The Case of two Self-Enforcing International Agreements for Environmental Protection

Dritan Osmani [a b * †], Richard S.J. Tol [b c d]

[a] International Max Planck Research School on Earth System Modelling (IMPRS-ESM)

[b] Research Unit Sustainability and Global Change, Hamburg University and Center for Marine and Atmospheric Science, Hamburg, Germany

[c] Institute for Environmental Studies, Vrije Universiteit, Amsterdam, The Netherlands

[d] Department of Engineering and Public Policy, Carnegie Mellon University, Pittsburgh, PA, USA

Revised Version, August 2006

Working Paper FNU 82[1]

Abstract

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. Extending 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 work far better than one self-enforcing IEA in terms of both welfare

*Corresponding author: Research Unit Sustainability and Global Change, Hamburg University and Center for Atmospheric Science, Bundesstrasse 55 (Pavillion Room 31), 20146 Hamburg, Germany +49 40 42838 6597 (voice) +49 40 42838 7009 (fax) dritan.osmani@zmaw.de

†We would like to thank Stefan Napel for his nice commnets and suggestions.

[1]This paper is extended further to the case of asymmetric countries in FNU Working Paper 187.

and environmental equality

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

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 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 the 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 captures 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 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 from coalition, a country assumes that all other countries remain in the

coalition (this is a consequence of the 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.

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 coalition 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 the 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 the emissions level based on the reaction functions of non-participants.

Ecchia/Mariotti (1998) distinguish two problems in the 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. The authors demonstrate that if the idea of farsightedness is placed into the model, the likelihood of larger coalition increases.

Considering asymmetric countries, *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 traded goods that are linked to environmental problems. He explains that if the public good agreement is linked to a club agreement, such as a trade agreement, the membership in IEAs can be raised. 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 is fund 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 have 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 (1998a), Finus/Rundshagen (1998b) 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 by 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 actually 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 Barrett's model of 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 an 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's 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 a large number of countries only when the difference between fullcooperative 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 makes some important assumptions which are:

- all countries are identical,
- each country's net benefit function is known and known to be known etc. 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,
- costs 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 *fullcooperative 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, $\gamma = c/b$.

The 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

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 $Q_n = (1 - \alpha)N q_n$. 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:

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

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

The solution is:

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

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

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

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

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

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

If first inequality 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 raise 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.*

We introduce an example in order to make this 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 stability conditions are satisfied for $\alpha = 0.5$.

The example indicates how one can find the number of countries that can form a self-enforcing IEA which is αN. A very simple algorithm for finding α (i = number of signatories) can be:

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

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

```
for  i = 1  to  N
α = i/N
if  [π_s(α) ≥ π_n(α − 1/N) ∧ π_n(α) ≥ π_s(α + 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*.

$\max \alpha$

$$s.t \quad [\pi_s(\alpha) \geq \pi_n(\alpha - 1/N) \wedge \pi_n(\alpha) \geq \pi_s(\alpha + 1/N)] \tag{12}$$

The problem can be formulated as of minimization one[2].

3 Two self-enforcing IEA

In the case of two self-enforcing agreements we have two coalition of signatories; the first coalition (C_{s_1}) with $\alpha_1 N$ countries, and the second one (C_{s_2}) with $\alpha_2 N$ countries, and $(1 - \alpha_1 - \alpha_2)N$ nonsignatories (C_n). Firstly the coalition of signatories (C_{s_1}) (*Stackelberg leader*[3]) and the second

[2] αN usually will not be an integer number, but we round down, then find $\alpha_{new} = rounddown(\alpha N)/N$. Using Matlab Optimization Toolbox, minimization proved to be 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.

[3] Note that this sequential game can be easily changed by taking as Stackelberg leader C_{s_2}. Or by taking both of C_{s_1} and C_{s_2} as Stackelbergs leaders playing a simultaneous Nash-Cournot equilibrium between each-other.

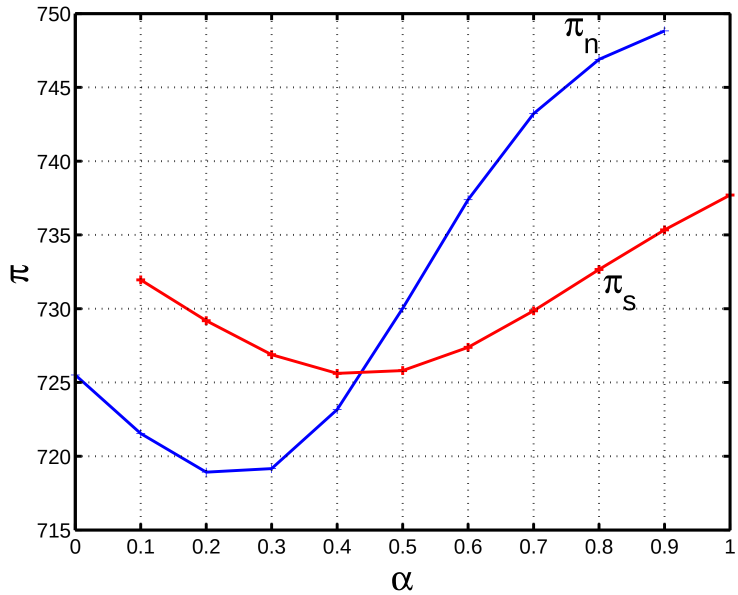

Figure 1: Stability analysis of IEA

coalition of signatories (C_{s_2}) (*first Stackelberg follower*) 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 (*second Stackelberg followers*) maximizes its own net benefit by taking the abatement level of signatories coalition and other nonsignatories as given. Let Q_{s_1} be the total abatement of C_{s_1}, q_{s_1} be the single signatory abatement of C_{s_1}; let Q_{s_2} be the total abatement of C_{s_2}, q_{s_2} be the single signatory abatement of C_{s_2}; 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 $Q_{s_1} = \alpha_1 q_{s_1} N$, $Q_{s_2} = \alpha_2 q_{s_2} N$, $Q_n = (1 - \alpha_1 - \alpha_2) q_n N$.

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,

$Q_s = Q_{s_1} + Q_{s_2}$,

Q_{s_1}: total abatement level of first coalition,

Q_{s_2}: total abatement level of second coalition,

π_{s_1} : the profit of a country of first coalition of signatories,

$\Pi_{s_1} = \sum_1^{\alpha_1 N} \pi_i = \alpha_1 N \pi_{s_1}$ the total profit of first coalition of signatories,

q_{s_1}: the abatement level of a country of first coalition of signatories,

π_{s_2}: the profit of a country of first coalition of signatories,

$\Pi_{s_2} = \sum_1^{\alpha_2 N} \pi_i = \alpha_2 N \pi_{s_2}$ the total profit of second coalition of signatories,

q_{s_2}: 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.

The profit function of country i for the first, the second coalition of signatories and for nonsignatories is given by:

$\pi_{s_1} = b(aQ - Q^2/2)/N - cq_{s_1}^2/2$

$\pi_{s_2} = b(aQ - Q^2/2)/N - cq_{s_2}^2/2$

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

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

$$Q_n(\alpha_1, \alpha_2, Q_{s_1}, Q_{s_2}) = (1-\alpha)(a - Q_s)/(\gamma + 1 - \alpha) \tag{13}$$

Note that above we have $Q_n = f(\alpha_1, \alpha_2, Q_{s_1}, Q_{s_2})$, so the Q_n is not independent variable anymore. In order to find $Q_{s_2} = f(\alpha_1, \alpha_2, Q_{s_1})$, we need to solve the following optimization problem:

$$\max \Pi_{s_2}(Q_{s_2}) \quad s.t \quad (13) \tag{14}$$

As $\Pi_{s_2} = b(aQ - Q^2/2) - cQ_{s_2}^2/(2\alpha_2 N)$, the above optimization problem can be transformed to a nonconstrained one by replacing the equation (13) to objective function Π_{s_2}. As $d^2\Pi_{s_2}/dQ_{s_2}^2 < 0$ then by $d\Pi_{s_2}/dQ_{s_2} = 0 \Rightarrow Q_{s_2} = f(\alpha_1, \alpha_2, Q_{s_1})$. We do not write explicitly $Q_{s_2} = f(\alpha_1, \alpha_2, Q_{s_1})$ because of the lengthy analytical formula, but note that Q_{s_2} is expressed by means of other variables. In order to find $Q_{s_1} = f(\alpha_1, \alpha_2)$, we need to solve the similar optimization problem:

$$\max \Pi_{s_1}(Q_{s_1})$$

$$s.t \quad Q_n(\alpha_1, \alpha_2, Q_{s_1}) = (1-\alpha)(a - Q_s)/(\gamma + 1 - \alpha), \quad Q_{s_2} = f(Q_{s_1}) \tag{15}$$

As $\Pi_{s_1} = b(aQ - Q^2/2) - cQ_{s_1}^2/(2\alpha_1 N)$ than the above optimization problem can be transformed to a nonconstrained one by replacing the constrains to objective function Π_{s_1}. As $d^2\Pi_{s_1}/dQ_{s_1}^2 < 0$ then by $d\Pi_{s_1}/dQ_{s_1} = 0 \Rightarrow Q_{s_1} = f_{s_1}(\alpha_1, \alpha_2)$. As we have $Q_{s_1} = f_{s_1}(\alpha_1, \alpha_2)$, we replace it in $Q_{s_2} = f(Q_{s_1}, \alpha_1, \alpha_2)$ and have $Q_{s_2} = f_{s_2}(\alpha_1, \alpha_2)$. We replace both of them in (13) then we get $Q_n = f_n(\alpha_1, \alpha_2)$. Finally we have all $\pi_{s_2}, \Pi_{s_2}, \pi_{s_1}, \Pi_{s_1}, \pi_n, \Pi_n$ 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 conditions of one self-enforcing agreements to be satisfied between three groups of countries, the coalition one of signatories, (C_{s_1}), the coalition two of signatories, (C_{s_2}) and the nonsignatories, (C_n) in order to have *intercoalition stability*. ***The intercoalition stability*** means a stable relations between C_{s_2} and C_n, C_{s_1} and C_{s_2} as well as C_{s_1} and C_{s_2}.

Definition 3.1 We have **intercoalition stability** if and only if the following conditions (16),(17) and (18) are satisfied:

$$[\pi_{s_1}(\alpha_1, \alpha_2) \geq \pi_n(\alpha_1 - 1/N, \alpha_2) \wedge \pi_n(\alpha_1, \alpha_2) \geq \pi_{s_1}(\alpha_1 + 1/N, \alpha_2)] \tag{16}$$

$$[\pi_{s_2}(\alpha_1, \alpha_2) \geq \pi_n(\alpha_1, \alpha_2 - 1/N) \wedge \pi_n(\alpha_1, \alpha_2) \geq \pi_{s_1}(\alpha_1, \alpha_2 + 1/N)] \tag{17}$$

$$[\pi_{s_2}(\alpha_1, \alpha_2) \geq \pi_{s_1}(\alpha_1 + 1/N, \alpha_2 - 1/N) \wedge \pi_{s_1}(\alpha_1, \alpha_2) \geq \pi_{s_2}(\alpha_1 - 1/N, \alpha_2 + 1/N)] \tag{18}$$

It is important to note that *conditions (16),(17) and (18) together describe all possible changes* *among C_{s_1},C_{s_2} 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

$$[\pi_{s_1}(\alpha_1,\alpha_2) \geq \pi_n(\alpha_1 - 1/N, \alpha_2) \wedge \pi_n(\alpha_1,\alpha_2) \geq \pi_{s_1}(\alpha_1 + 1/N, \alpha_2)]$$

$$[\pi_{s_2}(\alpha_1,\alpha_2) \geq \pi_n(\alpha_1, \alpha_2 - 1/N) \wedge \pi_n(\alpha_1,\alpha_2) \geq \pi_{s_1}(\alpha_1, \alpha_2 + 1/N)]$$

$$[\pi_{s_2}(\alpha_1,\alpha_2) \geq \pi_{s_1}(\alpha_1 + 1/N, \alpha_2 - 1/N) \wedge \pi_{s_1}(\alpha_1,\alpha_2) \geq \pi_{s_2}(\alpha_1 - 1/N, \alpha_2 + 1/N)]$$

The constrains of above optimization problem are just the conditions (16),(17) and (18). We use the MATLAB Optimization Toolbox to solve the above optimization problem.

As one would expect the starting point and rounding are cumbersome[4].

Let introduce an example in order to illustrate our results. The parameter values are: $a = 100, b = 1.5, c = 0.25, N = 10$. The solution of our nonlinear optimization problem is, $\alpha_1 = 0.54$, $\alpha_2 = 0.22$. After we round down, we have $\alpha_1 = 0.5$, $\alpha_2 = 0.2$, note that after rounding down our constrains (16), (17) and (18) are still satisfied. As $q_{s_1},\ q_{s_2},\ q_n,\ \pi_{s_1},\ \pi_{s_2},\ \pi_n$ 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 $\alpha \in [0,1]$, but the α's that we are interested in, satisfy that αN is a natural number.

[4]The starting point is slightly problematic but with the help of algorithm in Table (2) we can find a starting point for α_1. As the interval of α_2 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 $\alpha_1^{new} = rounddown(\alpha_1 N)/N$ and $\alpha_2^{new} = rounddown(\alpha_2 N)/N$. After rounding down we check if six constrains are still satisfied (for one self-enforcing IEA there were only two constrains).

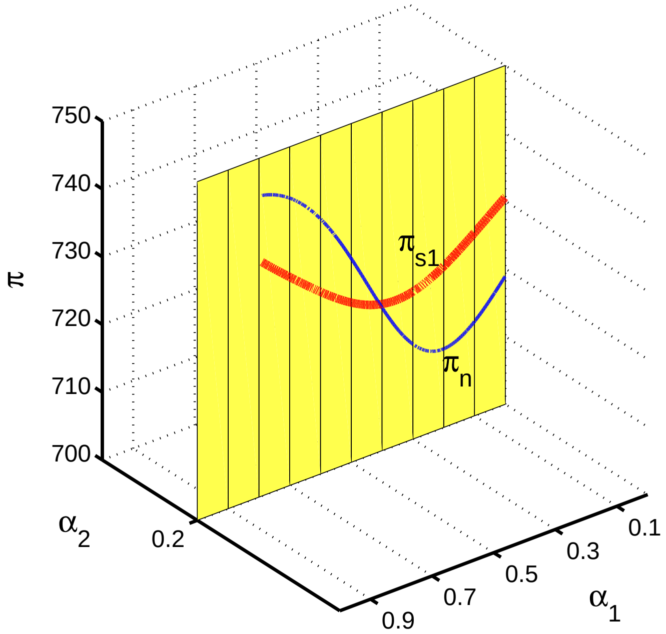

Figure 2: Graphical analysis of stability between first coalition and nonsignatories

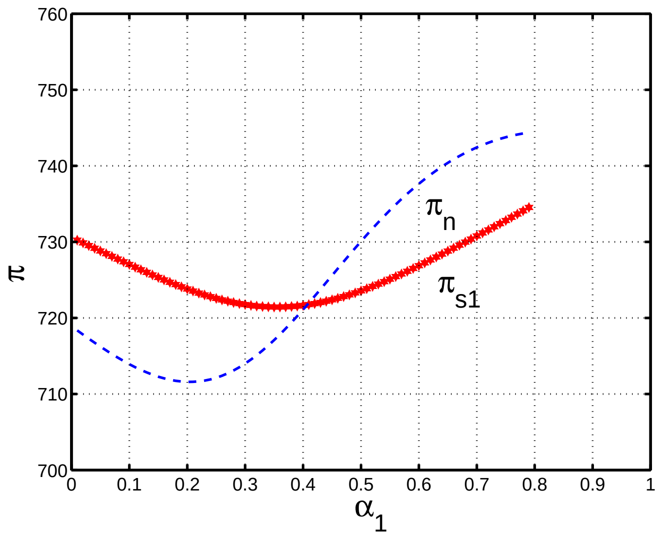

Figure 3: Graphical analysis of stability between first coalition and nonsignatories

In Figure (2) we introduce graphically the stable relation between π_{s_1}, the profit of a country of first coalition and π_n, the profit of a single nonsignatory (for $\alpha_1 = 0.5$ the relation is stable).

In the plane $\alpha_2 = 0.2$ (the size of second coalition is constant) parallel to YZ-plane, the π_{s_1}, π_n are function of only α_1. In Figure (3) we see the plane $\alpha_2 = 0.2$ only in 2 dimension. Note that if country changes its position from C_{s_1} to C_n or in the opposite direction he reduces his profit. This means the condition (16) is satisfied (any change of $\alpha_1 = 0.5$ with $1/N = 0.1$ reduces π_{s_1} and π_n).

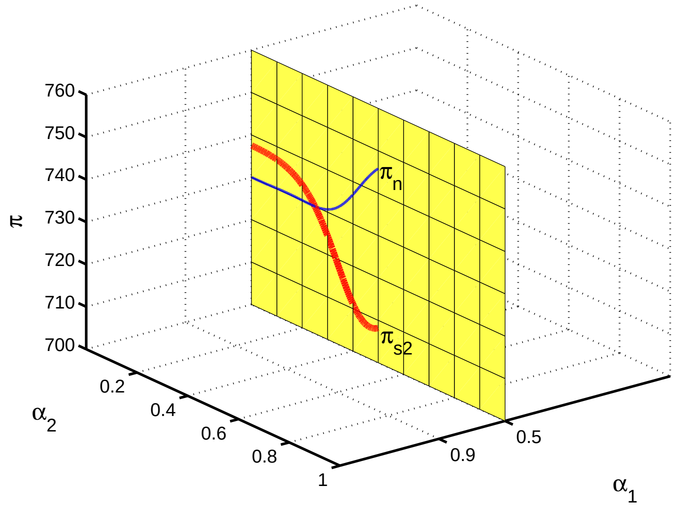

Figure 4: Graphical analysis of stability between second coalition and nonsignatories

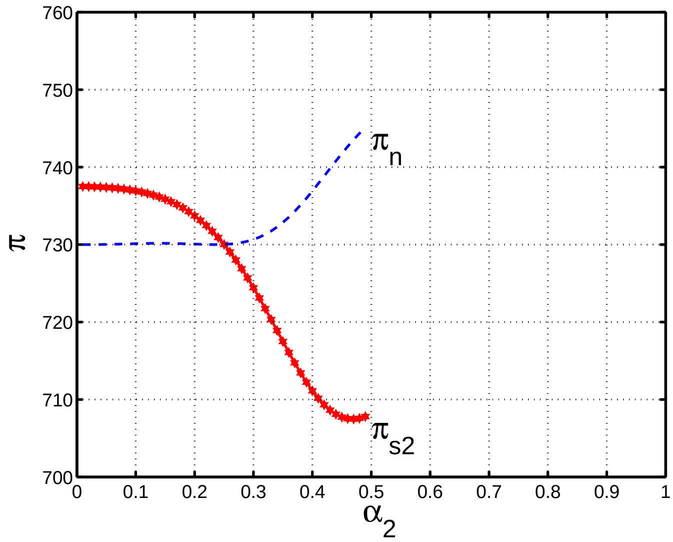

Figure 5: Graphical analysis of stability between second coalition and nonsignatories

The Figures (4) and (5) are similar to Figures (2) and (3) but we introduce graphically the stable relation between π_{s_2}, the profit of a country of first coalition and π_n, the profit of a single nonsignatory (for $\alpha_2 = 0.2$ the relation is stable). The graphical relation is shown in the plane $\alpha_2 = 0.5$ (the size of first coalition is constant) parallel to XZ-plane. This means the condition (16) is satisfied (any change of $\alpha_2 = 0.2$ with $1/N = 0.1$ reduces π_{s_2} and π_n).

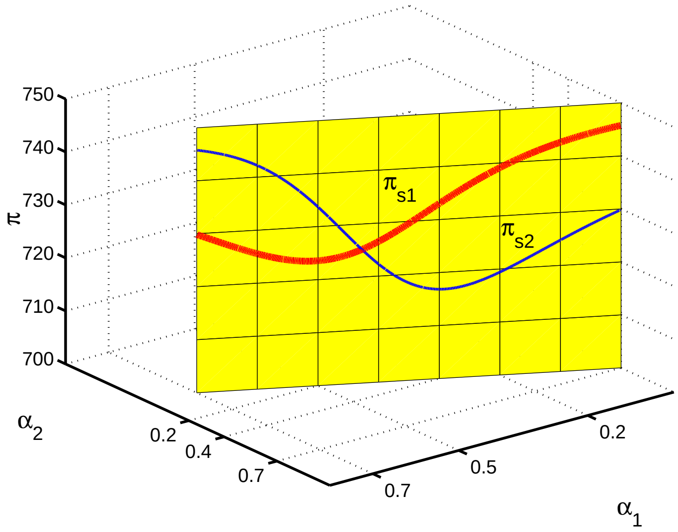

Figure 6: Graphical analysis of stability between first and second coalition

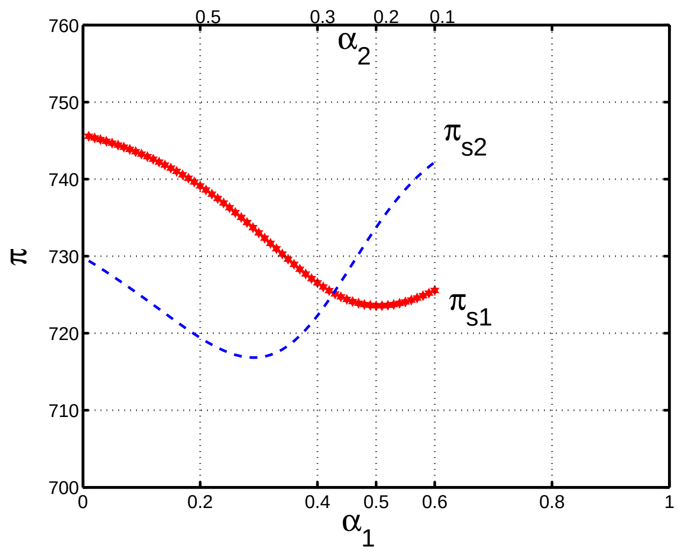

Figure 7: Graphical analysis of stability between first and second coalition

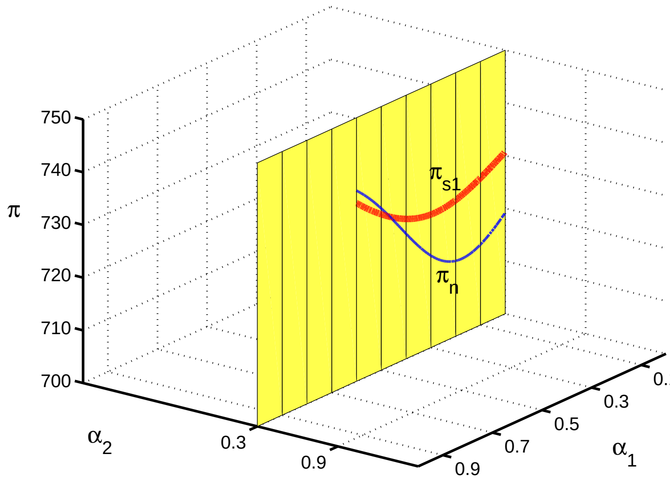

Figure 8: Graphical analysis of stability between first coalition and nonsignatories

In Figure (6) we present graphically the stable relation between π_{s_1}, the profit of a country of first coalition and π_{s_2}, the profit of a country of second coalition (for $\alpha_1 = 0.5, \alpha_2 = 0.2$ the relation is stable). In the plane $\alpha_1 + \alpha_2 = 0.7$ (the number of nonsignatories is constant) parallel to Z-axes,the π_{s_1}, π_{s_2} are function of only α_1 or α_2(as $\alpha_1 + \alpha_2 = 0.7 = constant$). We 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 Figure (7) we see the plane $\alpha_1 + \alpha_2 = 0.7$ in 2 dimension. In the upper part of the Figure (7) we put the values of α_2 too. Note that a country that changes its position from C_{s_1} to C_{s_2} or in the opposite direction reduces his profit (any change of $\alpha_1 = 0.5, \alpha_2 = 0.2$, simultaneously with $1/N = 0.1$ reduces π_{s_1} and π_{s_2}).

It is clear that *all introduced pictures holds simultaneously.*

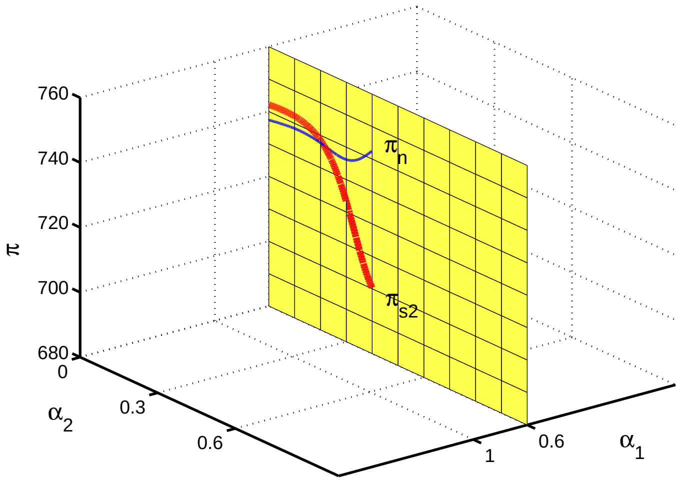

Figure 9: Graphical analysis of stability between second coalition and nonsignatories

In Figure (8) we introduce again the relation between π_{s_1}, the profit of a country of first coalition and π_n, the profit of a single nonsignatory, but now for $\alpha_2 = 0.3$. The first coalition is still stable, but the Figures (4) and (5) point out that the second coalition becomes unstable for $\alpha_2 = 0.3$.

In Figure (9) we introduce the relation between π_{s_2}, the profit of a country of second coalition and π_n, the profit of a single nonsignatory, but now for $\alpha_1 = 0.6$ (note that for $\alpha_1 = 0.4$ the same result holds). The second coalition is still stable, but the Figures (2) and (3) point out that the first coalition becomes unstable for $\alpha_1 = 0.6$.

So any change of position of a country (among C_{s_1}, C_{s_2} and C_n) breaks down the *intercoalition stablity*.

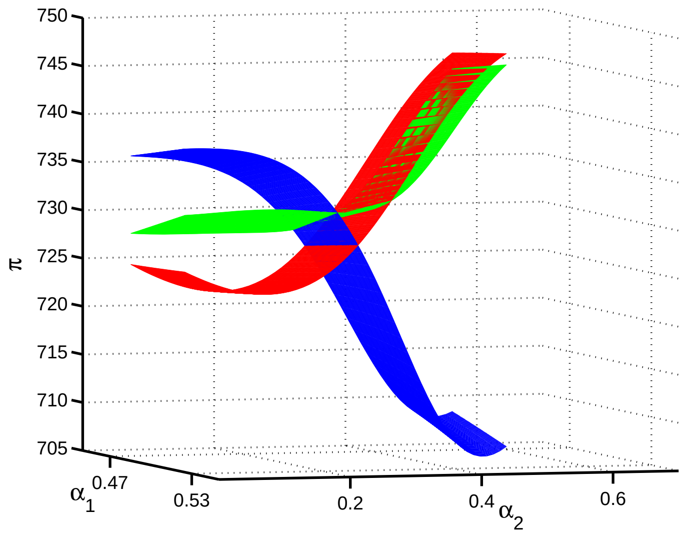

Figure 10: Graphical analysis of stability between first coalition, second coalition and nonsignatories. π_{s_1} is red, π_{s_2} is blue and π_n is green.

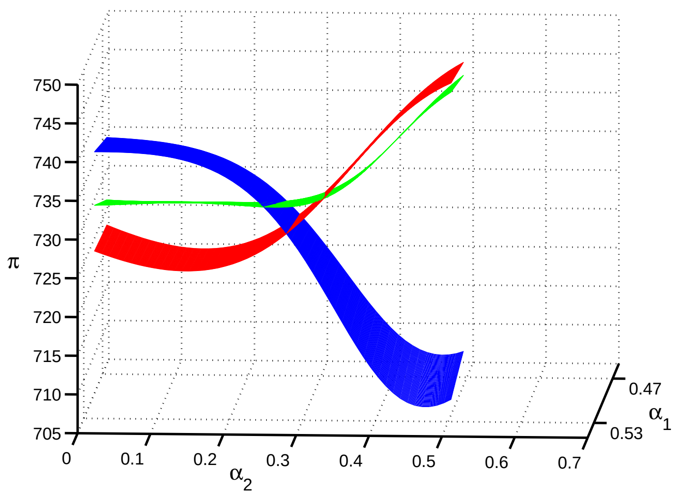

Figure 11: Graphical analysis of stability between first coalition, second coalition and nonsignatories. π_{s_1} is red, π_{s_2} is blue and π_n is green.

In Figures (10) and (11) we just present two 3-dimensional graphs (the same graph form different view) of the relation between π_{s_1}, the profit of a country of first coalition, π_{s_2}, the profit of a country of first coalition and π_n, the profit of a single nonsignatory.

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:

$\Pi_{\alpha=0} = N\pi_n = \Pi_n$: the global profit, no coalition.

$\Pi_{\alpha=1} = N\pi_s = \Pi_s$: the global profit, grand coalition.

$\Pi_{\alpha_1} = \alpha_1 N\pi_{s_1} + (1-\alpha_1)N\pi_n = \Pi_{s_1} + \Pi_n$: the global profit, one coalition.

$\Pi_{(\alpha_1,\alpha_2)} = \alpha_1 N\pi_{s1} + \alpha_2 N\pi_{s2} + (1-\alpha_1-\alpha_2)N\pi_n = \Pi_{s1} + \Pi_{s2} + \Pi_n$: the global profit, two coalitions.

$Q_{\alpha=0} = Nq_n = Q_n$: the global abatement, no coalition.

$Q_{\alpha=1} = Nq_s = Q_s$: the global abatement, grand coalition.

$Q_{\alpha_1} = \alpha_1 Nq_{s1} + (1-\alpha_1)Nq_n = Q_{s1} + Q_n$: the global abatement, one coalition.

$Q_{(\alpha_1,\alpha_2)} = \alpha_1 Nq_{s1} + \alpha_2 Nq_{s2} + (1-\alpha_1-\alpha_2)Nq_n = Q_{s1} + Q_{s2} + Q_n$: the global abatement, two coalitions.

the fraction of fully cooperative welfare

$(\Pi_{\alpha_1} - \Pi_{\alpha=0})/(\Pi_{\alpha=1} - \Pi_{\alpha=0})$: for one coalition.

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

the fraction of fully cooperative abatement

$(Q_{\alpha_1} - Q_{\alpha=0})/(Q_{\alpha=1} - Q_{\alpha=0})$: for one coalition.

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

α_1: the fraction of countries in one coalition.

$(\alpha_1 + \alpha_2)$: the fraction of countries in two coalitions.

As we know form simulation that *the important parameters are* γ *and* N we introduce results by varying these parameters.

The Figures (12), (13), and (14) use the data from Tables (3), (14) 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 (15), (16), and (17) 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 main 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.

We find that adding a second coalition improves welfare and environmental quality when the number of players is small and cost of pollution is high. That is, multiple coalitions help with continental environmental problems, but not with global environmental problems. At first sight, this conclusion is counterintuitive. Surely, bigger problems require a larger number of coalitions? However, the intuition behind the result follows from Barrett's (1994) analysis. Barrett (1994) shows that stable coalitions are either small or irrelevant. "He also shows" / "Here we extend that result to show" that the share of players that cooperate grows if the number of players fall.

Consider a serious environmental problem with a large number of players. According to Barrett

(1994), only a small coalition would form. If we take the cooperative players out of the population, we are left with a still large number of players with a still serious environmental problem. In this subpopulation, only a small coalition would form. So, a second coalition does not add much. In fact, the additional constraint of inter-coalition stability more than offsets the gains of cooperation in the second coalition.

Now consider a serious environmental problem with a medium number of players. According to Barrett (1994), only a small coalition would form. If we take these players out of the population, we are left with smaller number of players with a considerable environmental problem. In this subpopulation, a larger coalition would form. That is, a second coalition does improve welfare and environmental quality. In this case, the inter-coalition stability constraint reduces but not eliminates these gains.

If this intuition is correct, one may suspect that an environmental problem with a large number of players requires a high number of coalitions – and that only the "last" coalition will contribute to gains in welfare and environmental quality. However, with every additional coalition, the number of inter-coalition stability constraints grows combinatorially. This would offset these gains, and limits the number of coalitions that can form. This problem is deferred to future research.

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

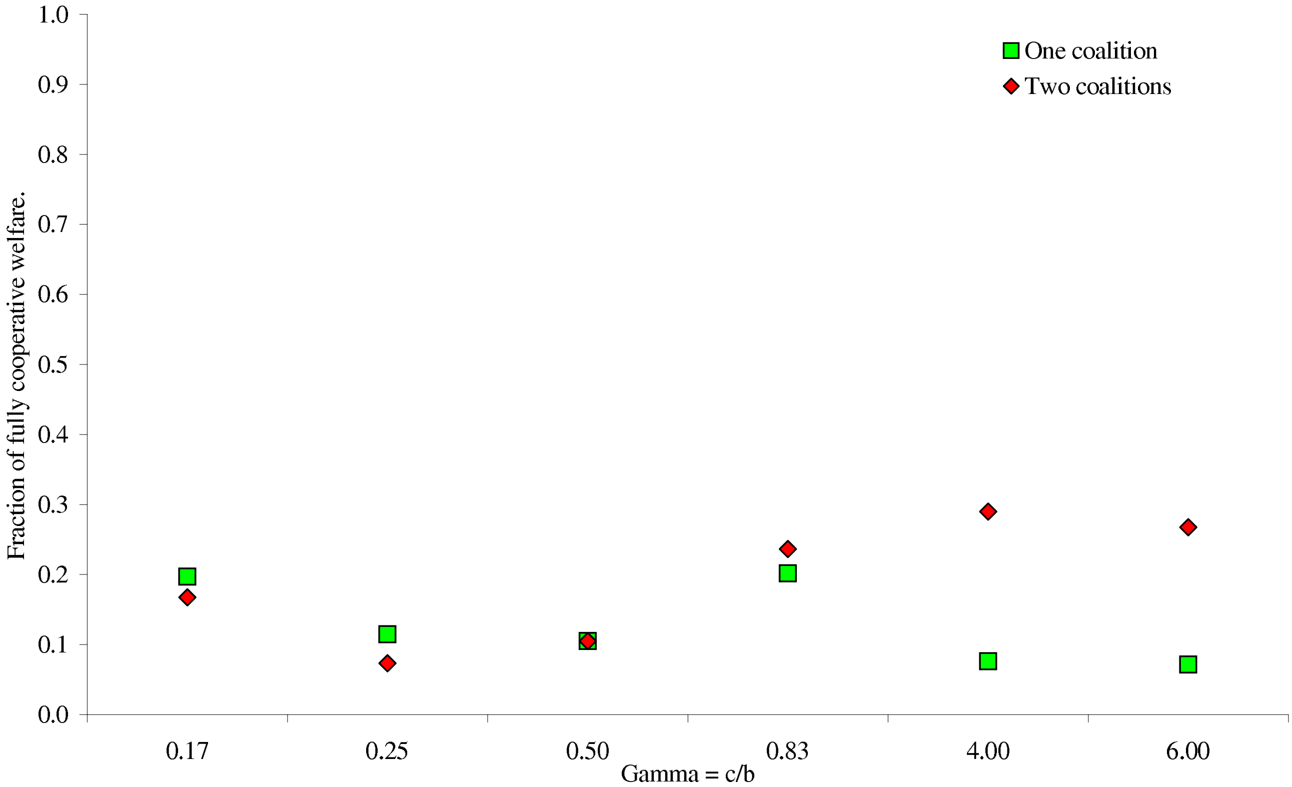

Figure 12: Profit Π as function of γ $(= c/b)$ for one and two self-enforcing IEA.

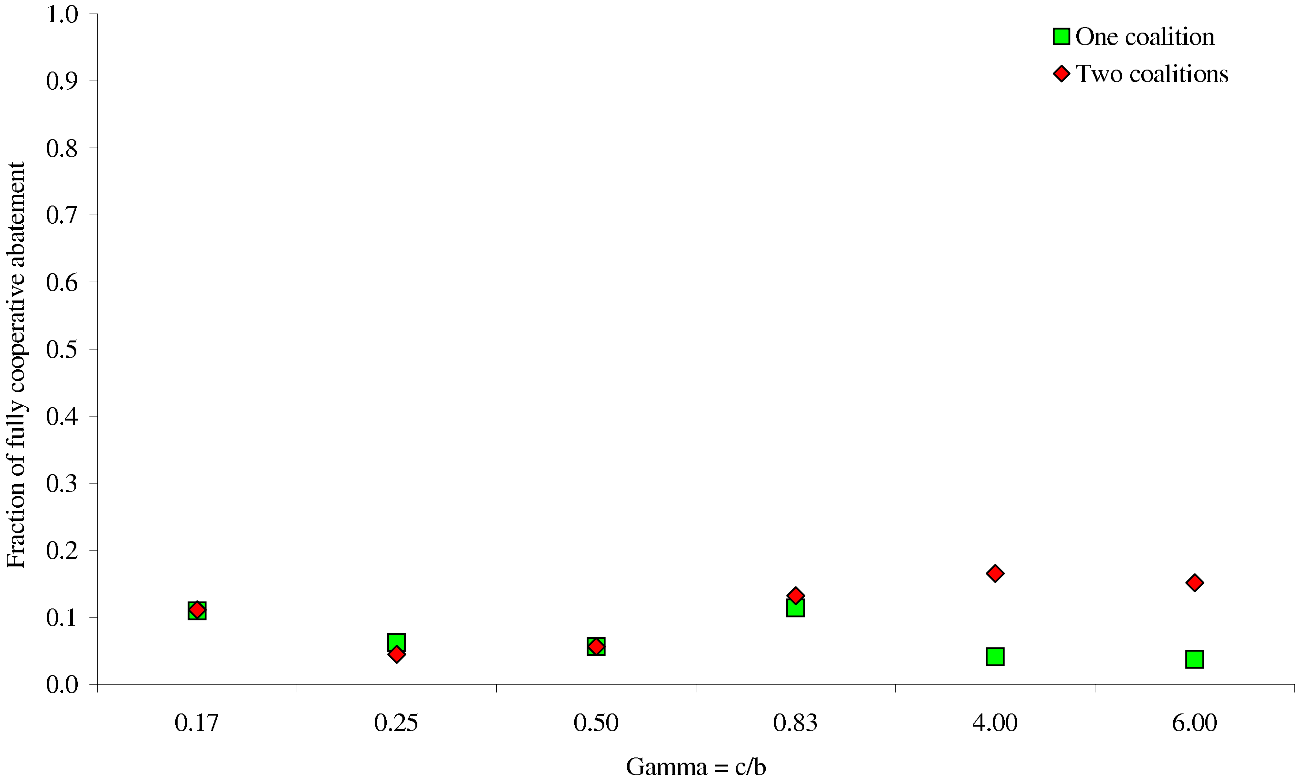

Figure 13: Abatement Q as function of γ ($= c/b$) for one and two self-enforcing IEA.

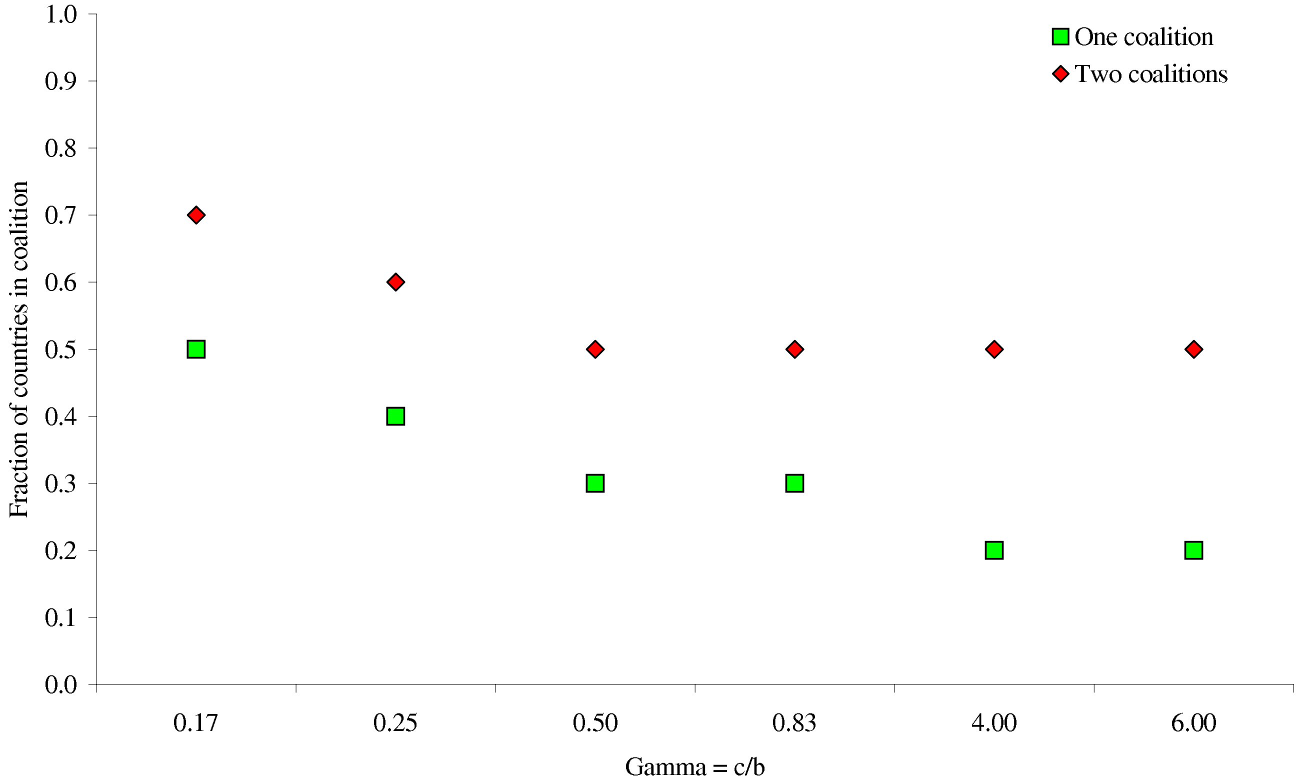

Figure 14: Coalition size as function of γ ($= c/b$) for one and two self-enforcing IEA.

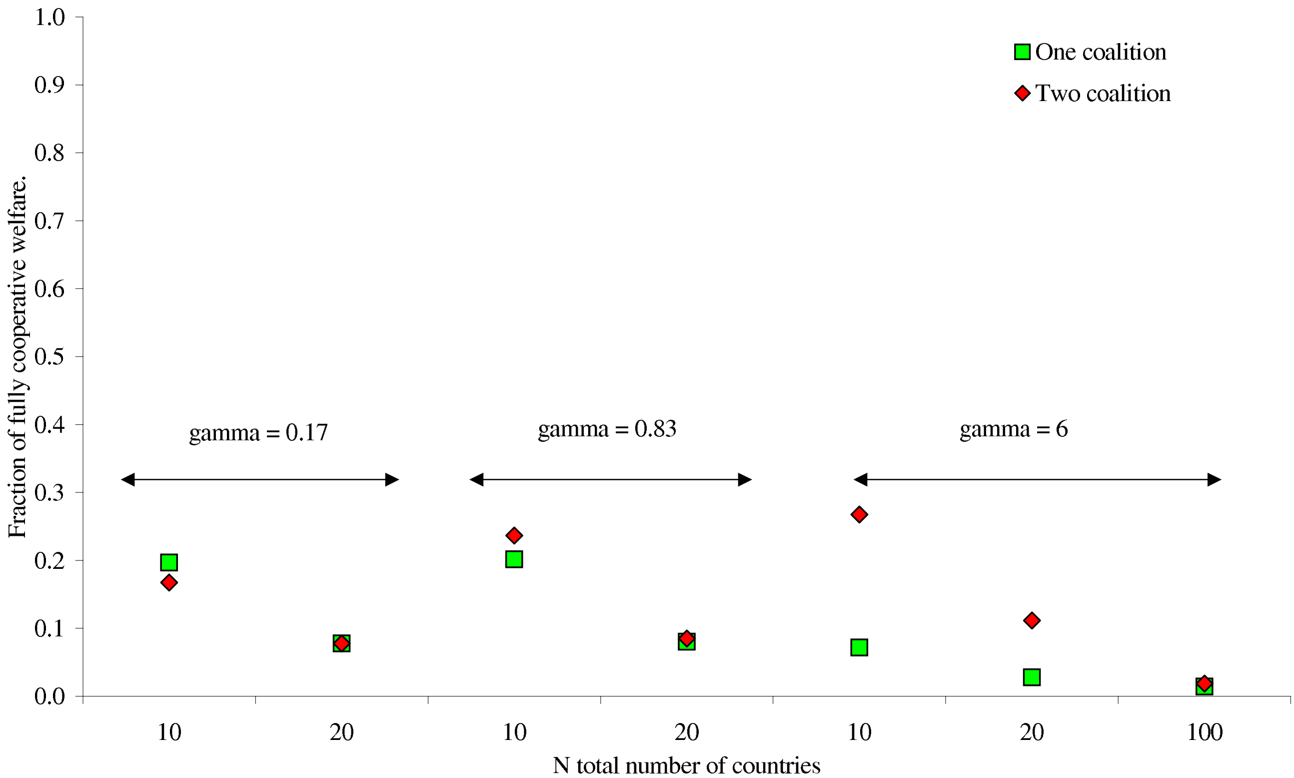

Figure 15: Profit Π as function of N and γ for one and two self-enforcing IEA.

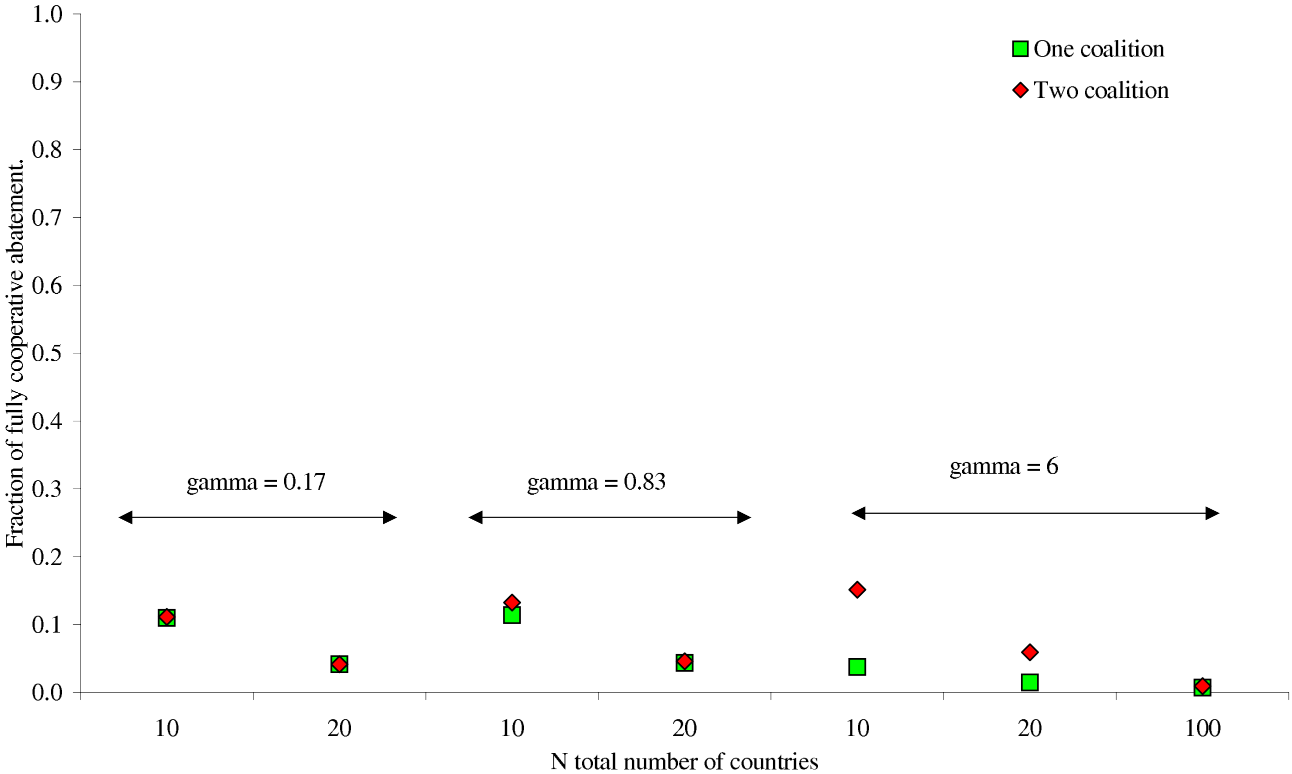

Figure 16: Abatement Q as function of N and γ for one and two self-enforcing IEA.

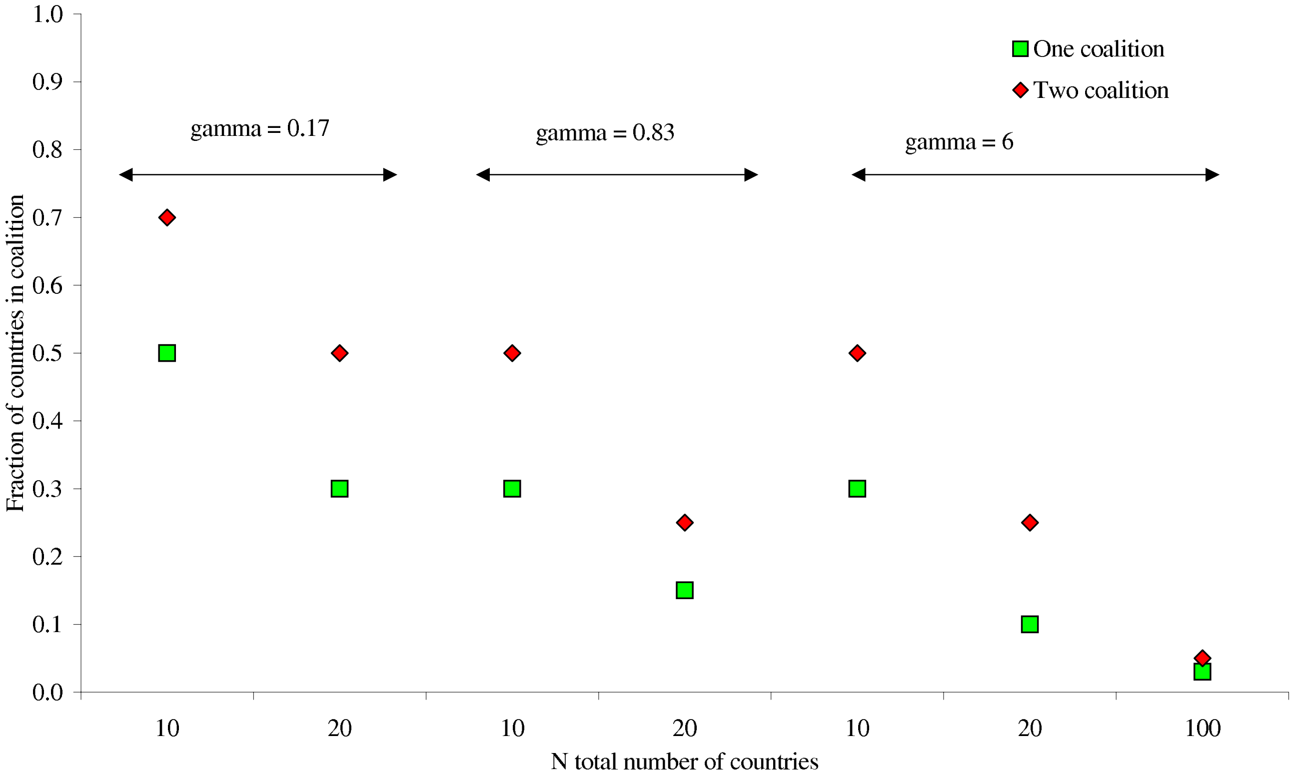

Figure 17: Coalition size as function of N and γ for one and two self-enforcing IEA.

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* ***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* $\boldsymbol{N}$.

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*

References

[1] Asheim, B.G, Froyn, B.C, Hovi. J, Menz, C.F. (2006) Regional versus Global Cooperation for Climate Control *Journal of Environmental Economics and Management 51,* 92-109.

[2] D'Aspremont, C.A, Jacquemin, J, Gabszeweiz, J, Weymark, J.A. (1983) On the Stability of Collusive Price Leadership *Canadian Journal of Economics 16,* 17-25.

[3] Barrett, S. (1992) On the Nature and Significance of International Environmental Agreements *Pethig, R. ed., Conflicts and Cooperation in Managing Environmental Resources, Springer-Verlag Berlin,* 18-33.

[4] Barrett, S. (1992) Convention on Climate Change: Economic Aspects of Negotiations *OECD, Paris.*

[5] Barrett, S. (1994a) Self-Enforcing International Environmental Agreements *Oxford Economic Papers 46,* 878-894.

[6] Reprinted in: Governing the Global Environment, (2003) *Carraro, C. ed., Edward Elgar, Cheltenham, UK,* 199-215.

[7] Barrett, S. (1994b) The Biodiversity Supergame. *Environmental and Resource Economics 4,* 111-122.

[8] Barrett, S. (1997a) Heterogeneous International Environmental Agreements *Carraro, C. ed., International Environmental Agreemens: Strategic Policy Issues, Edward Elgar, Cheltenham, UK,* 9-25.

[9] Barrett, S. (1997b) The Strategy of Trade Sanctions in International Environmental Agreements. *Resource and Energy Economics, 19,* 345-361.

[10] Bloch, F. (1995) Endogenous structures of Association in Oligopolies. *Rand J. Econ. 26,* 537-556.

[11] Bloch, F. (1996) Sequential Formation of Coalitions with Fixed Payoff Division and Externalities. *Games Econ. Behav. 14,* 90-123.

[12] Bloch, F. (1997) Noncooperative models of coalition formation in games with spillovers. *Carraro, C, Siniscalco, D. eds., New Direction in Economic Theory of Environment, Cambridge University Press, Cambridge.*

[13] Botteon, M, Carraro, C. (1997) Burden-Sharing and Coalition Stability in Environmental Negotations with Asymmetric Countries *Carraro, C. ed., International Environmental Agreemens: Strategic Policy Issues, Edward Elgar, Cheltenham, UK,* 26-55.

[14] Botteon, M, Carraro, C. (2001) Environmental Coalition with Heteregoneous Countries: Burden-Sharing and Carbon Leakage *Alistair, A. ed., Oxford University Press,* 38-66.

[15] Breton, M, Soubeyran, A. (1998) The Interaction between International Environmental and Trade Policies. *Carraro, C. ed., International Environmental Agreemens: Strategic Policy Issues, Edward Elgar, Cheltenham, UK,* 126-149.

[16] Carraro, C. (1997) The Structure of International Environmental Agreements *Paper presented at the FEEM/IPCC/Stanford EMF Conference on "International Environmental Agreements on Climate Change", Venice,* 309-328.

[17] Carraro, C. (2000) The Economics of Coalition Formation *Gupta, J, Grubb, M. eds., Climate Change and European Leadership Kluwer Academic Publishers* 135-156.

[18] Carraro, C, Eyckmans, J, Finus, M. (2005) Optimal Transfers and Participation Decisions in International Environmental Agreements *Working Papers FEEM 50.*

[19] Carraro, C, Marchiori, C, Oreffice, S. (2001) Endogenous Minimum Participation in International Environmental Treaties. *Mimeo, FEEM, Milano.*

[20] Carraro, C, Siniscalco, D. (1991) Strategies for the International Protection of the Environment *Working Papers FEEM.*

[21] Carraro, C, Siniscalco, D. (1993) Strategies for the International Protection of the Environment *J. Public Econ. 52,* 309-328.

[22] Carraro, C, Siniscalco, D. (1998) International Environmental Agreements: Incentives and Political Economy *European Economic Review 42,* 561-572.

[23] Chander, P, Tulkens, H. (1995) A Core-Theoretic Solution for the Design of Cooperative Agreemnets on Transfrontier Pollution *International Tax and Public Finance 2,* 279-293.

[24] Chander, P, Tulkens, H. (1997) The Core of an Economy with Multilateral Environmental Externalities *International Journal of Game Theory,* 379-401.

[25] Diamantoudi, E, Sartzetakis, E. (2001) Stable International Environmental Agreements: An Analytical Approach *University of Aarhus, Working Papers 10.*

[26] Ecchia, G, Mariotti, M. (1998) Coalitions Formation in International Environmental Agreements and Role of Institutions. *European Economic Review 42,* 573-582.

[27] Endres, A. (1996) Designing a Greenhouse Treaty: Some Economic Problems. *Eide, E, van den Bergh. R. eds., Law and Economics of the Environment. Juridisk Forlag, Oslo,* 201-224.

[28] Endres, A. (1997) Negotiating a Climate Convention - The Role of Prices and Quantities. *International Review of Law and Economics 17,* 201-224.

[29] Endres, A, Finus, M. (2002) Quotas May Beat Taxes in a Global Emission Game. *Tax and Public Finance 9,* 687-707.

[30] Finus, M. (2003) Stability and Design of International Environmental Agreements: The Case of Global and Transboundary Pollution *Folmer, H. and T. Tietenberg eds., International Yearbook of Environmental and Resource Economics, 2003/4, Edward Elgar, Cheltenham, UK,* 82-158.

[31] Finus, M. (2004) Modesty pays sometimes *Working Papers FEEM 68.*

[32] Finus, M. Rundshagen, B. (1998a) Toward a Positive Theory of Coalition Formation and Endogenous Instrumental Choice in Global Pollution Control. *Public Choice 96,* 145-186.

[33] Finus, M. Rundshagen, B. (1998b) Renegotiation- Proof Equilibria in a Global Emission Game when Players are Impatient *Environmental and Resource Economics 12,* 275-306.

[34] Finus, M, Rundshagen, B. (2003) Endogenous Coalition Formation in global Pollution Control: A Partition Function Approach. *Carraro, C. ed., Endogenous Formation of Economic Coalitions, Edward Elgar, Cheltenham, UK,* 199-243.

[35] Hoel, M, Schneider. K. (1997) Incentives to Participate in an International Environmental Agreement. *Environmental and Resource Economics 9* 153-170.

[36] Ioannidis. A, Papandreou. A, Sartzetakis. E. (2000) *International Environmental Agreements: a Literature Review Working Papers, GREEN.*

[37] Jeppesen, T, Andersen. P. (1998) Commitment and Fairness in Environmental Games. *Hanley, N, Folmer. H. eds., Game Theory and the Environment. Edward Elgar, Cheltenham, UK,* 65-83.

[38] Katsoulacos, Y. (1997) R & D Spillovers, Cooperation, Subsidies and International Agreements. *Carraro, C. ed., International Environmental Negotiations: Strategic Policy Issues. Edward Elgar, Cheltenham, UK,* 97-109.

[39] Petrakis. E, Xepapadeas. A. (1996) Environmental Consciousness and Moral Hazard in International Agreements to Protect the Environment. *Journal of Public Economics, 60* 95-110.

[40] Ray. D, Vohra, R. (1994) Equilibrium Binding Agreements. *unpublished manuscript Brown University.*

[41] Yi. S. S, Shin. H. (1995) Endogenous Formation of Coalitions in Oligopoly. *Dartmouth College Department of Economics WP No.95-2.*

[42] Yi. S. S. (1997) Stable Coalition Structures with Externalities. *Games and Economic Behavior, 20,* 201-237.

Working Papers

Research Unit Sustainability and Global Change

Hamburg University and Centre for Marine and Atmospheric Science

Osmani, D. and R.S.J. Tol (2005), The case of two self-enforcing international agreements for environmental protection, FNU-82 (submitted)

Schneider, U.A. and B.A. McCarl, (2005), Appraising Agricultural Greenhouse Gas Mitigation Potentials: Effects of Alternative Assumptions, FNU-81 (submitted)

Zandersen, M., M. Termansen, and F.S. Jensen, (2005), Valuing new forest sites over time: the case of afforestation and recreation in Denmark, FNU-80 (submitted)

Guillerminet, M.-L. and R.S.J. Tol (2005), Decision making under catastrophic risk and learning: the case of the possible collapse of the West Antarctic Ice Sheet, FNU-79 (submitted, Climatic Change)

Nicholls, R.J., R.S.J. Tol and A.T. Vafeidis (2005), Global estimates of the impact of a collapse of the West Antarctic Ice Sheet: An application of FUND, FNU-78 (submitted, Climatic Change)

Lonsdale, K., T.E. Downing, R.J. Nicholls, D. Parker, A.T. Vafeidis, R. Dawson and J.W. Hall (2005), Plausible responses to the threat of rapid sea-level rise for the Thames Estuary, FNU-77 (submitted, Climatic Change)

Poumadre, M., C. Mays, G. Pfeifle with A.T. Vafeidis (2005), Worst Case Scenario and Stakeholder Group Decision: A 5-6 Meter Sea Level Rise in the Rhone Delta, France, FNU-76 (submitted, Climatic Change)

Olsthoorn, A.A., P.E. van der Werff, L.M. Bouwer and D. Huitema (2005), Neo-Atlantis: Dutch Responses to Five Meter Sea Level Rise, FNU-75 (submitted, Climatic Change)

Toth, F.L. and E. Hizsnyik (2005), Managing the inconceivable: Participatory assessments of impacts and responses to extreme climate change, FNU-74 (submitted, Climatic Change)

Kasperson, R.E. M.T. Bohn and R. Goble (2005), Assessing the risks of a future rapid large sea level rise: A review, FNU-73 (submitted, Climatic Change)

Schleupner, C. (2005), Evaluation of coastal squeeze and beach reduction and its consequences for the Caribbean island Martinique, FNU-72 (submitted)

Schleupner, C. (2005), Spatial Analysis As Tool for Sensitivity Assessment of Sea Level Rise

Impacts on Martinique, FNU-71 (submitted)

Sesabo, J.K. and R.S.J. Tol (2005), Factors affecting Income Strategies among households in Tanzanian Coastal Villages: Implication for Development-Conservation Initiatives, FNU-70 (submitted)

Fisher, B.S., G. Jakeman, H.M. Pant, M. Schwoon. and R.S.J. Tol (2005), CHIMP: A Simple Population Model for Use in Integrated Assessment of Global Environmental Change, FNU-69 (Integrated Assessment Journal, 6 (3), 1-33)

Rehdanz, K. and R.S.J. Tol (2005), A No Cap But Trade Proposal for Greenhouse Gas Emission Reduction Targets for Brazil, China and India, FNU-68 (submitted, Climate Policy)

Zhou, Y. and R.S.J. Tol (2005), Water Use in Chinas Domestic, Industrial and Agricultural Sectors: An Empirical Analysis, FNU- 67 (Water Science and Technoloy: Water Supply, 5 (6), 85-93)

Rehdanz, K. (2005), Determinants of Residential Space Heating Expenditures in Germany, FNU-66 (Energy Economics 29) Ronneberger, K., R.S.J. Tol and U.A. Schneider (2005), KLUM: A Simple Model of Global Agricultural Land Use as a Coupling Tool of Economy and Vegetation, FNU-65 (submitted, Climatic Change)

Tol, R.S.J. (2005), The Benefits of Greenhouse Gas Emission Reduction: An Application of FUND, FNU-64 (submitted, Global Environmental Change)

Rckmann, C., M.A. St.John, U.A. Schneider, F.W. Kster, F.W. and R.S.J. Tol (2006), Testing the implications of a permanent or seasonal marine reserve on the population dynamics of Eastern Baltic cod under varying environmental conditions, FNU-63- revised (Fisheries Research, 85, 1-13)

Letsoalo, A., J. Blignaut, T. de Wet, M. de Wit, S. Hess, R.S.J. Tol and J. van Heerden (2005), Triple Dividends of Water Consumption Charges in South Africa, FNU-62 (Water Resources Research, 43, W05412)

Zandersen, M., Termansen, M., Jensen,F.S. (2005), Benefit Transfer over Time of Ecosystem Values: the Case of Forest Recreation, FNU-61 (submitted)

Rehdanz, K., Jung, M., Tol, R.S.J. and Wetzel, P. (2005), Ocean Carbon Sinks and International Climate Policy, FNU-60 (Energy Policy, 34, 3516-3526)

Schwoon, M. (2005), Simulating the Adoption of Fuel Cell Vehicles, FNU-59 (submitted)

Bigano, A., J.M. Hamilton and R.S.J. Tol (2005), The Impact of Climate Change on Domestic and International Tourism: A Simulation Study, FNU-58 (submitted)

Bosello, F., R. Roson and R.S.J. Tol (2004), Economy-wide estimates of the implications of climate change: Human health, FNU-57 (Ecological Economics, 58, 579-591)

Hamilton, J.M. and M.A. Lau (2004) The role of climate information in tourist destination choice decision-making, FNU-56 (forthcoming, Gssling, S. and C.M. Hall (eds.), Tourism and Global Environmental Change. London: Routledge)

Bigano, A., J.M. Hamilton and R.S.J. Tol (2004), The impact of climate on holiday destination choice, FNU-55 (Climatic Change, 76 (3-4), 389-406)

Bigano, A., J.M. Hamilton, M. Lau, R.S.J. Tol and Y. Zhou (2004), A global database of domestic and international tourist numbers at national and subnational level, FNU-54 (International Journal of Tourism Research, 9, 147-174)

Susandi, A. and R.S.J. Tol (2004), Impact of international emission reduction on energy and forestry sector of Indonesia, FNU-53 (submitted)

Hamilton, J.M. and R.S.J. Tol (2004), The Impact of Climate Change on Tourism and Recreation, FNU-52 (forthcoming, Schlesinger et al. (eds.), Cambridge University Press)

Schneider, U.A. (2004), Land Use Decision Modelling with Soil Status Dependent Emission Rates, FNU-51 (submitted)

Link, P.M., U.A. Schneider and R.S.J. Tol (2004), Economic impacts of changes in fish population dynamics: the role of the fishermens harvesting strategies, FNU-50 (submitted)

Berritella, M., A. Bigano, R. Roson and R.S.J. Tol (2004), A General Equilibrium Analysis of Climate Change Impacts on Tourism, FNU-49 (Tourism Management, 27 (5), 913-924)

Tol, R.S.J. (2004), The Double Trade-Off between Adaptation and Mitigation for Sea Level Rise: An Application of FUND, FNU-48 (Mitigation and Adaptation Strategies for Global Change, 12 (5), 741-753)

Erdil, E. and Yetkiner, I.H. (2004), A Panel Data Approach for Income-Health Causality, FNU-47

Tol, R.S.J. (2004), Multi-Gas Emission Reduction for Climate Change Policy: An Application of FUND, FNU-46 (Energy Journal (Multi-Greenhouse Gas Mitigation and Climate Policy Special Issue), 235-250)

Tol, R.S.J. (2004), Exchange Rates and Climate Change: An Application of FUND, FNU-45

(Climatic Change, 75, 59-80)

Gaitan, B., Tol, R.S.J, and Yetkiner, I. Hakan (2004), The Hotellings Rule Revisited in a Dynamic General Equilibrium Model, FNU-44 (submitted)

Rehdanz, K. and Tol, R.S.J (2004), On Multi-Period Allocation of Tradable Emission Permits, FNU-43 (submitted)

Link, P.M. and Tol, R.S.J. (2004), Possible Economic Impacts of a Shutdown of the Thermohaline Circulation: An Application of FUND, FNU-42 (Portuguese Economic Journal, 3, 99-114)

Zhou, Y. and Tol, R.S.J. (2004), Evaluating the costs of desalination and water transport, FNU-41 (Water Resources Research, 41 (3), W03003)

Lau, M. (2004), Kstenzonenmanagement in der Volksrepublik China und Anpassungsstrategien an den Meeresspiegelanstieg,FNU-40 (Coastline Reports (1), 213-224.)

Rehdanz, K. and D.J. Maddison (2004), The Amenity Value of Climate to German Households, FNU-39 (submitted)

Bosello, F., Lazzarin, M., Roson, R. and Tol, R.S.J. (2004), Economy-wide Estimates of the Implications of Climate Change: Sea Level Rise, FNU-38 (Environmental and Resource Economics, 37, 549-571)

Schwoon, M. and Tol, R.S.J. (2004), Optimal CO2-abatement with socio-economic inertia and induced technological change, FNU- 37 (Energy Journal, 27 (4), 25-60)

Hamilton, J.M., Maddison, D.J. and Tol, R.S.J. (2004), The Effects of Climate Change on International Tourism, FNU-36 (Climate Research, 29, 255-268)

Hansen, O. and R.S.J. Tol (2003), A Refined Inglehart Index of Materialism and Postmaterialism, FNU-35 (submitted)

Heinzow, T. and R.S.J. Tol (2003), Prediction of Crop Yields across four Climate Zones in Germany: An Artificial Neural Network Approach, FNU-34 (submitted, Climate Research)

Tol, R.S.J. (2003), Adaptation and Mitigation: Trade-offs in Substance and Methods, FNU-33 (Environmental Science and Policy, 8 (6), 572-578)

Tol, R.S.J. and T. Heinzow (2003), Estimates of the External and Sustainability Costs of Climate Change, FNU-32 (submitted)

Hamilton, J.M., Maddison, D.J. and Tol, R.S.J. (2003), Climate change and international tourism: a simulation study, FNU-31 (Global Environmental Change, 15 (3), 253-266)

Link, P.M. and R.S.J. Tol (2003), Economic impacts of changes in population dynamics of fish on the fisheries in the Barents Sea, FNU-30 (ICES Journal of Marine Science, 63 (4), 611-625)

Link, P.M. (2003), Auswirkungen populationsdynamischer Vernderungen in Fischbestnden auf die Fischereiwirtschaft in der Barentssee, FNU-29 (Essener Geographische Arbeiten, 35, 179-202)

Lau, M. (2003), Coastal Zone Management in the Peoples Republic of China An Assessment of Structural Impacts on Decisionmaking Processes, FNU-28 (Ocean & Coastal Management, No. 48 (2005), pp. 115-159.)

Lau, M. (2003), Coastal Zone Management in the Peoples Republic of China A Unique Approach?, FNU-27 (China Environment Series, Issue 6, pp. 120-124; http://www.wilsoncenter.org/topics/pubs/7-commentaries.pdf)

Roson, R. and R.S.J. Tol (2003), An Integrated Assessment Model of Economy-Energy-Climate The Model Wiagem: A Comment, FNU-26 (Integrated Assessment, 6 (1), 75-82)

Yetkiner, I.H. (2003), Is There An Indispensable Role For Government During Recovery From An Earthquake? A Theoretical Elaboration, FNU-25

Yetkiner, I.H. (2003), A Short Note On The Solution Procedure Of Barro And Sala-i-Martin for Restoring Constancy Conditions, FNU-24

Schneider, U.A. and B.A. McCarl (2003), Measuring Abatement Potentials When Multiple Change is Present: The Case of Greenhouse Gas Mitigation in U.S. Agriculture and Forestry, FNU-23 (submitted)

Zhou, Y. and Tol, R.S.J. (2003), The Implications of Desalination to Water Resources in China - an Economic Perspective, FNU-22 (Desalination, 163 (4), 225-240)

Yetkiner, I.H., de Vaal, A., and van Zon, A. (2003), The Cyclical Advancement of Drastic Technologies, FNU-21

Rehdanz, K. and Maddison, D. (2003) Climate and Happiness, FNU-20 (Ecological Economics, 52 111-125)

Tol, R.S.J., (2003), The Marginal Costs of Carbon Dioxide Emissions: An Assessment of the Uncertainties, FNU-19 (Energy Policy, 33 (16), 2064-2074).

Lee, H.C., B.A. McCarl, U.A. Schneider, and C.C. Chen (2003), Leakage and Comparative Advantage Implications of Agricultural Participation in Greenhouse Gas Emission Mitigation, FNU-18 (submitted).

Schneider, U.A. and B.A. McCarl (2003), Implications of a Carbon Based Energy Tax for U.S. Agriculture, FNU-17 (submitted).

Tol, R.S.J. (2002), Climate, Development, and Malaria: An Application of FUND, FNU-16 (forthcoming, Climatic Change). Hamilton, J.M. (2003), Climate and the Destination Choice of German Tourists, FNU-15 (revised and submitted).

Tol, R.S.J. (2002), Technology Protocols for Climate Change: An Application of FUND, FNU-14 (Climate Policy, 4, 269-287).

Rehdanz, K (2002), Hedonic Pricing of Climate Change Impacts to Households in Great Britain, FNU-13 (Climatic Change 74).

Tol, R.S.J. (2002), Emission Abatement Versus Development As Strategies To Reduce Vulnerability To Climate Change: An Application Of FUND, FNU-12 (Environment and Development Economics, 10, 615-629).

Rehdanz, K. and Tol, R.S.J. (2002), On National and International Trade in Greenhouse Gas Emission Permits, FNU-11 (Ecological Economics, 54, 397-416).

Fankhauser, S. and Tol, R.S.J. (2001), On Climate Change and Growth, FNU-10 (Resource and Energy Economics, 27, 1-17).

Tol, R.S.J.and Verheyen, R. (2001), Liability and Compensation for Climate Change Damages A Legal and Economic Assessment, FNU-9 (Energy Policy, 32 (9), 1109-1130).

Yohe, G. and R.S.J. Tol (2001), Indicators for Social and Economic Coping Capacity Moving Toward a Working Definition of Adaptive Capacity, FNU-8 (Global Environmental Change, 12 (1), 25-40).

Kemfert, C., W. Lise and R.S.J. Tol (2001), Games of Climate Change with International Trade, FNU-7 (Environmental and Resource Economics, 28, 209-232).

Tol, R.S.J., W. Lise, B. Morel and B.C.C. van der Zwaan (2001), Technology Development and Diffusion and Incentives to Abate Greenhouse Gas Emissions, FNU-6 (submitted).

Kemfert, C. and R.S.J. Tol (2001), Equity, International Trade and Climate Policy, FNU-5 (International Environmental Agreements, 2, 23-48).

Tol, R.S.J., Downing T.E., Fankhauser S., Richels R.G. and Smith J.B. (2001), Progress in Estimating the Marginal Costs of Greenhouse Gas Emissions, FNU-4. (Pollution Atmosphrique Numro Spcial: Combien Vaut lAir Propre?, 155-179).

Tol, R.S.J. (2000), How Large is the Uncertainty about Climate Change?, FNU-3 (Climatic Change, 56 (3), 265-289).

Tol, R.S.J., S. Fankhauser, R.G. Richels and J.B. Smith (2000), How Much Damage Will Climate Change Do? Recent Estimates, FNU-2 (World Economics, 1 (4), 179-206)

Lise, W. and R.S.J. Tol (2000), Impact of Climate on Tourism Demand, FNU-1 (Climatic Change, 55 (4), 429-449).