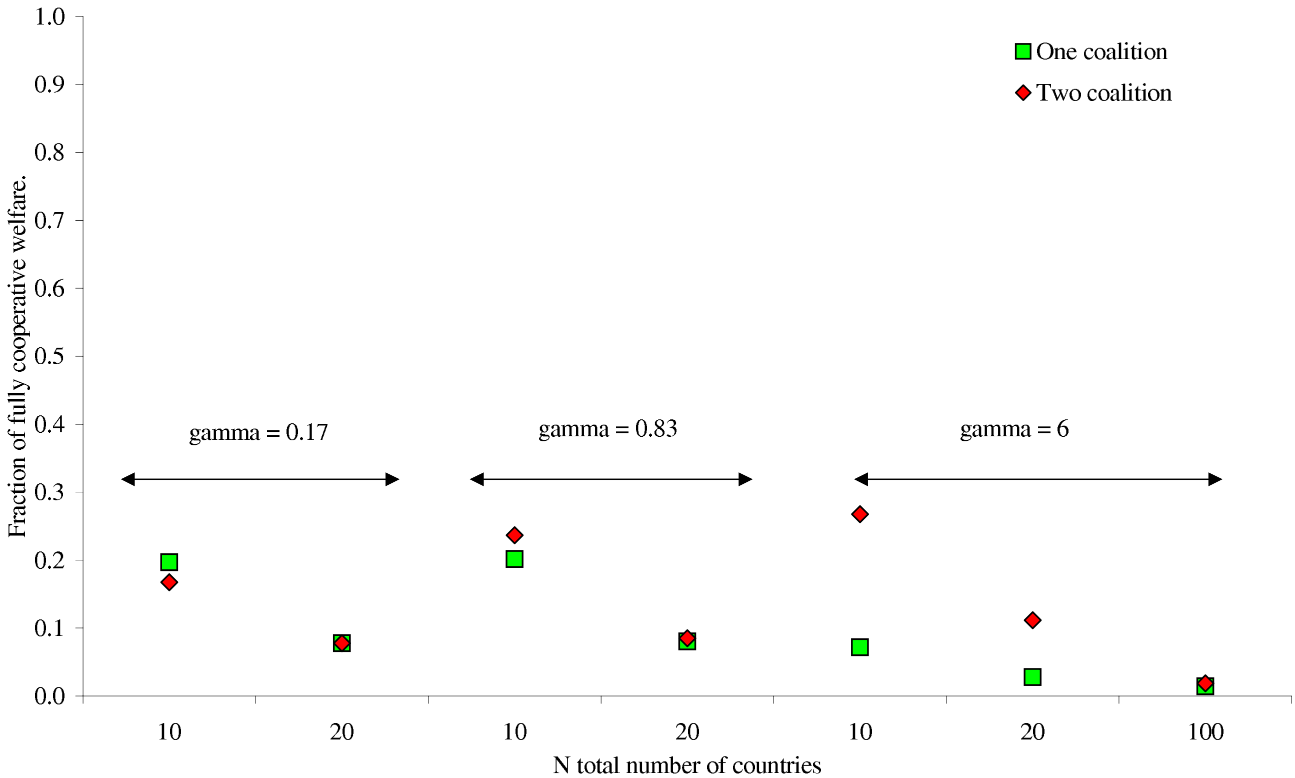

Figure 11: Profit Π as function of N and γ for one and two self-enforcing IEA.

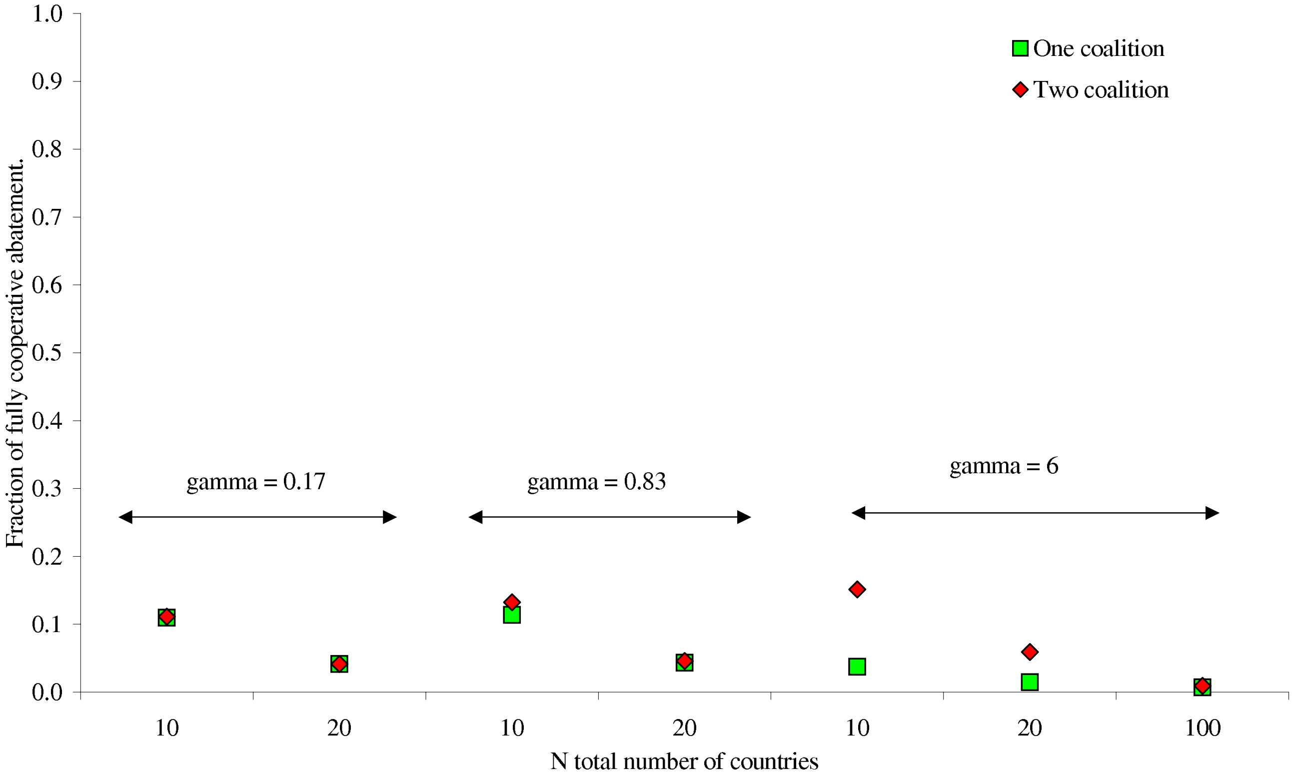

Figure 12: Abatement Q as function of N and γ for one and two self-enforcing IEA.

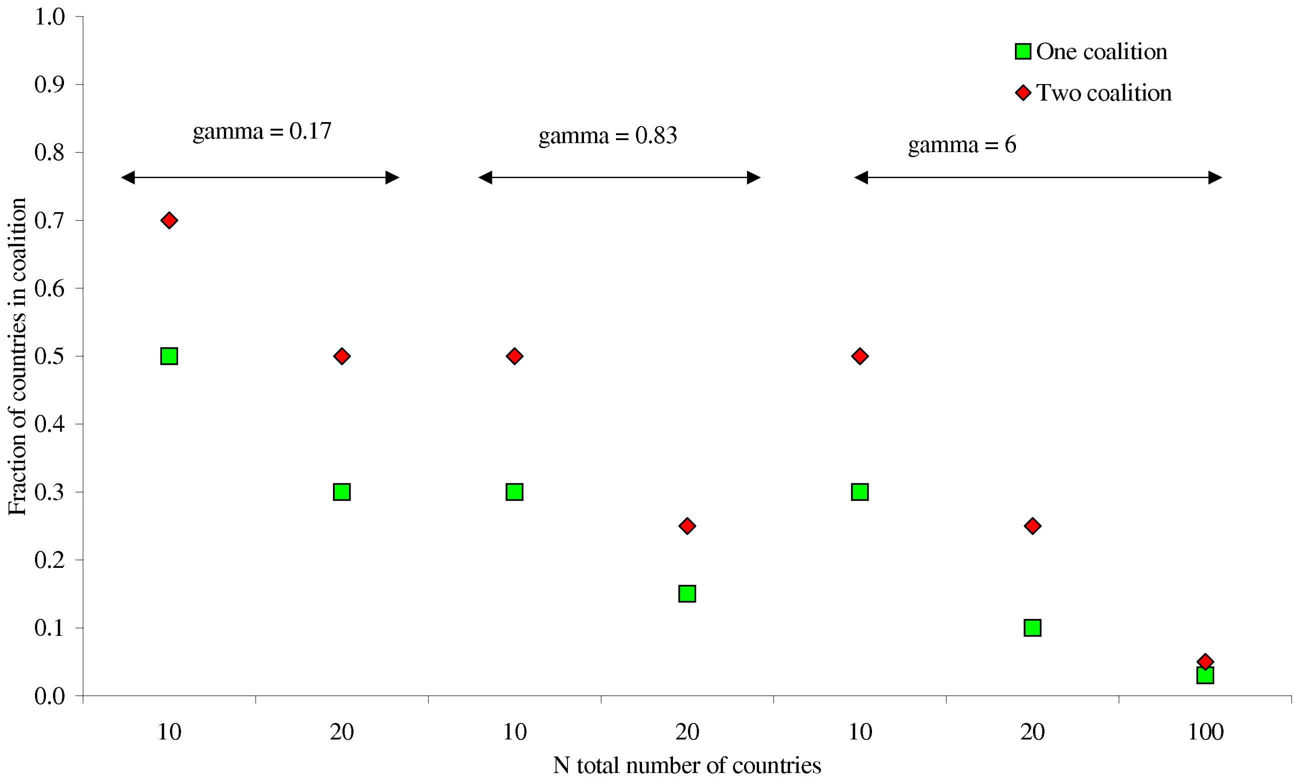

Figure 13: Coalition size as function of N and γ for one and two self-enforcing IEA.

Appendix

We present below a detailed description of our simulation.

Table (3) gives the total profit (Π) and global abatement level (Q) for noncooperative behavior ($\alpha = 0$) and cooperative behavior ($\alpha = 1$). Cooperation brings higher welfare and lower emissions.

Table (3) also shows the net benefit and the abatement level of a representative country of signatories coalition (C_s) as well as of a representative country of nonsignatories (C_n) when α is maximized *in the case of one self-enforcing IEA*. It shows the global net benefits Π and the global abatement level Q. As in Barrett(1994a) the coalition is larger if stakes are lower.

Insert Table 3 here.

Table (3) also shows the net benefit and the abatement level of a representative country of signatories coalition (C_{s1}, C_{s2}) as well as of a representative country of nonsignatories (C_n) when the sum ($\alpha_1 + \alpha_2$) is maximized *in the case of two self-enforcing IEA*. It shows the global net benefits Π and the global abatement level Q too.

We keep $a = 100, c = 0.25, N = 10$ unchanged *and vary* $b > c$ (for $b < c$ see Table (4)).

In the first part of the Table (3) (b is big compared to c, $\gamma = c/b$ is small and the coalitions are big). An abatement increase by the coalition C_{s2} is offset by abatement decrease by the coalition C_{s1} while the nonsignatories C_n play almost the same role in one and two self-enforcing IEA's. Total abatement goes down by having two coalitions. Total welfare also falls. Note that *single coalition is stable to the deviations of individual countries but not against deviations of a group of countries.*

In the second part of Table (3) ($b = 0.5$, b is smaller compared to c, $\gamma = c/b$ is small, the coalitions are still big) the coalition of signatories C_{s2} has the same benefits as the nonsignatories C_n, so we have no change on the environment quality and welfare if compared to one self-enforcing IEA.

In the third part of Table (3) (when $b = 0.3, \gamma = c/b$ is almost 1, the coalitions are small) *a second international IEA is benificial.* The coalition of signatories C_{s1} brings more benefits to the environment than the nonsignatories C_n by increasing the total abatement Q (by 1.2 per cent) and also improving the welfare compared to one self-enforcing IEA. But even for this example the increase in the abatement levels of C_{s1} is partly offset by the decrease in the abatement levels of C_{s2}, while the nonsignatories C_n play the same role in one and two self-enforcing IEA.

In Table (4) we introduce the similar results as in Table (3) for different values of parameters b, c. We keep $a = 100, N = 10, b = 0.25$ unchanged and *chose* $c > b$. In the first part of Table (4) $c = 1.5$, in the second part $c = 1$.

As we see in the first part of the Table (4) ($c = 1.5$, c is relatively big compared to b, $\gamma = c/b$ is big, the coalitions are small) but *the second self-enforcing IEA brings significant improvement compared to one self-enforcing IEA*. This is due to the fact that the abatement levels of coalition of signatories C_{s2} are much higher than the abatement level of coalition of signatories C_{s1} and nonsignatories C_n.

Insert Table 4 here.

In spite of the fact that abatement increase by the coalition C_{s2} is partly offset by abatement decrease by the nonsignatories C_n and the coalition of signatories C_{s1} we have still the improvement of Q by 34.2 per cent and total profit Π by 26.1 per cent. For $c = 1$ results are similar.

The difference of Q and Π between the two self-enforcing IEA and noncooperative behavior is big in both parts of Table (4).

Sensitivity analysis

The difference between the first and the second part of Table (5) is that we keep $b = 1.5, c = 0.25, N = 10$ unchanged but *we change a 10 times bigger, from $a = 100$ to $a = 1000$.*

Insert Table 5 here.

As we see the total profit Π is 100 times bigger (also individual profit π), the total abatement level Q is 10 times bigger (also individual abatement level q), but the size of signatories coalition remains constant.

The same analysis apply for the difference between noncooperative and cooperative behavior when a goes 100 to 1000. This is clearly concluded from the analytical formula for noncooperative and cooperative behavior.

In Table (6) we introduce the similar results as in Table (3) and Table (4) but *choosing b, c much bigger than before (from 10 to 100 times bigger).*

In the first part of Table (6) we rewrite result of the last part of Table (3) and in the second part of it we keep $a = 100, N = 10$ unchanged, but we change b, c 100 times bigger (from $b = 0.3$ to $b = 30$, from $c = 0.25$ to $c = 25$). As we see the first and second are qualitatively the same. In both parts two self-enforcing IEA brings a little improvement in environmental quality and welfare compared one self-enforcing IEA. The value of Q (and individual q) remains the same, but no surprise that the total profit Π (and individual π too) is 100 times bigger. The size of signatories coalition and nonsignatories remains constant.

In the third part of Table (6) we keep $a = 100, N = 10$ unchanged, but we change b around 17 times and c 10 times (from $b = 17.5$ to $b = 300$, from $c = 10$ to $c = 300$).

Insert Table 6 here.

As we see the third and forth part of Table (6) are still qualitatively similar. In both parts the second self-enforcing IEA brings a little improvement in environmental quality and welfare compared one self-enforcing IEA but in stead of a significant carbon-leakage phenomena we have only a smaller carbon-leakage phenomena. But here we have the value of Q (and individual q too) is around 1.3 times smaller, but the total profit Π (and individual π too) is around 15 times bigger. The size of signatories coalition is a little smaller.

The difference between the fifth and sixth part of Table (6) is that we increase b, c by 100 times (from $b = 0.25$ to $b = 25$, from $c = 1.5$ to $c = 150$). We keep $a = 100$ and $N = 10$ unchanged.

The difference in the results are identically the same as for the first part of Table (6) so we do not repeat the previous analysis.

The difference between the first part and the second part of Table (7) is that we keep $a = 100, b = 1.5, c = 0.25$ unchanged but *we change N form 10 to 20.* We have an improvement of welfare by 0.5 per cent but a little decrease of environmental quality. The individual abatement levels and profit are decreased by factor 2.

Insert Table 7 here.

The number of first coalition of signatories is two times bigger, while the second signatories coalition C_{s2} has one country more. In the first part of Table (7) the two self-enforcing IEA's benefit environment, but worsening the welfare while in the second part the two self-enforcing IEA's is working identically the same as one self-enforcing IEA. By increasing N the difference between one and two self-enforcing IEA decreases.

The difference between the third part and the fourth part of Table (7) is that we keep $a = 100, b = 0.3, c = 0.25$ unchanged but we change N from 10 to 20. We have a small decrease of welfare and a little decrease of environmental quality. Individual abatement levels and profit are lower by factor 2. The number of first and the second coalition signatories are the same. In the third part of Table (7) the two self-enforcing IEA is working better than one self-enforcing IEA. In the fourth part, the difference between one and two IEA's is larger than in the third part.

The difference of Q and Π between the two self-enforcing IEA and noncooperative behavior is smaller when N is bigger. By increasing N, the Q and Π for noncooperative behavior get bigger.

We introduce Table (8) in order to see that *the significant improvement in environment equality and welfare that we see in Table (4) are significantly reduced when we have a much bigger N.* The difference between the first part, the second and the third part of Table (8) is that we keep $a = 100, b = 25, c = 150$ unchanged but we change N form 10 to 20 and then to 100.

Insert Table 8 here.

As we can see the second s.e IEA brings significantly more improvement on environment equality and welfare (Q is improved by more than 34 per cent and Π by more than 26 per cent) when $N = 10$ (first part of Table (8)). When $N = 20$ (second part of Table (8)) we have relatively less improvement on environment equality and welfare (Q is improved by more than 18 per cent and Π by more than 15 per cent), compared with the case when $N = 10$. When $N = 100$ (third part of Table (8)) we have significantly less improvement on environment equality and welfare (Q is improved only by 1.14 per cent and Π only by 1.06 per cent), compared with the case when $N = 10$. When we change N we have the other changes we have already mentioned in the discussion of Table (7)).

Summary

When γ is small we have big coalitions of signatories but *the second self-enforcing IEA worsens the environment quality and welfare compared to one self-enforcing IEA*. When γ gets bigger, there comes a point where *the second self-enforcing IEA works the same as one self-enforcing IEA* but we have smaller coalitions of signatories. When $\gamma \approx 1$ *the second self-enforcing IEA brings a little improvement in environment quality and welfare compared to one self-enforcing IEA* in spite of the fact that the coalitions of signatories are even smaller. Only when γ is big and N is not so big *the second self-enforcing IEA brings significant improvement in environment and welfare compared one self-enforcing IEA*, but the increase of N reduced drastically the improvement. Having a bigger N (when γ is small) increases environmental quality but reduces welfare. A bigger N (when $\gamma \approx 1$) worsens a little the environment and the welfare. The individual q andπ, of both signatories and nonsignatories, decrease by the same amount (relatively) as N increases. A bigger a means better environmental equality and welfare. A bigger b and c means always a better welfare; if $b > c$ we have a little decrease in environmental equality; if $b \leq c$ we have a constant level of environmental equality.

The values of parameters for which two self-enforcing IEA brings a significant improvement compared to one self-enforcing IEA are: a big a, b and c (they guarantee good environmental quality and welfare level) and $b \leq c$ as well as a relatively small N (they guarantee two self-enforcing IEA brings a big improvement compared to one self-enforcing IEA).

Table 3: Comparing the abatement levels and benefits between one and two self-enforcing IEA *for different **b***. (*The symbol * we use to mark stability abatement values, and it is valid for all tables*).

a second s.e IEA reduces welfare, increases abatement									
a	b	c	N						
100	1.5	0.25	10						
α_1	α_2	q_{s1}	q_{s2}	q_n	π_{s1}	π_{s2}	π_n	Q	Π
0	-	-	-	8.57	-	-	725.51	85.7	7255.1
1	-	9.84	-	-	737.7	-	-	98.4	7377.0
0.5*	-	9.7*	-	7.7*	725.8*	-	730.0*	87.09*	7279.1*
0.5*	0.2*	10.6*	5.5*	7.7*	723.6*	733.7*	730.1*	87.11*	7275.5*
a second s.e IEA reduces welfare and abatement									
a	b	c	N						
100	1	0.25	10						
α_1	α_2	q_{s1}	q_{s2}	q_n	π_{s1}	π_{s2}	π_n	Q	Π
0	-	-	-	8	-	-	472	80	4720
1	-	9.76	-	-	487.8	-	-	97.6	4878.0
0.4*	-	8.9*	-	7.6*	472.2*	-	474.9*	81.1*	4738.1*
0.4*	0.2*	9.6*	5.9*	7.7*	470.1*	477.2*	474.2*	80.79*	4731.6*
a second s.e IEA leaves things unchanged									
a	b	c	N						
100	0.5	0.25	10						
α_1	α_2	q_{s1}	q_{s2}	q_n	π_{s1}	π_{s2}	π_n	Q	Π
0	-	-	-	6.67	-	-	216.67	66.7	2166.7
1	-	9.52	-	-	238.1	-	-	95.2	2381.0
0.3*	-	7.9*	-	6.3*	216.9*	-	219.8*	68.3*	2189.2*
0.3*	0.2*	7.9*	6.3*	6.3*	216.9*	219.8*	219.8*	68.3*	2189.2*
a second s.e IEA increases welfare and abatement									
a	b	c	N						
100	0.3	0.25	10						
α_1	α_2	q_{s1}	q_{s2}	q_n	π_{s1}	π_{s2}	π_n	Q	Π
0	-	-	-	5.45	-	-	115.29	54.5	1152.9
1	-	9.23	-	-	138.46	-	-	92.3	1384.6
0.3*	-	8.1*	-	4.9*	116.4*	-	121.5*	58.8*	1199.6*
0.3*	0.2*	7.7*	6.1*	4.9*	118.0*	120.8*	122.4*	59.5*	1207.7*

Table 4: Comparing the abatement levels and benefits between one and two self-enforcing IEA *for different* ***c***.

a second s.e IEA increases welfare and abatement									
a	b	c	N						
100	0.25	1.5	10						
α_1	α_2	q_{s1}	q_{s2}	q_n	π_{s1}	π_{s2}	π_n	Q	Π
0.2*	-	2.5*	-	1.4*	32.5*	-	35.6*	16.1*	349.6*
0.3*	0.2*	3.4*	2.4*	1.3*	39.4*	43.9*	46.9*	21.6*	440.7*
a second s.e IEA increases welfare and abatement									
a	b	c	N						
100	0.25	1	10						
α_1	α_2	q_{s1}	q_{s2}	q_n	π_{s1}	π_{s2}	π_n	Q	Π
0	-	-	-	2	-	-	43	20	430
1	-	7.14	-	-	89.29	-	-	71.4	892.9
0.2*	-	3.2*	-	1.9*	43.8*	-	47.2*	22.1*	465.3*
0.3*	0.2*	4.4*	3.2*	1.8*	51.4*	56.1*	59.6*	28.5*	564.2*

Table 5: Comparing the abatement levels and benefits between one and two self-enforcing IEA *for different* ***a***.

a second IEA reduces welfare and abatement									
a	b	c	N						
100	1.5	0.25	10						
α_1	α_2	q_{s1}	q_{s2}	q_n	π_{s1}	π_{s2}	π_n	Q	Π
0	-	-	-	8.57	-	-	725.51	85.7	7255.1
1	-	9.84	-	-	737.7	-	-	98.4	7377.0
0.5*	-	9.7*	-	7.7*	725.8*	-	730.0*	87.09*	7279.1*
0.5*	0.2*	10.6*	5.5*	7.7*	723.6*	733.7*	730.1*	87.11*	7275.5*
a	b	c	N						
1000	1.5	0.25	10						
α_1	α_2	q_{s1}	q_{s2}	q_n	π_{s1}	π_{s2}	π_n	Q	Π
0	-	-	-	85.71	-	-	72551.02	857.1	725510.2
1	-	98.36	-	-	73770.49	-	-	983.6	737704.9
0.5*	-	96.7*	-	77.4*	72580.6*	-	73002.1*	870.9*	727913.6*
0.5*	0.2*	105.7*	55.2*	77.3*	72356.7*	73372.7*	73006.5*	871.1*	727549.1*

Table 6: Comparing the abatement levels and benefits between one and two self-enforcing IEA *for big* ***b*** *and* ***c***.

				a second IEA improves welfare and abatement					
a	b	c	N						
100	0.3	0.25	10						
α_1	α_2	q_{s1}	q_{s2}	q_n	π_{s1}	π_{s2}	π_n	Q	Π
0	-	-	-	5.45	-	-	115.29	54.5	1152.9
1	-	9.23	-	-	138.46	-	-	92.3	1384.6
0.3*	-	8.1*	-	4.9*	116.4*	-	121.5*	58.8*	1199.6*
0.3*	0.2*	7.7*	6.1*	4.9*	118.0*	120.8*	122.4*	59.5*	1207.7*
a	b	c	N						
100	30	25	10						
α_1	α_2	q_{s1}	q_{s2}	q_n	π_{s1}	π_{s2}	π_n	Q	Π
0.3*	-	8.1*	-	4.9*	11640.0*	-	12147.8*	58.8*	119957.3*
0.3*	0.2*	7.7*	6.1*	4.9*	11801.7*	12076.6*	12242.8*	59.4*	120772.3*
				a second IEA improves welfare and abatement					
a	b	c	N						
1000	17.5	10	100						
α_1	α_2	q_{s1}	q_{s2}	q_n	π_{s1}	π_{s2}	π_n	Q	Π
0.03*	-	7.1*	-	6.4*	75729.8*	-	75777.5*	637.1*	7577608.6*
0.04*	0.03*	9.3*	7.2*	6.3*	75837.0*	76016.1*	76075.8*	641.8*	7606444.3*
a	b	c	N						
1000	300	300	100						
α_1	α_2	q_{s1}	q_{s2}	q_n	π_{s1}	π_{s2}	π_n	Q	Π
0.03*	-	7.6*	-	5.0*	1122251.9*	-	1127121.6*	503.9*	112697554.3*
0.03*	0.02*	7.4*	7.6*	4.9*	1128322.1*	1127920.9*	1132976.9*	507.8*	113268553.0*
				a second IEA improves welfare and abatement					
a	b	c	N						
100	0.25	1.5	10						
α_1	α_2	q_{s1}	q_{s2}	q_n	π_{s1}	π_{s2}	π_n	Q	Π
0.2*	-	2.5*	-	1.4*	32.5*	-	35.6*	16.1*	349.6*
0.3*	0.2*	3.4*	2.4*	1.3*	39.4*	43.9*	46.9*	21.6*	440.7*
a	b	c	N						
100	25	150	10						
α_1	α_2	q_{s1}	q_{s2}	q_n	π_{s1}	π_{s2}	π_n	Q	Π
0.2*	-	2.5*	-	1.4*	3248.4*	-	3558.3*	16.1*	34962.8*
0.3*	0.2*	3.4*	2.4*	1.3*	3942.6*	4385.2*	4693.4*	21.6*	44065.4*

Table 7: Comparing the abatement levels and benefits between one and two self-enforcing IEA *for different* $\boldsymbol{N}$.

a second IEA reduces welfare and abatement									
a	b	c	N						
100	1.5	0.25	10						
α_1	α_2	q_{s1}	q_{s2}	q_n	π_{s1}	π_{s2}	π_n	Q	Π
0	-	-	-	8.57	-	-	725.51	85.7	7255.1
1	-	9.84	-	-	737.7	-	-	98.4	7377.0
0.5*	-	9.7*	-	7.7*	725.8*	-	730.0*	87.09*	7279.1*
0.5*	0.2*	10.6*	5.5*	7.7*	723.6*	733.7*	730.1*	87.11*	7275.5*
a	b	c	N						
100	1.5	0.25	20						
α_1	α_2	q_{s1}	q_{s2}	q_n	π_{s1}	π_{s2}	π_n	Q	Π
0	-	-	-	8.57	-	-	730.1	85.7	7301.0
1	-	9.92	-	-	-	-	743.8	99.2	7438.0
0.3*	-	4.76*	-	4.12*	365.09*	-	365.79*	86.26*	7311.65*
0.3*	0.2*	4.76*	4.12*	4.12*	365.09*	365.79*	365.79*	86.26*	7311.65*
a second IEA increases welfare and abatement									
a	b	c	N						
100	0.3	0.25	10						
α_1	α_2	q_{s1}	q_{s2}	q_n	π_{s1}	π_{s2}	π_n	Q	Π
0	-	-	-	5.45	-	-	115.29	54.5	1152.9
1	-	9.23	-	-	138.46	-	-	92.3	1384.6
0.3*	-	8.1*	-	4.9*	116.4*	-	121.5*	58.8*	1199.6*
0.3*	0.2*	7.7*	6.1*	4.9*	118.0*	120.8*	122.4*	59.5*	1207.7*
a	b	c	N						
100	0.3	0.25	20						
α_1	α_2	q_{s1}	q_{s2}	q_n	π_{s1}	π_{s2}	π_n	Q	Π
0	-	-	-	5.45	-	-	117.15	54.5	1171.5
1	-	9.6	-	-	144	-	-	96.0	1440
0.15*	-	3.90*	-	2.62*	58.8*	-	59.8*	56.3*	1193.0*
0.15*	0.1*	3.87*	2.75*	2.62*	58.9*	59.8*	59.9*	56.4*	1194.3*

Table 8: Comparing the abatement levels and benefits between a successful two self-enforcing IEA *for different* ***N***.

a second IEA increases welfare and abatement									
a	b	c	N						
100	25	150	10						
α_1	α_2	q_{s1}	q_{s2}	q_n	π_{s1}	π_{s2}	π_n	Q	Π
0	-	-	-	1.43	-	-	3163.3	14.3	31632.7
1	-	6.25	-	-	7812.5	-	-	62.5	78125
0.2*	-	2.5*	-	1.4*	3248.4*	-	3558.3*	16.1*	34962.8*
0.3*	0.2*	3.4*	2.4*	1.3*	3942.6*	4385.2	4693.4*	21.6*	44065.4*
a	b	c	N						
100	25	150	20						
α_1	α_2	q_{s1}	q_{s2}	q_n	π_{s1}	π_{s2}	π_n	Q	Π
0	-	-	-	0.71	-	-	1619.9	14.3	32398
1	-	3.85	-	-	4807.7	-	-	76.9	96153.9
0.1*	-	1.2*	-	0.7*	1716.1*	-	1518.1*	15.2*	34171.3*
0.15*	0.1*	1.8*	1.2*	0.7*	1811.6*	1937.3*	2013.0*	18.0*	39504.3*
a	b	c	N						
100	25	150	100						
α_1	α_2	q_{s1}	q_{s2}	q_n	π_{s1}	π_{s2}	π_n	Q	Π
0	-	-	-	0.14	-	-	330.1	14.3	33010.2
1	-	0.94	-	-	1179.2	-	-	94.3	117924.5
0.03*	-	0.37*	-	0.14*	333.9*	-	342.5*	14.86	34219.7*
0.03*	0.02*	0.36*	0.24*	0.14*	337.7*	343.2*	346.1*	15.03*	34583.0*

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