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International Environmental Agreements: An Emission Choice Model with Abatement Technology

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Keywords: Environmental Agreements, JEL: D6, Q5, C7

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1 Introduction

Some of the most pressing environmental problems are related to transboundary and/or global pollutants, including global warming, ozone depletion, acid rain, air and water pollution. Transboundary and/or global pollution problems belong to the theory of the voluntary provision of a public good, more specific of a public bad. The absence of a supranational authority that could implement and enforce environmental policies on sovereign countries renters the required intervention very difficult. Thus, any International Environmental Agreement (IEA) has to be designed so that it is self-enforcing, that is, it must be in the self-interest of each country to join and stay in the agreement. An IEA is profitable if the net benefits for the countries in the coalition exceed the net benefits of the countries outside the coalition. Moreover, an IEA is considered to be stable if none of its signatories has an incentive to withdraw (internal stability) and none of the nonsignatories has an incentive to further participate in the agreement (external stability), assuming that the remaining players do not revise their membership decision (D'Aspremont, Jacquemin and Szewicz 1983).

In examining self-enforcing, stable IEAs, the literature uses either the cooperative or the non-cooperative game theoretic approach. Formalizing countries' behavior as a cooperative game, it has been shown that an IEA signed by all countries can be stable (chandler and Tulkens (1995) and (1997)). The non-cooperative approach examines both the case that countries move simultaneously and the case that the IEA signatories act as a leader. The simultaneous case has been examined by Carraro and Siniscalco (1993) and resolved by Finus and Rundshagen (2001), Cara and Rotillon and Rubio and Casino (2001), which assuming quandratic cost and benefit functions show that the stable IEA will be signed by no more than two countries. In the leadership approach, Barrett (1994) shows, through simulations of an abatement choice model, that the size of a stable coalition could range between two and the grand coalition depending on the relative size of cost and benefits. On the contrary Diamantoudi and Sartzetakis (2006) find, through analytical solution of an emission choice model, that the size of a stable coalition cannot exceed four countries, regardless of the value of the model's parameters.

The present paper attempts to contribute to the literature by employing a non-cooperative leadership game and allowing countries to choose both emission and abatement levels. In particular we expand the basic model, as presented in Diamantoudi and Sartzetakis (2006), by expressing each country's welfare as the difference between the benefits from the country's emissions and the costs from the country's abatement minus the damages from the aggregate emissions. We further assume that, in the first stage, the coalition of countries signing the IEA behaves cooperatively by maximizing the coalition's aggregate welfare and in the second stage, the non-signotories behave non-cooperatively by maximizing their individual welfare taking the coalition's choice as given. When the coalition maximizes its welfare in the first stage, it takes into account the non-signatories' behavior. To find the size of the self-enforcing, stable IEA we impose the internal and external stability conditions. As in the basic model we use quadratic functions for benefits derived from emissions and damages from net emissions and we introduce a quadratic abatement cost function. Each country's damages are a function of aggregate net emissions, the difference between aggregate emissions and abatement. We solve analytically the model up to a point and then we resort to numerical simulations in order to derive the size of the stable coalition. We find that the introduction of the abatement choice allows for larger stable coalitions. Furthermore, we find that the size of the stable coalition is highly sensitive to the values of the model's parameters. In particular, the lower is the cost of abatement relative to environmental damages –keeping all other parameters constant– the larger is the size of the stable coalition. However, our model always yields a larger stable coalition relative to the case that abatement is not an option. This is true even when the slope of marginal cost of abatement is substantially greater than the slope of environmental damages, within the restrictions derived from the non-negativity constraint on net emissions.

The main contribution of this paper is the introduction of abatement as a separate variable in the model. In the literature countries were choosing either the level of abatement (Barret (1994)) or the level of emissions (Diamantoudi and Sartzetakis (2006)). As was demonstrated in Diamantoudi and Sartzetakis (2006) the two approaches are equivalent and they yield the same results if in the emission model emissions are assumed positive and in the abatement model abatement does not exceed the flow of emissions. We allow countries to choose separately their emission and abatement levels and by doing so we enlarge the benefits of joining the coalition, resulting in a larger coalition size relative to the one choice variable models. A critical point is the slope of the best response functions of each country's choice variables to the other countries' choice of net emissions. We find that although each country free rides on other countries' emission reduction efforts, that is it increases its emissions as the rest of the countries decrease their net emission, it increases its own abatement in response to other countries' reduction in net emissions. Our results complement Barrett's (1994) suggestion that the size of the stable coalition depends on the model's parameters, even though we are imposing the constraint that the net emission flow is positive.

The literature has examined the links between IEAs and technology oriented agreements or R&D cooperation (Katsoulacos (1997), Lessmann and Edenhofer (2010)). In general, technology agreements and R&D cooperation are considered as club goods whose attractiveness may outweigh the incentive to free-ride. If coalition members can secure extra positive externalities among them, by linking for instance an environmental agreement to an R&D one with larger technology spillover effects among the coalition members, the size of the stable coalition will grow (Carraro and Siniscalco (1997)). Moreover, Hoel and Zeeuw (2010) allow the cost of adopting a breakthrough technology to vary with the level of R&D and show that a large stable coalition can result leading to a substantial improvement in average welfare. They find that the stability properties of IEAs improve relative to the case in which treaties focus only on emission reduction. Their result implies that it can indeed be beneficial for IEAs to consider breakthrough technologies and R&D whenever this is appropriate. However, Benchekroun and Chaudhuri (2012) show that technology improvements are not the panacea to all major transboundary pollution problems. They find that eco-innovations can reduce the stability of IEAs when using a farsighted stability concept. Implementing clean technologies may destabilize an otherwise stable grand coalition when countries are farsighted. Goeschl and Perino (2012) illustrate a hold-up problem created in the presence of intellectual property rights regarding new abatement technologies. They find that the presence of intellectual property rights reduces the size of the IEA leading to a reduction of their abatement commitment. Their results has some parallels with Barrett

(2006) who finds that a focus on breakthrough technologies cannot improve the performance of IEAs, with the exception of breakthrough technologies that exhibit increasing returns to scale.

The rest of the paper is organized as follows. Section 2 lays out the model and presents the case of non-cooperation and full cooperation, while also laying out the coalition formation model. Section 3 derives the size of the stable coalition using numerical simulations, and it provides the full numerical solution of the model. In the same Section the results of numerical simulations for the whole range of acceptable values of the parameters are presented. The last Section concludes the paper.

2 The Model

We assume that there exist n symmetric countries, $N = \{1, 2, 3, \ldots, n\}$, each of which generate emissions $e_i > 0$ due to their production and consumption activities, which affect negatively on all the other countries. We further assume that each country can engage in abatement $x_i \geqslant 0$ which is costly. Therefore, countries participate in a decision game with two choice variables: emission and abatement.

Social welfare of country i, W_i, is expressed as the total benefits country i receives from emitting, $B_i(e_i)$ minus the environmental damages $D_i(E - X)$ from the aggregate global net emissions (which are the difference between global emission $E = \sum_{i=1}^{n} e_i$ and global abatement $X_i = \sum_{i=1}^{n} x_i$) and country i's cost of abatement, $CA_i(x_i)$. Thus, country i's welfare is,

$$W_i = B_i(e_i) - D_i(E - X) - CA_i(x_i)$$

We assume that the benefit function is strictly concave, and in particular it takes the following quadratic form for country $i \in N$, $B_i(e_i) = b(ae_i - \frac{1}{2}e_i^2)$, where a and b are positive parameters, i.e. $a > 0$ and $b > 0$. We further assume that the damage function is strictly convex, employing a quadratic function for each country $i \in N$, $D_i(E) = \frac{1}{2}c(E - X)^2 = \frac{1}{2}c(\sum_{i=1}^{n}(e_i - x_i))^2$, where c is a positive parameter, i.e. $c > 0$. Finally, we assume that cost of abatement is also strictly convex, and in particular we use a quadratic formulation, $X_i(x_i) = \frac{1}{2}dx_i^2$, where d is a positive parameter indicating the slope of the marginal cost of abatement, i.e. $d > 0$. Therefore, country i's social welfare is,

$$W_i = b(ae_i - \frac{1}{2}e_i^2) - \frac{1}{2}c(\sum_{i=1}^{n}(e_i - x_i))^2 - \frac{1}{2}dx_i^2. \tag{1}$$

Before examining the maximum size of stable, self-enforcing coalitions, we analyze the two extreme cases of pure non-cooperation and full cooperation.

2.1 The pure non-cooperative case

In the non-cooperative case, each country chooses its emission and abatement levels taking the other countries' emission and abatement levels as given. This means that each country i plays a Cournot game maximizing its own welfare function. The first-order conditions of the welfare maximization problem (1) yield country i's emission and abatement reaction functions,

$$e_i = \frac{ab\,(c+d) - cd\sum_{j\neq i}(e_j - x_j)}{bc + d\,(b+c)} \tag{2}$$

and

$$x_i = \frac{abc + cb\sum_{j\neq i}(e_j - x_j)}{bc + d\,(b+c)} \tag{3}$$

respectively.

Since all the countries are symmetric, all of them generate the same level of emissions, denoted by e_{nc}, and make the same abatement effort, denoted by x_{nc}, at the equilibrium. In order to simplify the exposition of the results, we assume, $\gamma = \frac{c}{b}$, which indicates the relationship between environmental damages and benefits due to emissions, and $\delta = \frac{d}{c}$, which indicates the relationship between abatement cost and environmental benefits.

The solution of the reaction functions' system yields:

$$e_{nc} = \frac{a(n+\delta)}{n+\delta+n\gamma\delta}, \quad x_{nc} = \frac{an}{n+\delta+n\gamma\delta}. \tag{4}$$

Therefore, each country's net emissions are,

$$e_{nc} - x_{nc} = \frac{a\delta}{n+\delta+n\gamma\delta}.$$

Aggregate emission and abatement levels under the non-cooperative case are, $E_{nc} = e_{nc}n = \frac{a(n+\delta)}{n+\delta+n\gamma\delta}n$ and $X_{nc} = x_{nc}n = \frac{an}{n+\delta+n\gamma\delta}n$respectively.

2.2 The full cooperation case

In the case of full cooperation, emission and abatement decisions are taken together by all countries. The choice variables are derived by maximizing aggregate welfare. The first-order conditions yield emission e_c and abatement x_c levels,

$$e_c = \frac{a(n^2+\delta)}{n^2+\delta+n^2\gamma\delta}, \quad x_c = \frac{an^2}{n^2+\delta+n^2\gamma\delta}, \tag{5}$$

from which we derive each country's net emission level,

$$e_c - x_c = \frac{a\delta}{n^2+\delta+n^2\gamma\delta}.$$

Aggregate emission and abatement levels under the full cooperation case are, $E_c = e_c n = \frac{a(n^2+\delta)}{n^2+\delta+n^2\gamma\delta} n$ and $X_c = x_c n = \frac{an^2}{n^2+\delta+n^2\gamma\delta} n$respectively.

It is easy to verify that each country's net emissions are lower in the full cooperation case, i.e. $e_c - x_c < e_{nc} - x_{nc}$. In the full cooperation case, each country emits less ($e_c < e_{nc}$) and abates more ($x_c > x_{nc}$) relative to the non-cooperative case. Therefore, aggregate net emissions are less when all countries cooperate. For each country to be better off under the full cooperation case it must be hold that the parameter c (marginal environmental cost) must be large enough whereas the parameter d (marginal abatement cost) must be small enough.

A major problem, however, concerning the cooperation among countries is that, each country has an incentive to free-ride on the emissions reduction. It might be in a country's best interest to cheat on the agreement when the rest of the countries coordinate their actions according to the agreement's regulation. The free-rider country by doing so it increases its net emission level, reducing its own cost of abatement while enjoying the benefits from the overall pollution reduction resulting from the effort of the rest of the countries.

2.3 Coalition formation

The ratification of the IEA is depicted by the formation of a coalition. In particular, a set of countries $S \subset N$ sign an agreement and $N \backslash S$ do not. Let the size of coalition be denoted by $|S| = s$, total emissions generated by the coalition by E_s while each member of the coalition emits e_s, such that $E_s =$

se_s and total abatement by X_s while each member of the coalition abates x_s, such that $X_s = sx_s$. In a similar manner, each non-signatory emits e_{ns} and abates x_{ns}, giving rise to a total emission and abatement levels generated by all non-signatories $E_{ns} = (n-s)e_{ns}$ and $X_{ns} = (n-s)x_{ns}$ respectively. The aggregate emission and abatement levels are, $E = E_s + E_{ns} = se_s + (n-s)e_{ns}$ and $X = X_s + X_{ns} = sx_s + (n-s)x_{ns}$ respectively.

The equilibrium number of countries participating in an IEA, is derived by applying the notions of internal and external stability of a coalition as was originally developed by D'Aspremont et. al (1983) and extended to IEAs by Carraro & Siniscalco (1993) and Barrett (1994). The signatories behave cooperatively while the non-signatories act non-cooperatively after having observed the signatories' choices that is $e_{ns}(e_s)$ and $x_{ns}(x_s)$. Therefore, the non-signatiries' maximization problem is,

$$\max_{e_{ns},\, x_{ns}} \left[B(e_{ns}) - D\left[s\left(e_s - x_s\right) + \left(n-s-1\right)\left(e_i - x_i\right) + \left(e_{ns} - x_{ns}\right)\right] - CA_{ns}(x_{ns})\right].$$

The first order conditions of the above maximization problem yield the reaction functions presented in equations (2) and (3). However, now only $n-s$ countries stay outside of the emission reduction agreement emitting e_{ns}, and abating x_{ns}, while the rest s countries emit in total E_s and abate X_s. Substituting these into the reaction function (2) yields each non-signatory country's emissions $e_{ns}\left(e_s, x_s\right)$ as a function of the signatory countries' emission e_s and abatement x_s. Furthermore, substitution into the reaction function (3) yields each non-signatory country's abatement $x_{ns}\left(e_s, x_s\right)$ as a function of the signatory countries' emission e_s and abatement x_s.

Signatories maximize the coalition's welfare, sW_s, taking explicitly into account $N \backslash S$'s behavior. That is, signatories choose e_s and x_s by solving the following maximization problem,

$$\max_{e_s,\, x_s} s\left[B(e_s) - D\left[s\left(e_s - x_s\right) + \left(n-s\right)\left(e_{ns}\left(e_s, x_s\right) - x_{ns}\left(e_s, x_s\right)\right)\right] - CA_s(x_s)\right].$$

The first-order conditions of the above maximization problem yield the emission and the abatement effort levels of the signatories,

$$e_s = a\left(1 - \frac{ns\gamma\delta^2}{\Psi}\right), \tag{6}$$

$$x_s = \frac{ans\delta}{\Psi}, \tag{7}$$

where $\Psi = \Omega^2 + s^2\delta + s^2\gamma\delta^2$ and $\Omega^2 = n - s + \delta + \gamma\delta(n - s)$. Therefore, the net emission level of the signatories is,

$$e_s - x_s = a(1 - ns\delta\frac{(1 + \gamma\delta)}{\Psi}). \tag{8}$$

Aggregate emission and abatement levels by the signatories are, $E_s = a(1 - \frac{ns\gamma\delta^2}{\Psi})s$ and $X_s = \frac{ans\delta}{\Psi}s$ respectively. The aggregate net emission levels are,

$$E_s - X_s = a(1 - ns\delta\frac{(1 + \gamma\delta)}{\Psi})s \tag{9}$$

Substituting e_s and x_s into the non-signatories' reaction functions, we derive the non-signatories' emission and abatement effort level,

$$\begin{aligned} e_{ns} &= \frac{a(n - s + \delta)}{\Omega} - \frac{\alpha\gamma s\delta}{\Omega}(1 - \frac{ns\delta(1 + \gamma\delta)}{\Psi}), & (10) \\ x_{ns} &= \frac{a(n - s)}{\Psi} + \frac{\alpha s}{\Omega}(1 - \frac{ns\delta(1 + \gamma\delta)}{\Psi}) \ . & (11) \end{aligned}$$

Therefore, the net emission level of the non-signatories is,

$$e_{ns} - x_{ns} = \frac{a\delta}{\Omega} - s\frac{a(1 + \gamma\delta)}{\Omega}(1 - \frac{ns\delta(1 + \gamma\delta)}{\Psi}). \tag{12}$$

Aggregate emission and abatement levels by non-signatories are, $E_{ns} = (\frac{a(n-s+\delta)}{\Omega} - \frac{\alpha\gamma s\delta}{\Omega}(1 - \frac{ns\delta(1+\gamma\delta)}{\Psi}))(n-s)$ and $X_{ns} = (\frac{a(n-s)}{\Psi} + \frac{\alpha s}{\Omega}(1 - \frac{ns\delta(1+\gamma\delta)}{\Psi}))(n-s)$ respectively. The aggregate net emission level is,

$$E_{ns} - X_{ns} = (\frac{a\delta}{\Omega} - s\frac{a(1 + \gamma\delta)}{\Omega}(1 - \frac{ns\delta(1 + \gamma\delta)}{\Psi}))(n - s) \tag{13}$$

From (9) and (13), global net emission level $E - X = (E_{ns} - X_{ns}) + (E_s - X_s)$ is,

$$E - X = \sum_{i=1}^{n}(e_i - x_i) = \frac{an\delta\Omega}{\Psi}.$$

Unlike the previous two cases, the non-cooperative and the full cooperation case, where $e_{nc} - x_{nc} = \frac{a\delta}{n+\delta+n\gamma\delta} > 0$ and $e_c - x_c = \frac{a\delta}{n^2+\delta+n^2\gamma\delta} > 0$ always hold, in the coalition formation case we have to restrict the parameters of the model in order to guarantee interior solutions. Therefore, we need to restrict the parameters so that $e_s - x_s > 0$ and $e_{ns} - x_{ns} > 0$. The following proposition establishes the necessary conditions for interior solutions.

Proposition 1 *$e_s - x_s > 0$ and $e_{ns} - x_{ns} > 0$ if and only if $0 < \gamma < \frac{4}{n(n-4)}$, $0 < \delta < \frac{n(n-4)}{4-\gamma n(n-4)}$, $n > 4$ and $n > \frac{2\delta}{(1+\gamma\delta)^2}(\delta + \sqrt{\delta(1+\delta+\gamma\delta)})$.*

The intuitive explanation behind these conditions is that for net emissions to be positive it must be that the relative impact of environmental cost to benefits due to emissions ($\gamma = \frac{c}{b}$) is not very high. Also, the relative impact of abatement cost to environmental cost ($\delta = \frac{d}{c}$) it must be not very high as well.

These restrictions are similar in nature to the restrictions derived from the positivity constraint on emission in Diamantoudi and Sartzetakis (2006) and which actually restricted the size of the stable coalition to 2, 3 or 4 countries. The restrictions on the relative size of damages to benefits defined the difference in the optimal size of the coalition between the works of Diamantoudi and Sartzetakis (2006) and Barrett (1994). In the present work we place restrictions on both the relative size of damages to benefits and the relative size of abatement cost to damages.

Substituting the equilibrium values of the choice variables from (6), (7), (10) and (11) we derive the indirect welfare function of signatories (W_s) and non-signatories (W_{ns}),

$$W_s = ba^2\frac{1}{2}(1 - \frac{\gamma n^2\delta^2}{\Psi}), \tag{14}$$

$$W_{ns} = ba^2\frac{1}{2}(1 - \frac{1}{\Psi^2}\gamma n^2\Omega^2(\delta + \delta^2(1+\gamma))). \tag{15}$$

Proposition 2 establishes the properties of these indirect welfare functions, in a way similar to Diamantoudi and Sartzetakis (2006).

Proposition 2 *We consider the indirect welfare function of signatories and non-signatories, (W_s) and (W_{ns}) respectively. If we define $s^{\min} = 1 + \frac{(1+\delta\gamma)}{(1+\delta+\delta\gamma)}(n-1)$, then,*

(i) $s^{\min} = \arg\min_{s\in\Re\cap[0,n]} W_s(s)$, that is, $s^{\min}$ is the s at which W_s is minimized,

(ii) $W_s(s)$ increases in s if $s > s^{\min}$ and it decreases in s if $s < s^{\min}$,

(iii) $w_{ns}(s) \lesseqgtr w_s(s)$ for all $s \lesseqgtr s^{\min}$.

The proof of the above Proposition follows from the proof in Diamantoudi and Sartzetakis (2006). The above defined properties of the indirect welfare function imply that the indirect welfare function of the non-signatories cuts the indirect welfare function of the signatories from below at its minimum. which is defined by $s^{\min}$.

3 The size of a Stable IEA

To determine the size of a stable IEA, denoted by s^*, we use the internal and external stability conditions. The internal stability implies that no country in the coalition has an incentive to leave the coalition, while external stability implies that no country outside the coalition has an incentive to join the coalition, according to D'Aspemont, Jacquemin and Szewicz (1983). Formally, the internal and external stability conditions take the following form,

$$w_s(s^*) \geq w_{ns}(s^* - 1) \text{ and } w_s(s^* + 1) \leq w_{ns}(s^*),$$

respectively.

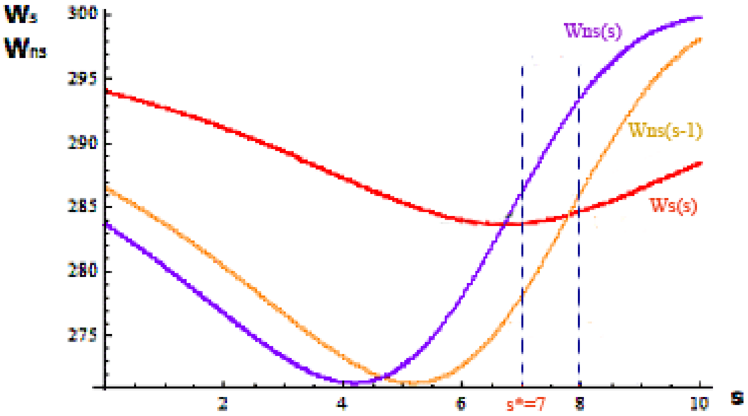
To determine the size of a stable coalition we choose to resort to numerical simulations. Since our purpose is to examine the effect of the introduction of abatement effort on the size of the coalition, we choose the same parameter values used in Diamantoudi and Sartzetakis (2006). That is, we assume the following values for the parameters: $n = 10$, $a = 10$, $b = 6$, and $c = 0.39999$, which results in $\gamma = 0.066665$. These values satisfy the restrictions set in *Proposition 2*, since the parameter γ is less than $\gamma < \frac{4}{n(n-4)} < 0.066667$.

In our model we have to restrict the value of the parameter δ according to the condition $n > \frac{2\delta}{(1+\gamma\delta)^2}(\delta + \sqrt{\delta(1 + \delta + \gamma\delta)})$ set in *Proposition 2.* This condition yields, $0 \leq \delta < 1.63704$ and we choose $\delta = 0.6$. We take a small value for the parameter δ (this means a large value for the parameter c and a small value for the parameter d) in order to be sure that the signatories will be better off under the coalition formation than under the Cournot game (acting non-cooperatively). With $\delta = 0.6$, and given $c = 0.39999$ we have $d = 0.239994$. Therefore, the environmental damage is greater than the abatement cost parameter.

Using all the above specifications, we confirm that the size of the stable IEA is $s^* = 7$. This size satisfies all the constraints for $e_s - x_s > 0$ and $e_{ns} - x_{ns} > 0$ and also the internal and external stability conditions. Note that for the same parameter values, the optimal size of the coalition in Diamantoudi and Sartzetakis (2006) is $s^* = 3$.

In Figure 1, we plot the indirect welfare functions against different coalition sizes s. The red curve depicts $W_s(s)$, the purple curve $W_{ns}(s)$ and the orange curve $W_{ns}(\ s-1)$. Notice that $W_{ns}(s-1)$ is a horizontal shift of $W_{ns}(s)$.

Figure 1 plots the functions for all possible values of $s = 0, ..., 10$. According to the Figure 1 for coalition $s^* = 7$, the internal condition is satisfied i.e. $W_s(s^*) \geq W_{ns}(\ s^* - 1)$ since the red curve is above the orange curve. Moreover, coalition $s^* = 7$ is externally stable i.e. $w_s(s^* + 1) \leq w_{ns}(s^*)$ since at $s = s^* + 1 = 8$ the orange curve is above the red curve. Therefore, the coalition of size $s^* = 7$ is stable.



The size of a Stable IEA

Remark 1 *When the option of abating emissions is considered, the optimal size of the coalition is significantly greater relative to the case that abatement is not a choice.*

Similar to the analysis in Diamantoudi and Sartzetakis (2006) the stable coalition size is the higher integer following the size of the coalition for which the welfare of the signatories is at its minimum, $s^{\min}$ and for which $W_s = W_{ns}$. This point is $s^{\min} = 1 + \frac{(1+\delta\gamma)}{(1+\delta+\delta\gamma)}(n-1) = 6.70732$.

3.1 The model's numerical solution

In order to complete the analysis, we compute the values of the model's variables using the above specified values of the parameters. Table 1 presents the values of the parameters for the non-cooperation and the full cooperation case.

Table 1. Non-cooperation and Full Cooperation Cases

Variable	Value
Non-cooperative case	
e_{nc}	9.63637
E_{nc}	96.3637
x_{nc}	9.09092
X_{nc}	90.9092
$E_{nc} - X_{nc}$	5.4545
w_{nc}	283.736
Full cooperation case	
e_c	9.6176
E_c	96.176
x_c	9.56024
X_c	95.6024
$E_c - X_c$	0.5736
w_c	288.528

The above values confirm the theoretical result that under the non-cooperative case countries emit more and abate less relative to the case of full cooperation, i.e. $e_{nc} > e_c$ and $x_{nc} < x_c$. Moreover, total net emissions under non-cooperation, $E_{nc} - X_{nc}$, are almost ten times larger than under full cooperation, $E_c - X_c$. Furthermore, social welfare is higher in the full cooperation case, i.e. $W_c > W_{nc}$.

The results of the simulation of the coalition formation model using the same parameter values are summarized in the following Table.

Table 2. Coalition Formation Case

Variable	Value
Coalition formation	
Non-signatories	
e_{ns}	9.66498
x_{ns}	8.37566
$e_{ns} - x_{ns}$	1.28932
w_{ns}	286.194
Signatories	
e_s	9.62175
x_s	9.4564
$e_s - x_s$	0.16535
w_s	283.789
Total net emissions	
E	96.3472
X	91.3218
$\sum_{i=1}^{n}(e_i - x_i)$	5.0254

These values confirm that signatories emit less and abate more than non-signatories, i.e. $e_s < e_{ns}$ and $x_s > x_{ns}$. Moreover, the net emissions are significantly smaller for the signatories, $e_s - x_s$, than for the non-signatories, $e_{ns} - x_{ns}$. The total net emissions, $\sum_{i=1}^{n}(e_i - x_i)$, include the activities from both signatories, which are $s = 7$, and non-signatories, which are $(n - s) = 3$. Furthermore, total net emissions are smaller relative to the non-cooperative case but larger than the full cooperation case.

3.2 Comparative static analysis

In the simulations presented above we used a value for the parameter δ that is below 1, indicating that the abatement cost parameter d is smaller than the emission damage parameter c. In particular we have used the value $\delta = 0.6$. However, the constraint derived from Proposition 1 for the values of all other parameters is $0 \leq \delta < 1.63704$. In order to ensure that the main result of the paper holds for any of the permitted values of the parameters, we simulate the model for two extreme values of δ, namely, $\delta = 0.0000001$ and $\delta = 1.637$. The first case indicates that abatement cost is negligible relative to environmental damages, while the second we assume that abatement costs exceed environmental damages. Table 3 presents the results of the simulations, including in the first column the case presented in the previous Sections.

Table 3. Coalition Formation under different values of δ

Case study[1]	**1**	**2**	**3**
δ	0.6	$1 * 10^{-7}$	1.637
c	0.399	0.399	0.399
d	0.239	$3.99 * 10^{-8}$	0.655
$s^{\min}$	6.707	10	4.635
s^*	7	10	5
Non-signatories			
e_{ns}	9.665	10	9.192
x_{ns}	8.375	9	7.406
$e_{ns} - x_{ns}$	1.289	1	1.785
w_{ns}	286.2	300	250.7
Signatories			
e_s	9.622	10	9.079
x_s	9.456	10	8.439
$e_s - x_s$	0.165	$1 * 10^{-8}$	0.639
w_s	283.8	300	244.7
Total net emissions			
E	96.347	100	91.354
X	91.322	100	79.229
$\sum_{i=1}^{n}(e_i - x_i)$	5.025	$1 * 10^{-7}$	12.124

The results of the simulations presented in Table 3 reveal that the value of the parameter δ is crucial in determining the size of the stable IEA. As we show above, when $\delta = 0.6$, the size of the stable coalition is $s^* = 7$. When δ takes a very low value, i.e. $\delta = 0.0000001$, the number of signatory countries increases, reaching the size of the grand coalition, $s^* = 10$. On the contrary, when δ takes a very high value, i.e. $\delta = 1.637$, the number of signatory

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[1] The values in the table are rounded to the nearest ten, hundred, and/or thousand according to the needs of calculations.

countries decreases to $s^* = 5$. Notice though that even when the abatement cost parameter takes the highest value allowed by the model's constraints, the size of the stable coalition is higher than the case in which countries have only one choice variable (either emission or abatement).

In the case in which δ approaches zero and the the grand coalition emerges, countries' emissions are the lowest possible receiving the highest welfare. This is because the slope of the marginal abatement cost is lower than the slope of the marginal environmental cost. In this case it is individually rational for the countries to abate.

4 Conclusions

The present paper examines the size of stable IEAs concerning transboundary environmental problems. A coalition is considered stable when no signatories wish to withdraw while no more countries wish to participate. We assume that the coalition behaves as a leader maximizing its members' aggregate welfare while the countries outside the coalition maximize their own welfare independently, taking the choice of the coalition as given. We further assume a benefit function that is concave in the country's own emissions, an environmental damage function that is convex in aggregate net emissions and an abatement cost function that is convex in the country's abatement effort. Each country chooses both its emission and abatement levels. Within this framework we find that the size of the stable coalition depends on the model's parameters but it is always larger than in the case in which countries are allowed to choose either emission or abatement level. Our results complement Barrett's (1994) suggestion that the size of the stable coalition depends on the model's parameters, even though we are imposing the constraint that the net emission flow is positive.

There are a number of directions in which this research project can be extended. First a full analytical solution of the model should be provided. Second the introduction of abatement technology in the emission model allows us to explore possible spillover effects. It should be explored whether the positive externalities resulting from spillovers could offset the existing free-riding incentives.

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