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Documentos de Trabajo

3

2008

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Abstract

In this working paper a two-stage game of international environmental agreement formation with asymmetric countries is analytically solved. The equilibrium of the game allows to determine the number of countries interested in signing the agreement. Two cases are studied. In the first case, the countries differ only in the abatement costs, and in the second case, in the environmental damages. In both cases, two different institutional settings, one without side payments and another with side payments, are considered. The results establish that the asymmetry assumption has no important effects on the scope of cooperation in comparison with the symmetric case if side payments are not used or the only difference among countries is given by the abatement costs. However, when the only difference is given by the environmental damages, the result is that the level of cooperation that can be bought through a self-financed side payment system increases with the degree of asymmetry.

Key words

Self-enforcing international environmental agreements, linear environmental damages, public bad.

Resumen

En este documento de trabajo se resuelve analíticamente un juego en dos etapas de formación de un acuerdo medioambiental internacional con países asimétricos. El equilibrio del juego permite determinar el número de países interesados en firmar el acuerdo. Se estudian dos casos. En el primero, los países se diferencian solamente en los costes de reducción de emisiones, y en el caso segundo, en los daños medioambientales. En ambos casos, se consideran dos marcos institucionales diferentes: uno sin pagos colaterales y otro con ellos. Los resultados establecen que el supuesto de asimetría no tiene efectos importantes sobre el alcance de la cooperación, en comparación con el caso simétrico, si no se utilizan pagos colaterales o si la única diferencia entre los países está dada por los costes de reducción de emisiones. Sin embargo, cuando los países difieren sólo en los daños medioambientales, el resultado es que el nivel de cooperación que se puede comprar mediante un sistema de pagos colaterales autofinanciado aumenta con el grado de asimetría.

Palabras clave

Acuerdos medioambientales internacionales estables, daños medioambientales lineales, mal público global.

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EDITA / PUBLISHED BY
Fundación BBVA, 2008
Plaza de San Nicolás, 4. 48005 Bilbao

DEPÓSITO LEGAL / LEGAL DEPOSIT NO.: M-11.452-2008
IMPRIME / PRINTED BY: Rógar, S. A.

Impreso en España – *Printed in Spain*

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CONTENTS

1. Introduction

CLIMATE change, the depletion of the ozone layer, and a loss of biological diversity are some of the most important environmental problems facing contemporary societies. The main characteristic of these kinds of problems is their international dimension, because of the common property of environmental resources and the transboundary effects of many polluting activities. Hence, managing environmental issues requires transnational cooperation. However, the lack of a supranational authority with enough coercive power above sovereign nations determines that international environmental cooperation must be reached by voluntary agreements. Therefore, International Environmental Agreements (IEAs) should be designed in such a way that the agreement will be not only profitable, but also self-enforcing, i.e., there must be incentives for countries, while acting in their own self-interest, to join or to stay in an agreement.

One of the earliest definitions of a self-enforcing agreement used in the literature on IEAs was the stability concept proposed by D'Aspremont et al. (1983) in their analysis of a cartel formation [1]. According to these authors an IEA will be stable if no signatory country has incentives to leave the agreement, and if no non-signatory has incentives to join the IEA, taking as given the membership decisions of all other countries [2].

In this paper we propose a revision of this concept to consider the possibility of side payments and we apply it to analyze the stability of IEAs under the assumption of asymmetry. With this aim we solve analytically a two-stage game where in the first stage each country decides whether or not to join an IEA (the membership game), and in the second stage each country determines its emissions and signatories can also determine a

1. Models based on this definition include for instance Carraro and Siniscalco (1993) and Barrett (1994) where it is assumed that countries are identical.

2. There are a number of other concepts of what makes an agreement self-enforcing. Chander and Tulkens (1995, 1997) draw on cooperative game concepts. Other concepts, such as farsightedness, have been developed, for instance, by Ecchia and Mariotti (1997,1998) and Ray and Vohra (2001); see Finus (2001) and Wagner (2001) for excellent overviews on the design of stable IEAs, and, more recently, Barrett (2003) for a broad exposition of the strategy of environmental treaty-making.

vector of self-financed side payments (the emission game). In the first stage the signing of the agreement operates as a commitment device that guarantees its full compliance by the signatories. To make tractable the analysis we assume that there are only two types of countries and that the environmental damages are linear with respect to total emissions. Moreover, we distinguish two cases. In the first case, we assume that the only difference among countries is given by the abatement costs, and in the second case, by the environmental damages. In both cases, we consider two different institutional settings, one without side payments and another with side payments.

Our findings establish that the asymmetry among countries has no relevant effects on the scope of environmental cooperation in comparison with the symmetric case if side payments are not allowed. When this occurs only countries of the same type are interested in joining the agreement with one exception: if the countries differ only in the environmental damages, a bilateral agreement consisting of one country of each type can be self-enforcing provided that the difference in the marginal environmental damages between the two countries is not very large. When side payments are taken into account the effects depend on the kind of asymmetry considered. With side payments a country with large abatement costs can buy the cooperation of a country with small abatement costs. However, when the number of signatories increases the incentives of the countries with low abatement costs to withdraw from the agreement increase, whereas the available resources to buy the cooperation for the countries with large abatement costs do not increase in the same amount or may even decrease. The result is that the cooperation that can be bought through side payments is very limited.

When the only difference among countries is given by the environmental damages, the result is that the level of cooperation that can be bought through a self-financed side payment system increases with the difference in the marginal environmental damages. This implies that an agreement with a high degree of participation may be self-enforcing if the degree of asymmetry among the countries is sufficiently large. Finally, we obtain that cooperation can be only bought by one or two countries with large environmental damages, i.e., by one or two countries of the same type. This result leads us to think that the level of cooperation could be higher in a model with more than two types of countries. This conjecture has been recently confirmed by Weikard (2005) in a completely asymmetric model where the choice variable is the emission abatement and the marginal benefits of total abatement are constant. He shows, in accordance with our results, that the grand coalition can be stabilized through a system of side payments if the marginal benefits of one country are sufficiently large[3].

Petrakis and Xepapadeas (1996) show, also in a model with linear environmental damages, that the grand coalition can be stabilized through a system of self-financed side payments if the countries with larger environmental damages, identified in the paper as environmentally conscious countries (ENCCs), commit to cooperate provided that the difference in the environmental damages between the ENCCs and the countries with lower environmental damages, identified as the less environmentally conscious countries (LENCCs), is big enough[4]. The main difference with our analysis is that we do not assume commitment with respect to membership. In other words, we do not assume that there exists a previous commitment of a set of countries to cooperation before side payments are used to enlarge the agreement as Carraro and Siniscalco (1993) and Petrakis and Xepapadeas (1996) do. In our model all the signatories commit to cooperate acting in their own self-interest[5].

More recently, Barrett (2001) has shown in a model without commitment that side payments can sustain a vastly superior level of cooperation compared to the agreement without side payments if there exists strong asymmetry. He argues that strong asymmetry supports a change in the rules of the game by effectively *committing* some countries to being non-signatories to an agreement eschewing transfers. In this case, international cooperation can be bought and transfers become the vehicle for increasing participation. In this paper we show that this is also the case in a more general setting and we emphasize the fact that strong asymmetry generates the resources to eliminate the free-riding incentives of the countries with low environmental damages and in this way makes viable an agreement with a higher level of cooperation. Moreover, we show that

3. We would obtain the same result in our model if there were only one or two countries with large environmental damages.

4. Carraro and Siniscalco (1993) also show that commitment can increase the number of signatories by means of self-financed side payments in a model with quadratic environmental damages and identical countries.

5. Hoel and Schneider (1997) point out, also in a model with linear environmental damages where all the countries are identical except in some non-environmental costs that depends on the number of signatories and represents the effects of social norms, that the prospect of receiving a transfer tends to reduce the incentive a country might have to join the agreement. In fact, they found that if the maximal stable coalition without transfers is smaller than the grand coalition, then the maximal stable coalition with transfers is smaller than the maximal stable coalition without transfers. Comparing these results with the ones obtained in this paper it seems clear that Hoel and Schneider's (1997) result depends critically on their specification of the non-environmental costs.

there exists a positive relationship between the degree of cooperation and the degree of asymmetry[6].

Finally, we would like to comment on the interesting papers written by Eyckmans and Finus (2004) and Weikard (2005). In these two papers a revision of the standard definition of a self-enforcing agreement to consider the possibility of side payments very similar to ours is presented although, in both papers, the definition of stability is based on a previous definition of a sharing scheme whereas we emphasize that the stability issue can be analyzed without specifying previously a sharing rule. Nevertheless, this is not a big difference since it is easy to check that our statements of what is understood by a stable agreement with asymmetric countries converge to the same condition to get a higher level of cooperation with side payments: an agreement only can be self-enforcing is the aggregate gains from cooperation are enough to eliminate the free rider incentives of the countries that lose joining the agreement. The main difference of our paper with Eyckmans and Finus (2004) is about the level of cooperation that can be reached using transfers. Eyckmans and Finus (2004) shows that for any transfer scheme that belongs to the set of almost ideal sharing schemes there exists at least one stable non-trivial coalition[7]. However, given the generality of their model they cannot establish which could be the scope and gains associated to the stable non-trivial coalition. In our paper, we take a step forward in this direction although paying the price of working with a less general model. We analytically show that the level of cooperation that can be reached using transfers increases with the difference in the environmental damages which implies that an agreement consisting of a great number of countries may be self-enforcing if the difference in the environmental damages is sufficiently large[8]. As regards Weikard's (2005) paper, firstly, we would like to point out that his model

6. In Barrett's (2001) model there are also two types of countries but countries are restricted to select only two actions: to pollute or to abate. In our model we assume that countries can select their emissions from zero to the level of business as usual emissions. This change the nature of the game and the kind of equilibria that characterize the solution.

7. See their corollary 1 in page 10 where a non-trivial coalition is a coalition consisting of at least two countries and their definition of an almost ideal sharing scheme in page 6.

8. In a later paper, see Carraro, Eyckmans and Finus (2005), these authors have completed their theoretical analysis with an empirical application. They found using the CLIMNEG World Simulation Model proposed by Eyckmans and Tulkens (2003) that transfers make a difference which, on the other hand, is consistent with the theoretical results obtained in this paper.

on the provision of public goods of section 5 is very similar to one solved in this paper[9]. However, given the complete asymmetry he assumes, which makes the model pretty complex, the unique result obtained about the level of cooperation is that the grand coalition can be self-enforcing if the degree of asymmetry is sufficiently large[10]. In this working paper we complete this result showing that between the grand coalition and the fully noncooperative equilibrium there can exist partial coalitions that can be also self-enforcing depending of the differences in the environmental damages between the countries. Finally, we also show that what is determinant to explain the level of cooperation is the degree of asymmetry in the environmental damages no in the abatement costs[11].

Finally, we would like to clarify two issues. Firstly, we realize that the linearity of environmental damages we assume yields orthogonal reaction functions, i.e., the optimal emissions of a country do not depend on the emissions of the rest of countries which can be viewed as something very restrictive[12]. However, we think that our model can be useful, at least in a first approach, since the symmetric version of the model establishes that the level of cooperation reached through a self-enforcing agreement cannot be greater than three countries. Given this outcome for the symmetric case, we can interpret any deviation from this result as an effect of the asymmetry and we can measure this effect on the scope of

9. Weikard's (2005) model is a public good model with linear benefits and quadratic costs, and completely asymmetric, whereas our model is a public bad model with linear (environmental) damages and quadratic abatement costs, and two types of countries.

10. See his proposition 3 in page 18. Notice that by definition to check the stability of the grand coalition is not necessary to look at the external stability condition what, on the other hand, makes the analysis simpler.

11. In the revision of the literature we have just presented we have focused on the theoretical contributions to the issue studied in the paper but we should mention as well that there exist several papers that have addressed the same issue using numerical simulations or empirical models. See, for instance, Hoel (1992), Barrett (1997), Botteon and Carraro (1997, 2001), and more recently Bosello, Buchner and Carraro (2003), Carraro, Eyckmans and Finus (2005), Altamirano-Cabrera and Finus (2006) and Weikard, Finus and Altamirano-Cabrera (2006). Roughly speaking, all paper basically conclude that transfers can be conducive to the success of self-enforcing agreements, but that outcomes crucially depend on the particular transfer rule, the model and the data set. This is very clear in Carraro, Eyckmans and Finus (2005) where the outcomes of different transfer schemes are compared for the same empirical model.

12. Nevertheless, this assumption has been used frequently in the literature on the stability of international environmental agreements by other authors. See Hoel (1992), Petrakis and Xepapadeas (1996), Botteon and Carraro (1997), Hoel and Schneider (1997) and more recently Breton, Fredj and Zaccour (2006).

cooperation just comparing the number of signatories with three. Last but not least the model can be analytically solved[13]. Secondly, following the approach adopted by Carraro and Siniscalco (1993), Barrett (1994), Chander and Tulkens (1997) and by many scholars afterwards, we focus on the case where only one IEA is formed and the only question remaining is the size of the self-enforcing agreement. We are aware that this approach eliminates the possibility that different countries form different agreements, i.e., the possibility of an equilibrium with more than one agreement[14]. Nevertheless, we think that this approach may be reasonable for global environmental problems, such as the climate change problem, for which IEAs are usually unique and launched by the United Nations. In the last analysis, it could be interpreted as an institutional constraint.

The structure of the working paper is as follows. In section 2, we set up the model and introduce the definition of a stable IEA. In section 3, we solve the Nash equilibrium of the emission game for a given number of signatories. In section 4, we solve the symmetric case to use it as a benchmark. In section 5 and 6, we analyze the stability of IEAs with and without side payments considering, in section 5, that the only difference among countries is given by the abatement costs and, in section 6, that is given by the environmental damages. Section 7 summarizes our conclusions.

13. Although it is already available an analytical solution of the symmetric case with quadratic environmental damages, see Rubio and Ulph (2006), it is not so clear that an analytical solution for the asymmetric case can be obtained since the model becomes pretty complex when the non-negativity constraints on emissions are taken into account. See again Rubio and Ulph (2006). However, in our paper the non-negativity constraints do not create any difficulty in the analysis because the only thing we need to guarantee that these constraints are satisfied is high enough business as usual emissions.

14. However, it is not clear that the results are going to change a lot if the possibility of forming multiple coalitions is taken into account. At least, this is the finding obtained by Bosello, Buchner and Carraro (2003). In his empirical paper where multiple coalitions are allowed, no coalition structure with multiple coalitions is internally stable.

2. Self-Enforcing International Environmental Agreements

2.1. The model

Consider N countries that pollute a common environment and bargain over emission control of a specific pollutant. We assume that there are two types of countries: type 1 and type 2 so that $N_1 + N_2 = N$. We define $x_{ij} \geq 0$ as the emissions level generated by a country j of type i, and $X = \sum_{i,j}^{N} x_{ij} = \sum_{j=1}^{N_1} x_{1j} + \sum_{j=1}^{N_2} x_{2j}$ as the total emissions generated by all N countries. Each country derives a gross benefit from its emissions (think of the economic benefits of burning fossil fuels) so that the reduction of the emissions for controlling pollution implies some abatement costs denoted by $(c_i/2)(\delta_i - x_{ij})^2$. The parameter $\delta_i > 0$, that stands for the business as usual emission level, depends on the national technology, the economic structure, and the level of development. The parameter $c_i > 0$ represents the marginal cost of national abatement, depends on the national technology, and measures the intensity of the use of the pollutant for the production of goods and services. Each country also suffers environmental damages which depend on the total emissions according to the following expression $m_i X$, where $m_i > 0$ is the marginal environmental damage which depends on the environmental (natural) endowment of the country. Then, each country has a cost function which depends on its emissions just as on the total emissions[15]:
$C_{ij} = \frac{1}{2} c_i \left(\delta_i - x_{ij}\right)^2 + m_i X$ where $i = 1, 2$ and $j = 1, 2, ..., N_i$.

2.2. A self-enforcing IEA

We model the formation of an IEA as a two-stage game, in which in the first stage (the *Membership Game*) each country decides whether or not to

15. This is the cost function used by Botteon and Carraro (1997).

join a unique IEA, and in the second stage (the *Emissions Game)* each country determines its emissions and signatories can also determine a vector of self-financed side payments. We will describe each game briefly, in reverse order since we compute the subgame-perfect equilibria of this two-stage game by backward induction.

The emission game

Suppose that, as the outcome of the first-stage game, there are n_1 signatories of type 1 and n_2 signatories of type 2 (a typical signatory being denoted by s) and $(N_1 - n_1)$ non-signatory countries of type 1 and $(N_2 - n_2)$ non-signatory countries of type 2 (a typical non-signatory being denoted by f, for fringe or free-rider). Non-signatory countries choose their emissions acting non-cooperatively and taking as given the emissions of all other countries in order to minimize its own costs of controlling pollution. On the other hand, signatory countries choose emissions also acting non-cooperatively against non-signatories in order to minimize the *aggregate* costs of the $n = n_1 + n_2$ signatories. Signatories also take as given the strategy of non-signatories. Thus, emissions are given by the *partial agreement Nash equilibrium* with respect to a coalition defined by Chander and Tulkens (1995). Once the equilibrium is reached, signatories can establish a system of monetary transfers or side payments, T^s_{ij}, among them. Then, the costs of signatories and non-signatories at the equilibrium are given by $C^f_{ij}(n)$ and $C^s_{ij}(n) + T^s_{ij}$ with $\sum^n_{i,j} T^s_{ij} = 0$.

The membership game

We assume that in the first stage, countries play a *simultaneous open membership with a single agreement and full compliance*. In a single agreement formation game, the strategies for each country are to sign or not to sign and the agreement is formed by all players who simultaneously have chosen to sign. Under open membership any country is free to join the agreement if it is interested. Finally, we assume that the signature of the agreement is binding on signatories so that they acquire a commitment to stay and implement the agreement during the second stage of the game so that full compliance is achieved[16].

For these kinds of games, the definition of coalitional stability is due to D'Aspremont et al. (1983) which has been frequently applied in the

16. These assumptions are in line with the mainstream of the literature on coalition theory. For an overview see for instance Yi (2003).

literature on IEAs as for instance by Hoel (1992), Carraro and Siniscalco (1993) and Barrett (1994), among others.

Definition 1. *An IEA without side payments consisting of* n *signatories is self-enforcing if* $C_{ij}^{s}(n) \leq C_{ij}^{f}(n-1)$ *for all signatories and* $C_{ij}^{f}(n) \leq C_{ij}^{s}(n+1)$ *for all non-signatories.*

The first inequality, that is also known as the *internal stability condition,* simply means that any signatory country is at least as well-off staying in the IEA as quitting, assuming that all other countries do not change their membership decisions. The second inequality, that is also known as the *external stability condition,* similarly requires that any non-signatory is at least as well-off remaining a non-signatory than joining the IEA, assuming, again, that all other countries do not change their membership decisions. Actually, we can also define a self-enforcing IEA as a Nash equilibrium of the membership game [17].

Next, we rewrite this definition to take into account the possibility of side payments among signatories.

Definition 2. *An IEA consisting of* n *signatories is potentially self-enforcing if there exists at least one self-financed side payment system such that* $C_{ij}^{s}(n) + T_{ij}^{s}(n) < C_{ij}^{f}(n-1)$ *for all signatories and there does not exist any self-financed side payment system such that* $C_{ij}^{f}(n) \geq C_{ij}^{s}(n+1) + T_{ij}^{s}(n+1)$ *for all non-signatories.*

In other words, an agreement consisting of n countries is stable if the countries that win with the agreement can buy the cooperation of the countries that are interested in signing the agreement only if they are adequately compensated, and it is not possible to do the same for an agreement consisting of $n+1$ countries. We assume in the first part of the definition a strict inequality because it seems reasonable that, when transfers are included in the international negotiations, the countries that benefit from the agreement will not be interested in buying the cooperation if this means that all their gains must be transferred to the other countries, and that the countries that lose from the agreement will not be interested in selling the cooperation if they do not obtain, at least, a marginal gain. In the second part of the definition, we use a weak inequality because an agreement consisting of $n+1$ countries is not going

17. This interpretation of a self-enforcing agreement as a Nash equilibrium of the membership game was first established by Finus and Rundshagen (2003). See also an explanation of this equivalence in Rubio and Ulph (2006).

to be stable so that no transfers will be applied and it does not seem necessary to be as strict as in the other case [18].

Thus, the first part of definition 2 would operate as the internal stability condition with side payments and the second part as the external stability condition. This second part could be written as well saying that for all the possible self-financed side payment system $C_{ij}^{f}(n) \leq C_{ij}^{s}(n+1) + T_{ij}^{s}(n+1)$ holds for all non-signatories. Moreover, it is important to understand that $T_{ij}^{s}(n)$ stands for the transfer that receives the signatory j of type i when the agreement consists of n signatories whereas $T_{ij}^{s}(n+1)$ stands for the case of an agreement consisting of $n+1$ signatories. Thus, they belong to two different systems of side payments [19].

Given this definition is straightforward to show the following:

Lemma 1. *An IEA consisting of* n *signatories is potentially self-enforcing through a self-financed side payment system if and only if* $\sum_{i,j}^{n}\left(C_{ij}^{s}(n) - C_{ij}^{f}(n-1)\right) < 0$ *and* $\sum_{i,j}^{n+1}\left(C_{ij}^{s}(n+1) - C_{ij}^{f}(n)\right) \geq 0$.

Proof. Suppose that an agreement consisting of n countries is not self-enforcing without side payments but that $\sum_{i,j}^{n}\left(C_{ij}^{s}(n) - C_{ij}^{f}(n-1)\right) < 0$. If the agreement is not self-enforcing without side payments it must be true that at least one country loses with the agreement, i.e., $C_{ij}^{s}(n) - C_{ij}^{f}(n-1) > 0$. In this case there must exist $\tilde{n}$ signatories with $\tilde{n} \in [1, n)$ for which $C_{ij}^{s}(n) - C_{ij}^{f}(n-1) < 0$ and $\mid \sum_{i,j}^{\tilde{n}}\left(C_{ij}^{s}(n) - C_{ij}^{f}(n-1)\right) \mid > \sum_{i,j}^{n-\tilde{n}}\left(C_{ij}^{s}(n) - C_{ij}^{f}(n-1)\right) > 0$ hold. Then there exists at least one system of self-financed side payments through which the $\tilde{n}$ signatories can buy the cooperation of the countries that lose joining the agreement so that for all signatories $C_{ij}^{s}(n) + T_{ij}^{s}(n) < C_{ij}^{f}(n-1)$ and the agreement is internally stable. Now we check that if an agreement consisting of n signatories is internally stable then condition $\sum_{i,j}^{n}\left(C_{ij}^{s}(n) - C_{ij}^{f}(n-1)\right) < 0$ must be satisfied. The internal stability condition can be written as $T_{ij}^{s}(n) < C_{ij}^{f}(n-1) - C_{ij}^{s}(n)$ for all signatories so that adding terms we get

18. Nevertheless, we would like to point out that the same results are obtained if weak inequalities are assumed although in this case a rule should be established to decide which would be the stable coalition if the two conditions are satisfied as an equality.

19. We use in definition 2 the word *potentially* because the agreement could not be implemented finally because of a disagreement in the distribution of the gains coming from cooperation.

$\sum_{i,j}^{n} T_{ij}^{s}(n) = 0 < \sum_{i,j}^{n} \left(C_{ij}^{f}(n-1) - C_{ij}^{s}(n) \right)$ which implies that $\sum_{i,j}^{n} \left(C_{ij}^{s}(n) - C_{ij}^{f}(n-1) \right) < 0$. Next, suppose that an agreement consisting of $n+1$ countries is not self-enforcing without side payments and that $\sum_{i,j}^{n+1} \left(C_{ij}^{s}(n+1) - C_{ij}^{f}(n) \right) \geq 0$. In this case although there could exist $\tilde{n}$ countries with $\tilde{n} \in [1, n+1)$ for which $C_{ij}^{s}(n+1) - C_{ij}^{f}(n) < 0$, $| \sum_{i,j}^{\tilde{n}} \left(C_{ij}^{s}(n+1) - C_{ij}^{f}(n) \right) | \geq \sum_{i,j}^{n+1-\tilde{n}} \left(C_{ij}^{s}(n+1) - C_{ij}^{f}(n) \right) > 0$ does not hold. Then there does not exist any system of self-financed side payments such that for all signatories $C_{ij}^{s}(n+1) + T_{ij}^{s}(n+1) \leq C_{ij}^{f}(n)$ and the agreement consisting of $n+1$ signatories is internally unstable. Then, by definition, we can conclude that an agreement consisting of n signatories is externally stable. Finally, we check that if an agreement consisting of n signatories is externally stable then condition $\sum_{i,j}^{n+1} \left(C_{ij}^{s}(n+1) - C_{ij}^{f}(n) \right) \geq 0$ must be satisfied. The external stability condition establishes that for all possible self-financed side payment system $C_{ij}^{f}(n) \leq C_{ij}^{s}(n+1) + T_{ij}^{s}(n+1)$ holds for all non-signatories. This condition can be written as $C_{ij}^{f}(n) - C_{ij}^{s}(n+1) \leq T_{ij}^{s}(n+1)$ so that adding terms we obtain $\sum_{i,j}^{n+1} \left(C_{ij}^{f}(n) - C_{ij}^{s}(n+1) \right) \leq \sum_{i,j}^{n+1} T_{ij}^{s}(n+1) = 0$ which implies that $\sum_{i,j}^{n+1} \left(C_{ij}^{s}(n+1) - C_{ij}^{f}(n) \right) \geq 0$. Thus, we can conclude that if conditions $\sum_{i,j}^{n} \left(C_{ij}^{s}(n) - C_{ij}^{f}(n-1) \right) \leq 0$ and $\sum_{i,j}^{n+1} \left(C_{ij}^{s}(n+1) - C_{ij}^{f}(n) \right) \geq 0$ are satisfied, the internal and external stability conditions hold for an agreement consisting of n signatories and the agreement is self-enforcing.

Looking at each national difference $C_{ij}^{s}(n) - C_{ij}^{f}(n-1)$ it can be established whether the side payment must be positive or negative for a particular signatory, i.e., it can be established whether a country must compensate to other countries or whether it must be compensated by other countries and which is the maximum side payment that it is ready to pay to buy the cooperation of other countries in the first case and which is the minimum side payment that it is ready to receive to sell its cooperation in the second case. If the agreement is self-enforcing we know that the sum of maximum side payments that some countries are ready to pay to buy cooperation is greater than the sum of minimum side payments that the other countries ask for selling the cooperation. Then there must exist at least one sharing rule that makes the agreement stable [20]. Finally, we would like to point out that this result opens a new line of research on the stability of coalitions since it shows that it is possible to separate the stability analysis from the distributional problem of the gains coming from cooperation. In other words, using proposition 1, the stability of an agreement can be analyzed independently of the sharing rule used by the coalition. Thus, if the conditions in proposition 1 are satisfied we know that the free-rider incentives can eliminated through a system of side payments. Maybe this system do not satisfy other attractive properties but we know that there exists at least one instrument to make stable the agreement.

20. It is easy to show that the agreement is also profitable for the signatories because of the positive spillovers that characterize the emissions game. See section 3 for a complete explanation.

3. The Nash Equilibrium of the Emission Game

SUPPOSE that, as the outcome of the first-stage game, there are $n = n_1 + n_2$ signatories and $(N - n)$ non-signatories. A non-signatory country takes as given the emissions of the other countries and chooses x_{ik}^f to solve

$$\min_{\{x_{ik}^f\}} C_{ik}^f = \frac{1}{2} c_i \left(\delta_i - x_{ik}^f\right)^2 + m_i X,$$

where $X = \sum_{i,j}^n x_{ij}^s + \sum_{i,j}^{N-n} x_{ij}^f$. The first order conditions (FOC) yields $x_{ik}^f = \delta_i - (m_i/c_i),\ i = 1, 2$. Then as all non-signatories of the same type choose the same emissions, we can simplify the notation and use x_i^f to represent the non-signatory emissions of type i country. Moreover, given the linearity of the damage function, the best-reply functions are orthogonal which means that the optimal non-signatory emissions do not depend on the signatory emissions[21]. This also means that non-signatory emissions do not depend on the level of cooperation.

On the other hand, signatories are assumed to coordinate in order to minimize their aggregate costs taking as given the emissions of non-signatories.

$$\min_{\{x_{ij}^s\}} C(n_1, n_2) = \sum_{i,j}^n C_{ij}^s = \sum_{i,j}^n \left(\frac{1}{2} c_i \left(\delta_i - x_{ij}^s\right)^2 + m_i X\right).$$

The FOC yield

$$x_{ij}^s = \delta_i - \frac{\sum_i m_i n_i}{c_i},\ \ i = 1, 2. \tag{3.1}$$

21. In the literature on IEAs, this kind of situation is also known as an emissions game without carbon leakage.

Again we can simplify the notation using x_i^s to represent the signatory emissions of type i countries[22]. However, in this case, signatory emissions decrease with the size of the agreement.

The aggregate emissions are

$$X(n_1, n_2) = \sum_i^s \left(\delta_i - \frac{\sum_i m_i n_i}{c_i} \right) + \sum_i^f \left(\delta_i - \frac{m_i}{c_i} \right),$$

which yields the following expression after developing the additions

$$\begin{aligned} X\left(n_1, n_2\right) &= N_1 \left(\delta_1 - \frac{m_1}{c_1} \right) + N_2 \left(\delta_2 - \frac{m_2}{c_2} \right) \\ &\quad - \frac{n_1}{c_1} \left(m_1 \left(n_1 - 1 \right) + m_2 n_2 \right) - \frac{n_2}{c_2} \left(m_1 n_1 + m_2 \left(n_2 - 1 \right) \right). \end{aligned} \tag{3.2}$$

Notice that the aggregate emissions decrease with respect to the size of the agreement.

Finally, we obtain the cost functions of signatories and non-signatories.

$$C_i^s\left(n_1, n_2\right) = \frac{1}{2c_i} \left(\sum_i m_i n_i \right)^2 + m_i X\left(n_1, n_2\right), \ i = 1, 2, \tag{3.3}$$

$$C_i^f\left(n_1, n_2\right) = \frac{m_i^2}{2c_i} + m_i X\left(n_1, n_2\right), \ i = 1, 2. \tag{3.4}$$

Although non-signatories always choose the same emissions irrespective of the size and composition of the coalition, their cost functions depend on the emissions chosen by signatories since environmental damages are a function of the total emissions. The result is that both the cost functions of non-signatories and the cost functions of signatories depend on the size and composition of the agreement[23]. Moreover, it is easy to check from (3.4) that non-signatory costs are decreasing with the size of the agreement given that the aggregate emissions decrease with the number of signatories. This means that in this game there are positive spillovers since an increase in the number of

22. A high enough δ_i guarantees that emissions are positive.

23. Notice that if $(n_1, n_2) = (N_1, N_2)$, the emissions and costs corresponding to the fully cooperative equilibrium are obtained from (3.1) and (3.3), and that if $(n_1, n_2) = (0, 0)$ the costs corresponding to the fully non-cooperative equilibrium are obtained from (3.4).

signatories reduces the non-signatories' costs. Consequently, we can conclude that if the internal stability condition is satisfied for a country, the profitability condition is also satisfied[24]. However, the effect of an increase of the number of signatories on the costs of a signatory depends on the type of country that enters the agreement. If we calculate the first partial derivatives of the cost function of a country of type i with respect to number of signatories of type i we obtain

$$\frac{\partial C_i^s}{\partial n_i} = m_i^2 \left(\frac{1 - n_i}{c_i} - \frac{n_j}{c_j} \right), \quad i, k = 1, 2, \quad i \neq k.$$

This derivative is negative for $n_i \geq 1$ so that if there is a signatory of type i in the agreement, the entry of a new country of type i reduces the costs of the signatory of type i. However, if we calculate the cross effects the sign is ambiguous: the enter of a new country of type i to the agreement can increase or decrease the costs of a country of type k.Finally, it is easy to check that for a given number of signatories, the costs of non-signatories are lower than the costs of signatories of the same type and that this difference increases with the number of signatories.

The formal analysis of stability using (3.3) and (3.4) becomes intractable. For that reason, in this paper we develop the stability analysis in two steps. First, we assume that there are not differences in marginal environmental damages among countries and we focus on the differences in marginal abatement costs. After that, we will analyze the case for which countries are asymmetric in marginal environmental damages, but symmetric in marginal abatement costs. In this way, we will have an idea concerning the effects of asymmetry on the scope of cooperation.

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24. Remember that the internal stability condition requires that $C_i^s(n) \leq C_i^f(n-1)$ or $C_i^s(n) + T_i^s(n) \leq C_i^f(n-1)$, then as $C_i^f(n-1) < C_i^f(0)$ we get that $C_i^s(n) < C_i^f(0)$ or $C_i^s(n) + T_i^s(n) < C_i^f(0)$ so that the profitability condition holds.

4. The Symmetric Model

HERE we present the results of the symmetric model with the objective of having a benchmark for comparing the results obtained under asymmetry. Using the results of section 3 we obtain for the symmetric case the following

$$x^f = \delta - \frac{m}{c}, \quad x^s(n) = \delta - \frac{m\,n}{c}, \tag{4.1}$$

$$C^f(n) = \frac{m^2}{2c} + mX(n), \quad C^s(n) = \frac{m^2 n^2}{2c} + m\,X(n), \tag{4.2}$$

where the aggregate emissions are given by (3.2)

$$X(n) = N\left(\delta - \frac{m}{c}\right) - \frac{n}{c}\left(m(n-1)\right). \tag{4.3}$$

If all the countries are identical, the cooperation cannot be bought through side payments since all the countries will have the same incentive to free ride if the agreement is not internally stable. In this case we use the stability conditions of definition 1 to analyze the stability of an IEA. Beginning with the internal stability condition we obtain the following expression

$$C^s(n) - C^f(n-1) = \frac{m^2}{2c}(n^2 - 4n + 3) \leq 0 \quad \text{for } n = \{2, 3\}, \tag{4.4}$$

whereas the external stability condition yields

$$C^f(n) - C^s(n+1) = -\frac{m^2}{2c}n(n-2) \leq 0 \quad \text{for all } n \geq 2. \tag{4.5}$$

Therefore, only partial coalitions consisting of 2 or 3 countries can be stable. So with symmetric countries the maximum level of cooperation that can be reached through a stable agreement is of 3 countries[25].

25. This is the same result that is obtained for the case of countries that maximize the net benefits coming from emissions. See for instance Breton, Fredj and Zaccour (2006) where they use a linear quadratic gross benefit function and linear environmental damages.

5. The Nash Equilibrium of the Membership Game with Differences in Abatement Costs

IN this section we assume that $m_1 = m_2 = m,\ \delta_1 = \delta_2 = \delta,\ and\ c_1 \neq c_2$*. In addition, we normalize c_2 equal to one and we introduce the assumption that countries of type 1 support larger abatement costs, that is, $c_1 > 1$. Considering these assumptions the costs functions for signatories and non-signatories according to their type can be calculated from expressions of section 3. Using these costs functions we have analyzed the stability for two different settings: with and without side payments.

5.1. Stable IEA without side payments

As we have shown in section 3, if internal stability conditions are satisfied, profitability conditions also hold. Consequently, in this section we develop the stability analysis using only the internal and external stability conditions. The result of this analysis is summarized in the following proposition.

Proposition 2. *The maximum level of cooperation that can be reached through a self-enforcing IEA without side payments consists of three countries of the same type independently of the differences in the abatement costs.*

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*. Notice that the marginal abatement costs depend both on δ and c in the following way: $c_i(\delta_i - x_i)$. This means that if we assume that there exists a difference in δ_i, we are assuming that the countries differ only in the intersection point with the vertical axis of the marginal abatement cost function. However, if we assume a difference in c_i, the countries differ not only in the intersection point with the vertical axis but also in the slope of the marginal abatement cost function. Thus, as the difference in c_i incorporates both a change in the intersection point and a change in the slope, in order to simplify the analysis we assume in the paper that there are not differences in δ but only in c.

Proof. See appendix A.1.

This result establishes that when the agreement consists of countries of the same type there is not differences with the symmetric case and that any agreement with different types of countries is not stable. Basically, the logic behind this result is that the internal stability condition for countries of type 1 is satisfied when the differences in the abatement costs is large enough whereas to satisfy the internal stability condition for countries of type 2, the contrary is required. The conclusion is that there do not exist values for c_1 satisfying the internal stability condition for an agreement with both types of countries.

5.2. Stable IEA with side payments

As we have just shown in the previous section, if side payments are not taken into account, the maximum size of a stable coalition is equal to three countries but of the same type. Now, we are going to explore the possibility of reaching a larger coalition if side payments are explicitly considered. Therefore, the aim of this section is to find the values for n_1 and n_2 that satisfy the conditions of lemma 1.

Using lemma 1 the following result is obtained

Proposition 3. *Only an IEA consisting of two signatories of different type is potentially self-enforcing through a self-financed payment system independently of the differences in the abatement costs.*

Proof. See appendix A.2.

If the countries in the agreement are of the same type, the free rider incentive is the same for all the signatories and the cooperation cannot be expanded using side payments. In this case proposition 1 applies. If the countries in the agreement are different, one country of type 1 can buy the cooperation of one country of type 2. However, when the number of signatories increases the incentives of the countries of type 2 to withdraw from the agreement also increase whereas the available resources of the countries of type 1 to buy the cooperation do not increase in the same proportion or even they can decrease [26]. On the other hand, with two or more signatories of type 1, the agreement is not stable because in this case are the signatories of this type the ones that are interested in leaving the

26. This could occur, according to what has been established in section 3, when a new country of type 2 enters in the agreement. In this case, the costs of the signatory of type 1 could increase or decrease since the sign of the cross effects is ambiguous.

agreement. The result is that an agreement consisting of three countries is not stable. Thus, only two countries, one of type 1 and another of type 2 can form a self-enforcing agreement with side payments with difference only in abatement costs.

6. The Nash Equilibrium of the Membership Game with Differences in Environmental Damages

IN this section we assume that $\delta_1 = \delta_2 = \delta,\ c_1 = c_2 = c,\ and\ m_1 \neq m_2$, actually we consider that $m_2 = 1$ and $m_1 > 1$. Therefore, we face a game where countries of type 1 support larger marginal environmental damages. Considering these assumptions, the costs functions for signatories and non-signatories according to their type can be calculated from expressions of section 3. Using these costs functions we have analyzed the stability in two different settings: with and without side payments.

6.1. Stable IEA without side payments

As in the previous case studied in section 5, we are going to focus only on the internal and external stability conditions. Applying these conditions we obtain the following result

Proposition 4. *The maximum level of cooperation that can be reached through a self-enforcing IEA without side payments consists of three countries of the same type independently of the differences in the environmental damages. An agreement consisting of one country of type 1 and one country of type 2 can be as well self-enforcing if the differences in the environmental damages are not very large.*

Proof. See appendix A.3.

If the agreement consists of countries of the same type, again there are not differences with the symmetric case. However, now an agreement consisting of one country of type 1 and one country of type 2 can be stable if the difference in the environmental damages in relative terms is not greater than 40%. The reason that explains this result is that if the environmental damages are not very large, the cooperation between two countries of different type can be profitable for both since the reduction in emissions that both have to support will not be very large either. In this case, the profitability of the agreement implies its internal stability since for a bilateral agreement, the alternative to be in the agreement is to support the costs corresponding to the fully non-cooperative equilibrium that with low environmental damages are greater for both types of countries. However, with a second country of type 2 in the agreement, the alternative for the countries of type 2 to be in the agreement is to be a free rider of an agreement with two signatories what with positive externalities yields lower costs so that the agreement is not internally stable. Then by definition of the stability conditions, the agreement consisting of one country of type 1 and one country of type 2 is externally stable and given that it is also internally stable we can conclude that it is self-enforcing. This limits the scope of the cooperation between countries of different type to a bilateral agreement provided that the differences in the environmental damages are not very large. Summarizing, we cannot expect that the asymmetry in the environmental damages makes the formation of an agreement with a high degree of participation possible.

6.2. Stable IEA with side payments

We have concluded in the previous section that, if countries differ only in environmental damages and side payments are not allowed, our candidates for being stable agreements are coalitions whose size is lower than or equal to 3. Hence, in this section, we are going to analyze if larger stable coalitions can be reached when transfers between countries are taken into account.

The results of our analysis can be summarized as follows.

Proposition 5. *The level of cooperation that can be bought through a self-financed payment system increases with the difference in the environmental damages provided that cooperation is only bought by one or two countries of type 1.*

Proof. See appendix A.4.

This proof says that a country of type 1 or two countries of type 1 can buy the cooperation of some countries of type 2 and that the larger are the environmental damages, the larger is the level of cooperation that can be bought. In table 6.1 the relationship between the environmental damages and the number of signatories is represented according to the results obtained in the proof of proposition 4. In this proof we find that for any level of cooperation n, there exists an interval of values for m_1 for which this level of cooperation is stable. These intervals are represented in table 6.1. In the first column appears the level of cooperation defined by the number of signatories, in the second one the range of values of m_1 that supports the corresponding level of cooperation when the agreement consists of only one signatory of type 1 and $n-1$ signatories of type 2, and in the third one appears the range of values of m_1 that supports the corresponding level of cooperation when the agreement consists of two signatories of type 1 and $n-2$ signatories of type 2. Thus, for instance, when $m_1 = 4$ one country of type 1 can buy the cooperation of three countries of type resulting in an agreement consisting of four countries. However, for the same value of the marginal environmental damages, two countries of type 1 only can buy the cooperation of one country of type 2 resulting in an agreement of three countries. Nevertheless, the table shows that in both cases the level of cooperation increases with the difference in the environmental damages between both types of countries[27]. According to this result, the maximum level of cooperation that can be reached through a system of side payments is $N_2 + 2$ depending of the degree of asymmetry, i.e., the grand coalition cannot be a self-enforcing agreement except when in the game there are only one or two countries of type 1.

TABLE 6.1: Asymmetry and cooperation

n	$m_1(n_1 = 1)$	$m_1(n_1 = 2)$
3	(1,3.73]	(1,7.87]
4	(3.73,5.83]	(7.87,18.16]
5	(5.83,7.87]	(18.16,32.43]
6	(7.87,9.90]	(32.43,50.69]
7	(9.90,11.92]	(50.69,72.94]
8	(11.92,13.93]	(72.94,99.20]
9	(13.93,15.94]	(99.20,129.45]
10	(15.94,17.94]	(129.45,163.70]

The reason of why only one or two countries of type 1 can belong to a self-enforcing agreement is very similar to the reason that explains the second part of proposition 3: an agreement consisting of two countries is always internally stable if is profitable. With only two countries the

27. Remember that we have normalize $m_2 = 1$.

agreement is profitable because if the countries do not form the agreement they have to support a greater cost, the cost corresponding to the fully non-cooperative equilibrium that it is always greater independently of the differences in the environmental damages. The result is that the agreement is also internally stable since in this case the two signatories do not have any incentive to leave from the agreement. In other words, for an agreements consisting of two signatories of the same type, the profitability implies the internal stability of the agreement given the inefficiency of the fully non-cooperative equilibrium. However, with three countries of the same type, the alternative to be in the agreement is to be a free rider of an agreement with two signatories and the result is different. Now the signatories have an incentive to exit from the agreement and, moreover, this incentive is the same for the three countries since they are identical. The consequence is that an agreement with more than two signatories of type 1 is not internally stable since in this case they have also an incentive to act as free riders so that an agreement with more than two countries of type 1 cannot be self-enforcing[28].

Finally, we would like to point out that looking at the figures in table 6.1 it is clear that a strong asymmetry is going to be needed to support a high degree of cooperation. For instance, with two signatories of type 1 the marginal environmental damage must belong to interval $(7.87, 18.16]$ to buy the cooperation of two countries of type 2 whereas the marginal environmental damage must belong to interval $(129.45, 163.79]$ for buying the cooperation of eight countries of type and forming an agreement consisting of ten countries. However, when there is only one signatory of type 1, the degree of asymmetry required to reach an agreement of ten countries is not so strong. This suggests that maybe with more types of countries, the same level of cooperation could be reached with a lower degree of asymmetry. Obviously, this is a conjecture that should be investigated in the future.

28. In the symmetric case the agreement can be formed by three countries because without side payments the stability conditions are defined as weak conditions. Notice that for $n = 3$ the internal stability condition is zero for the symmetric case. See (4.4).

7. Conclusions

IN this working paper, we have analyzed the stability of IEAs under the assumption of asymmetry when countries agree to use side payments. To model the formation of an IEA we have proposed a two-stage game we have analytically solved. The timing of the game is the following: in the first stage each country decides or not to join a unique IEA and in the second each country chooses its emissions and signatories can also establish a system of self-financed side payments. In this setting an agreement will be self-enforcing if no signatory country has incentives to leave the agreement and if no non-signatory has incentives to join the agreement, taking as given the membership decisions of all other countries and the transfers that they receive or pay.

Our findings allow us to conclude that the asymmetry between countries has no relevant effects on the scope of environmental cooperation in comparison with the symmetric case if side payments are not allowed. In this case only countries of the same type are interested in joining the agreement yielding the same result that in the symmetric case although we have found that if the countries differ only in the environmental damages a bilateral agreement consisting of one country of each type can be self-enforcing provided that the difference in the marginal environmental damages between the two countries is not very large. With side payments the effects depend on the kind of asymmetry. When the differences are in the abatement costs the cooperation cannot be enlarged through a system of side payments. On the contrary, when the countries differ in the environmental damages the level of cooperation that can be bought through a self-financed payment system increases with the degree of asymmetry. This result confirms in a more general setting the one obtained by Barrett (2001) that establishes that a strong asymmetry can lead to a high degree of international cooperation if side payments are used. Moreover, our result establishes formally a positive relationship between the scope of cooperation and the degree of asymmetry.

The following step of this research should be try to generalize our conclusions to more than two types of countries, actually, a case that considers that all the countries are different would be interesting. It would be also of interest to study the case with increasing environmental damages. Another possible future research line would be to use the definition of stability with side payments and the conditions of lemma 1 to evaluate if the more common sharing rules used in the literature can or cannot promote the cooperation from a non-cooperative game-theoretic approach, in other words, the compatibility between these rules and the conditions of lemma 1 that guarantee the stability with side payments.

Appendices

Appendix A.1. Proof of proposition 1

USING the expressions of section 3, the cost functions for non-signatories are

$$C_1^f(n_1,n_2)=\frac{m^2}{2c_1}+m\,X(n_1,n_2)\,,\;\;C_2^f(n_1,n_2)=\frac{m^2}{2}+m\,X(n_1,n_2)\,, \tag{A.1.1}$$

and for signatories are

$$C_1^s(n_1,n_2) = \frac{m^2(n_1+n_2)^2}{2c_1}+m\,X(n_1,n_2)\,, \tag{A.1.2}$$

$$C_2^s(n_1,n_2) = \frac{m^2(n_1+n_2)^2}{2}+m\,X(n_1,n_2)\,, \tag{A.1.3}$$

where the aggregate emissions are given by the following expression

$$X(n_1,n_2)=N_1\left(\delta-\frac{m}{c_1}\right)+N_2(\delta-m)-\left(\frac{n_1}{c_1}+n_2\right)(n_1+n_2-1)\,m. \tag{A.1.4}$$

In the analysis of the stability we have to distinguish three possible cases: 1. An agreement consisting of countries of type 1; 2. An agreement consisting of countries of type 2; 3. A mixed agreement joined by countries of type 1 and type 2.

Case 1. For this case the internal stability condition is written as follows

$$C_1^s(n_1,0)-C_1^f(n_1-1,0)=\frac{m^2}{2c_1}\left(n_1^2-4n_1+3\right)\leq 0,$$

which is satisfied for $n_1=\{2,3\}$. Therefore we have the same result that in the symmetric case.

Case 2. If in the agreement there are only countries of type 2, the internal stability condition is

$$C_2^s(0,n_2)-C_2^f(0,n_2-1)=\frac{m^2}{2}\left(n_2^2-4n_2+3\right)\leq 0,$$

that again establishes that the largest stable agreement consists of three countries of type 2.

Case 3. First of all, let us consider the internal stability condition for the countries of type 1

$$\begin{aligned} & C_1^s(n_1,n_2) - C_1^f(n_1-1,n_2) \\ = \; & \frac{m^2}{2c_1}\left((n_1+n_2)^2 - 4n_1 - 2n_2 + 3 - 2c_1 n_2\right) \leq 0, \end{aligned} \quad \text{(A.1.5)}$$

which is satisfied if

$$c_1 \geq \frac{(n_1+n_2)^2 - 4n_1 - 2n_2 + 3}{2n_2}. \quad \text{(A.1.6)}$$

The internal stability condition for the countries of type 2 is

$$\begin{aligned} & C_2^s(n_1,n_2) - C_2^f(n_1,n_2-1) \\ = \; & \frac{m^2}{2c_1}\left(c_1\left((n_1+n_2)^2 - 4n_2 - 2n_1 + 3\right) - 2n_1\right) \leq 0, \end{aligned} \quad \text{(A.1.7)}$$

which holds if

$$c_1 \leq \frac{2n_1}{(n_1+n_2)^2 - 4n_2 - 2n_1 + 3}. \quad \text{(A.1.8)}$$

(A.1.6) and (A.1.8) give us a lower bound and an upper bound to c_1. Therefore an agreement consisting of $n = n_1 + n_2$ countries is *internally stable* if and only if

$$\frac{(n_1+n_2)^2 - 4n_1 - 2n_2 + 3}{2n_2} \leq c_1 \leq \frac{2n_1}{(n_1+n_2)^2 - 4n_2 - 2n_1 + 3}. \quad \text{(A.1.9)}$$

As $n = n_1 + n_2$ (A.1.9) can be rewritten as follows

$$\frac{n^2 - 2n_1 - 2n + 3}{2(n-n_1)} \leq c_1 \leq \frac{2n_1}{n^2 - 4n + 2n_1 + 3}. \quad \text{(A.1.10)}$$

It is obvious that in order to have at least one value for c_1 satisfying (A.1.10), the upper bound must be higher or equal to the lower bound. So, the following inequality must be satisfied

$$\frac{n^2 - 2n_1 - 2n + 3}{2(n-n_1)} \leq \frac{2n_1}{n^2 - 4n + 2n_1 + 3}, \quad \text{(A.1.11)}$$

that can be rewritten as

$$\begin{aligned}\left(n^2 - 2n_1 - 2n + 3\right)\left(n^2 - 4n + 2n_1 + 3\right) &\leq 4n_1\left(n - n_1\right), \\ n^4 - 6n^3 + 14n^2 - 18n + 9 &\leq 0.\end{aligned}$$

Calculating the roots of this polynomial we find that (A.1.11) is only satisfies when $n = \{2, 3\}$. When $n = 3$, (A.1.10) is satisfied only if $c_1 = 1$ which contradicts our initial hypothesis[29]. Therefore, there does not exist a self-enforcing mixed agreement with more than 2 signatories. Let us deal with the bilateral agreement. Internal stability conditions hold if $c_1 \in (1, 2]$ defined by (A.1.10) for $n = 2$ and $n_1 = 1$. However, the external stability condition of countries of type 1

$$C_1^f(1,1) - C_1^s(2,1) = \frac{m^2}{c_1}(c_1 - 1) \leq 0$$

holds only if $c_1 < 1$. Again, we arrive to a contradiction. Therefore, we can conclude that there does not exist a self-enforcing agreement consisting of both types of countries.

29. Remember that we have assumed that $c_1 > 1$.

Appendix A.2. Proof of proposition 2

WE focus on an agreement with countries of the two types. According to the conditions of lemma 1 an agreement with n_1 signatories of type 1 and n_2 signatories of type 2 is self-enforcing if the following conditions are satisfied

$$n_1\left(C_1^s(n_1,n_2) - C_1^f(n_1-1,n_2)\right)$$

$$+n_2\left(C_2^s(n_1,n_2) - C_2^f(n_1,n_2-1)\right) < 0, \qquad (A.2.1)$$

$$(n_1+1)\left(C_1^s(n_1+1,n_2) - C_1^f(n_1,n_2)\right)$$

$$+n_2\left(C_2^s(n_1+1,n_2) - C_2^f(n_1+1,n_2-1)\right) \geq 0, \qquad (A.2.2)$$

$$n_1\left(C_1^s(n_1,n_2+1) - C_1^f(n_1-1,n_2+1)\right)$$

$$+(n_2+1)\left(C_2^s(n_1,n_2+1) - C_2^f(n_1,n_2)\right) \geq 0, \qquad (A.2.3)$$

where the two last conditions correspond to the second condition in lemma 1 when there are only two types of countries.

According to (A.1.5) and (A.1.7) condition (A.2.1) can be written as

$$n_1\frac{m^2}{2c_1}\left((n_1+n_2)^2 - 4n_1 - 2n_2 + 3 - 2c_1n_2\right)$$
$$+n_2\frac{m^2}{2c_1}\left(c_1\left((n_1+n_2)^2 - 4n_2 - 2n_1 + 3\right) - 2n_1\right) < 0,$$

that eliminating n_1+n_2 using $n_1+n_2=n$ and n_2 using $n_2=n-n_1$ yields

$$\frac{m^2}{2c_1}(n^2-4n+3)(n_1+c_1(n-n_1)) < 0.$$

This expression is negative only if $n=2$ so that only a bilateral agreement with one country of type 1 and one country of type 2 can be self-enforcing. Moreover, this expression allows us to establish that any agreement with three or more countries cannot be stabilized through a system of side payments independently of its composition which implies that conditions (A.2.2) and (A.2.3) hold for $n = 2$. Thus, the unique self-enforcing agreement consists of two countries, one of type 1 and another of type 2.

Appendix A.3. Proof of proposition 3

USING the expressions of section 3, the costs functions for non-signatories are

$$C_1^f\left(n_1,n_2\right)=\frac{m_1^2}{2c}+m_1\,X\left(n_1,n_2\right),\;\; C_2^f\left(n_1,n_2\right)=\frac{1}{2c}+X\left(n_1,n_2\right), \quad \text{(A.3.1)}$$

and for signatories are

$$\begin{aligned} C_1^s\left(n_1,n_2\right) &= \frac{1}{2c}(m_1n_1+n_2)^2+m_1X(n_1,n_2), && \text{(A.3.2)}\\ C_2^s\left(n_1,n_2\right) &= \frac{1}{2c}(m_1n_1+n_2)^2+X(n_1,n_2), && \text{(A.3.3)} \end{aligned}$$

where the aggregate emissions are given by the following expression

$$\begin{aligned} X(n_1,n_2) &= N_1\left(\delta-\frac{m_1}{c}\right)+N_2\left(\delta-\frac{1}{c}\right)\\ &\quad -\frac{n_1}{c}\left((n_1-1)m_1+n_2\right)-\frac{n_2}{c}\left(m_1n_1+n_2-1\right). \quad \text{(A.3.4)} \end{aligned}$$

As in the proof of proposition 1 we distinguish three cases.

Case 1. If we have an agreement consisting only of countries of type 1, the internal stability condition is written as follows

$$C_1^s\left(n_1,0\right)-C_1^f\left(n_1-1,0\right)=\frac{m_1^2}{2c}\left(n_1^2-4n_1+3\right)\leq 0,$$

which is satisfied only for $n_1=\{2,3\}$. So we have again the same result that in the symmetric case.

Case 2. If in the agreement there are only countries of type 2, the internal stability condition is the same than in case 1 and, therefore, the conclusion is also the same.

Case 3. Now the internal stability condition for the countries of type 1 is

$$C_1^s(n_1, n_2) - C_1^f(n_1 - 1, n_2) = \frac{1}{2c}\left(\left(n_1^2 - 4n_1 - 2n_2 + 3\right)m_1^2 + 2n_2(n_1 - 1)m_1 + n_2^2\right) \leq 0, \quad \text{(A.3.5)}$$

which is satisfied if

$$\left(n_1^2 - 4n_1 - 2n_2 + 3\right)m_1^2 + 2n_2(n_1 - 1)m_1 + n_2^2 \leq 0. \quad \text{(A.3.6)}$$

On the other hand, the internal stability condition for the countries of type 2 is

$$C_2^s(n_1, n_2) - C_2^f(n_1, n_2 - 1) = \frac{1}{2c}\left(n_1^2 m_1^2 + 2n_1(n_2 - 1)m_1 + n_2^2 - 2n_1 - 4n_2 + 3\right) \leq 0, \quad \text{(A.3.7)}$$

which holds when

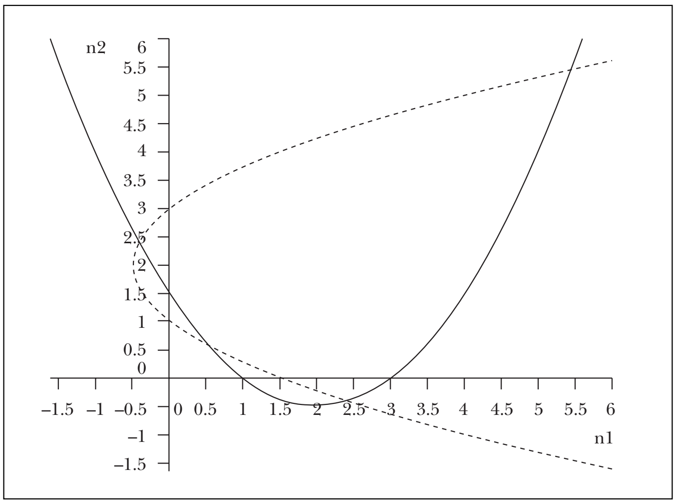
$$n_1^2 m_1^2 + 2n_1(n_2 - 1)m_1 + n_2^2 - 2n_1 - 4n_2 + 3 \leq 0. \quad \text{(A.3.8)}$$

When in the agreement there are countries of both types (A.3.6) and (A.3.8) are negative or zero only if both $n_1^2 - 4n_1 - 2n_2 + 3$ and $n_2^2 - 2n_1 - 4n_2 + 3$ are negative. To find the values of n_1 and n_2 that satisfies these two conditions we represent $n_1^2 - 4n_1 - 2n_2 + 3 = 0$ and $n_2^2 - 2n_1 - 4n_2 + 3 = 0$ in the space (n_1, n_2). The graphical representation of both conditions is shown in graphic A.3.1.

Thus, only the agreements with a composition (n_1, n_2) that belongs to the area represented in graphic A.3.1 can satisfy the internal stability conditions. In total there are fifteen agreements that could satisfy the internal stability conditions: (5,5), (4,4), (4,3), (3,4), (2,4), (3,3), (4,2), (3,2), (2,3), (3,1), (2,2), (1,3), (2,1), (1,2) and (1,1).

Now, we have to check whether these agreement really satisfy conditions (A.3.6) and (A.3.8). For an agreement with five countries of type 1 and five countries of type 2 condition (A.3.6) yields $-2m_1^2 + 40m_1 + 25 \leq 0$ so that the internal stability condition holds for the countries of type 1 if $m_1 \geq 20.61$. On the other hand, condition (A.3.8) yields $25m_1^2 + 40m_1 - 2 \leq 0$ so that the internal stability condition holds for the countries of type 2 if $m_1 \leq 0.04$. Both conditions are incompatible

GRAPHIC A.3.1: Values of n_1 and n_2 that could satisfy the internal stability condition



and moreover we have assumed that $m_1 > 1$ so that an agreement with five countries of type 1 and five countries of type 2 is not self-enforcing since the internal stability condition is not satisfied. It is easy to check that this also happens for the rest of agreements except for an agreement with one country of type 1 and one country of type 2*. In this case, condition (A.3.6) is satisfied when m_1 is higher than 0.70 and condition (A.3.8) when m_1 is lower than 1.41. This means that an agreement signed by one country of each type is internally stable if $m_1 \in (1, 1.41]$. Moreover, in this case it is easy to check that the external stability condition also holds. For a non-signatory of type 1 the external stability condition is given by

$$C_1^f(1,1) - C_1^s(2,1) = -\frac{1}{2c}(m_1^2 + 2m_1 + 1) \leq 0,$$

which is satisfied for all m_1. For a non-signatory of type 2 the external stability condition is also given by the same difference. The result is that a bilateral agreement with a country of type 1 and a country of type 2 is self-enforcing if $m_1 \in (1, 1.41]$.

*. For this reason we omit all the calculations related with these agreements and we develop only the case of a bilateral agreement with one country of each type.

Appendix A.4. Proof of proposition 4

WE focus on an agreement with countries of the two types. First, we write the first condition of lemma 1 given by (A.2.1) using (A.3.5) and (A.3.7)

$$\frac{n_1}{2c}\left(\left(n_1^2-4n_1-2n_2+3\right)m_1^2+2n_2(n_1-1)m_1+n_2^2\right)$$
$$+\frac{n_2}{2c}\left(n_1^2m_1^2+2n_1(n_2-1)m_1+n_2^2-2n_1-4n_2+3\right)<0,$$

that substituting n_2 by $n-n_1$ and operating yields

$$\frac{1}{2c}[n_1(n_1(n-2)-2n+3)m_1^2+2n_1(n-n_1)(n-2)m_1$$
$$+(n-n_1)\left(n^2-4n+3-n_1(n-2)\right)]<0. \tag{A.4.1}$$

Next, we show that when $n_1\geq 3$ and $n\geq 4$ the agreement cannot be self-enforcing. When $n_1\geq 3$ and $n\geq 4$ we have that $n_1(n-2)-2n+3$ in (A.4.1) is positive since

$$n_1>\frac{2n-3}{n-2}. \tag{A.4.2}$$

Notice that $(2n-3)/(n-2)$ decreases with respect to n and is equal to 2.5 for $n=4$.

On the other hand, $n^2-4n+3-n_1(n-2)$ can be positive or negative depending of the values of n_1 and n. When this term is positive we have that the left-hand side of (A.4.1) is positive since $(n-n_1)(n-2)$ is also positive for $n_1\geq 3$ and $n\geq 4$. In this case, the internal stability condition does not hold and the agreement cannot be self-enforcing. If $n^2-4n+3-n_1(n-2)$ is negative, the quadratic equation

$$n_1(n_1(n-2)-2n+3)m_1^2+2n_1(n-n_1)(n-2)m_1$$
$$+(n-n_1)\left(n^2-4n+3-n_1(n-2)\right)=0 \tag{A.4.3}$$

has a positive real root for m_1 given by the following expression

$$m_1^+=\frac{-2n_1(n-n_1)(n-2)+\left(4n_1(n-n_1)(2n-3)(n^2-4n+3)\right)^{1/2}}{2n_1(n_1(n-2)-2n+3)}, \tag{A.4.4}$$

so that in this case the internal stability condition requires that m_1 is lower than this positive real root. Observe that the quadratic function defined in the left-hand side of (A.4.3) is negative for $m_1 = 0$ and increasing for $m_1 > 0$ so that the internal stability condition only holds for values of m_1 between zero and m_1^+. Next, we show that (A.4.4) is lower than the unity.

Let us suppose that this root is higher or equal to the unity. Then it must be satisfied that

$$-2n_1(n-n_1)(n-2) + \left(4n_1(n-n_1)(2n-3)(n^2-4n+3)\right)^{1/2}$$
$$-2n_1(n_1(n-2)-2n+3) \geq 0,$$

that operating yields

$$\left(4n_1(n-n_1)(2n-3)(n^2-4n+3)\right)^{1/2} \geq 2n_1(n^2-4n+3).$$

Finally, squaring and simplifying we get

$$\frac{2n-3}{n-2} \geq n_1,$$

that contradicts (A.4.2). Thus when $n^2 - 4n + 3 - n_1(n-2)$ in (A.4.1) is negative m_1 must be lower than the unity to satisfy (A.4.1) but we have assumed that $m_1 > 1$.Thus, the internal stability condition is not satisfy either when $n^2 - 4n + 3 - n_1(n-2)$ is negative and we have to conclude that when $n_1 \geq 3$ and $n \geq 4$ the agreement cannot be self-enforcing for non-fulfilment of the internal stability condition.

Next, we show that when $n_1 < 3$ and $n \geq 4$ the agreement is self-enforcing. For $n_1 = 2$ (A.4.1) is satisfied when

$$-2m_1^2 + 4(n-2)^2 m_1 + (n-2)\left(n^2-6n+7\right) < 0, \tag{A.4.5}$$

that it is satisfied for

$$m_1 > \bar{m}_1(n) = (n-2)^2 + \frac{1}{2}\sqrt{2(n-2)(2n^3-11n^2+18n-9)} > 1. \tag{A.4.6}$$

So for each n there exists a critical value for m_1 defined by (A.4.6) such that if m_1 is larger than this critical value an agreement consisting of n signatories satisfies the internal stability condition. Moreover, it is easy to check that (A.4.6) is increasing with respect to n so that the critical values are ordered as follows: $\bar{m}_1(n) < \bar{m}_1(n+1) < \bar{m}_1(n+2)$... Then for $m_1 \in (\bar{m}_1(n), \bar{m}_1(n+1)]$ an agreement consisting of n signatories satisfies both the internal stability condition and the external stability condition and consequently is self-enforcing.

For $n_1 = 1$ (A.4.1) holds when

$$(1-n)m_1^2 + 2(n-1)(n-2)m_1 + (n-1)\left(n^2 - 5n + 5\right) < 0,$$

that it is satisfied for

$$m_1 > \tilde{m}_1(n) = n - 2 + (n^2 - 4n + 3)^{1/2} > 1. \tag{A.4.7}$$

So again for each n there exists a critical value for m_1 defined by (A.4.7) such that if m_1 is larger than this critical value an agreement consisting of n signatories satisfies the internal stability condition. Moreover, it is easy to check that (A.4.7) is increasing with respect to n so that the critical values are ordered as follows: $\tilde{m}_1(n) < \tilde{m}_1(n+1) < \tilde{m}_1(n+2)$... Then for $m_1 \in (\tilde{m}_1(n), \tilde{m}_1(n+1)]$ an agreement consisting of n signatories satisfies both the internal stability condition and the external stability condition and consequently is self-enforcing.

To finish this proof we show that when $n = 3$ the agreement is self-enforcing if there are one or two countries of type 1. For $n_1 = 2$ and $n = 3$ (A.4.1) is written as $(1/c)(-2m_1^2 + 4m_1 - 2)$ that is negative for $m_1 > 1$. Thus the agreement is internally stable for any value of m_1. To check if the agreement is also externally stable we have to find out if the non-signatories are not interested in entering the agreement. If a non-signatory of type 1 enters the agreement we have an agreement with three countries of type 1 and one country of type 2. For this case (A.4.1) is written as $(1/c)(3m_1^2 + 12m_1 - 3)$ that is positive for $m_1 > 1$ so that this agreement cannot be stabilized through a system of side payments. In the other case, if a non-signatory of type 2 enters the agreement we have an agreement with two countries of type 2 and two countries of type 1. For this second case (A.4.1) is written as $(1/c)(-2m_1^2 + 16m_1 - 2)$ that is negative for m_1 larger than 7.87. Thus we can conclude that if $m_1 \in (1, 7.87]$ an agreement consisting of two countries of type 1 and one country of type 2 is self-enforcing.

For $n_1 = 1$ and $n = 3$ (A.4.1) is also written as $(1/c)(-2m_1^2 + 4m_1 - 2)$ thus the agreement is internally stable for any value of m_1. On the other hand, if a non-signatory of type 1 enters the agreement we have an agreement with two countries of type 1 and two countries of type 2 that as we have just seen is not internally stable for $m_1 \leq 7.87$. In the other case, if a non-signatory of type 2 enters the agreement we have an agreement with one country of type 1 and three countries of type 2. For this case (A.4.1) yields $(1/c)(-3m_1^2 + 12m_1 + 3)$ that is positive or zero for $m_1 \leq 4.24$. So that we can conclude that if $m_1 \in (1, 4.24]$ an agreement consisting of one country of type 1 and two countries of type 2 is self-enforcing.

Finally, we analyze the case of a bilateral agreement with one country of each type. In this case the internal stability condition is satisfied for $m_1 > 1$. However, the external stability condition is not satisfied. As we have just checked an agreement with two countries of type 1 and one country of type 2 is internally stable for $m_1 > 1$ and the same happens for an agreement with one country of type 1 and two countries of type 2. For this reason an agreement with one country of each type is not self-enforcing since it is not externally stable. Non-signatories have interest in joining the agreement. So we can conclude that one or two countries of type 1 can buy the cooperation of the countries of type 2 and that the scope of cooperation increases with the differences in the environmental damages. According to these results the maximum level of cooperation that can be reached through a system of side payments is $N_2 + 2$ provided that the marginal environmental damages are sufficiently large.

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* A first version of this working paper was presented at the XXIX Symposium of Economic Analysis, Pamplona, December 16-18, 2004, the XIV Annual Conference of the European Association of Environmental and Resource Economists, Bremen, June 23-26, 2005, the II Congress of the Spanish-Portuguese Association of Environmental and Natural Resources Economics, Lisbon, June 2-3, 2006 and the VI Meeting on Game Theory and Practice Dedicated to Development, Natural Resources and the Environment, Saragossa, July 10-12, 2006. We are grateful to J. C. Pereau for useful comments. Financial support from the BBVA Foundation is acknowledged.

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