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International Environmental Agreements - Stability with Transfers among Countries

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Keywords: International Environmental Agreements, Heterogeneous Countries, Transfers

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Abstract

The paper examines the stability of self-enforcing International Environmental Agreements (IEAs) among heterogeneous countries, allowing for transfers. We employ a two-stage, non-cooperative model of coalition formation. In the first stage each country decides whether or not to join the agreement, while in the second stage countries choose their emissions simultaneously. Coalition members agree also to share the gains from cooperation in the first stage. We use quadratic benefit and environmental damage functions and assume two types of countries differing in their sensitivity to the global pollutant. In examining the impact of transfers on the coalition size, we apply the notion of Potential Internal Stability (PIS). Results show that transfers can increase cooperation among heterogeneous countries. However, the increase in the coalition size, relative to the case without transfers, comes only from countries belonging to the type with the lower environmental damages, which are drawn into the coalition by the transfers offered. Furthermore, the level of cooperation increases with the degree of heterogeneity. However, the reduction in aggregate emissions achieved by the enlarged coalition is very small leading to dismal improvement in welfare, which confirms the "paradox of cooperation".

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1 Introduction

Climate change is arguably the most important and pressing problem humanity currently faces. There is almost unanimous international consensus that "warming of the climate system is unequivocal" and that "human influence on the climate system is clear" (IPCC, 2014). Thus, decisive and speedy policy action to mitigate climate change is required. Although 165 countries have already submitted their pledges to reduce their greenhouse gas emissions, known as the Nationally Determined Contributions (NDCs), following the 21st Conference of the Parties of the United Nations Framework Convention on Climate Change (UNFCCC) in Paris, there are serious doubts as to whether the national pledges will be materialized and, even if they do, whether they will be enough to meet the target of 2°C increase in average global temperatures. The slow progress of coordinating action at the international level to mitigate climate change is a typical example of the obstacles faced in the provision of public goods (or the mitigation of public bad). Given that costs of reducing Greenhouse Gases (GHGs) are very high while their benefits are spread globally, countries may choose not to implement the necessary policies opting instead to free-ride on other countries' actions. Climate change shares these problems with a number of other global environmental problems, such as ozone depletion, biodiversity and marine pollution. For some of these issues, International Environmental Agreements (IEAs) have been reached, successfully tackling the problem, such as the Montreal Protocol on substances responsible for the depletion of the ozone layer. In some other areas, such as climate change, international negotiations to strengthen actions are still ongoing.

The importance of climate change and the inability of the international community to achieve a global agreement to successfully address the problem, has spurred a substantial literature on IEAs in recent years. A large part of the literature, recognizing the interdependence among countries' choices and the widely spread externalities, which lead to the strategic behavior of countries involved in negotiating IEAs, uses game theory as the tool of analysis. A critical characteristic of IEAs is the lack of a supranational authority that could implement and enforce environmental policies on sovereign states. Like in any other pure public good provision problem, every country has an incentive to free ride on others' efforts. It does so by avoiding the cost of abating its emissions while at the same time enjoying the benefits of lower aggregate emissions achieved by the countries that remain faithful to the agreement. Since the socially optimal outcome cannot be enforced, IEAs differ from a typical public good and thus, IEAs have to be self-enforcing in the sense that they have to account for the countries' incentives to cheat on or withdraw from the agreement.

The main body of this literature assumes that countries signing the IEA form a coalition and maximize the coalition's aggregate welfare, while taking into consideration non-members' non-cooperative behavior that results from maximizing their individual welfare. Within this non-cooperative framework, countries' behavior is modelled as a two stage game, where in the first stage countries decide whether to join the coalition, while in the second they choose their emissions. The subgame perfect Nash equilibrium of the resulting two-stage game is usually derived by applying the notions of the internal and external stability conditions developed in D'Aspremont et al. (1983). Assuming quadratic cost and benefit functions and simultaneous choice of emissions, it has been shown that stable coalitions consist of no more than two countries (De Cara and Rotillon, 2001; Finus and Rundshagen, 2001; Rubio and Casino, 2001; among others). If the coalition is assumed to be a leader, the coalition formation is more successful. Barrett (1994) suggests that a stable coalition may achieve a high degree of cooperation, including the grand coalition, but only when the gains of cooperation are small. In contrast, Diamantoudi and Sartzetakis (2006), imposing the appropriate positivity constraints on emissions, show that stable coalitions could have no more than four members. The same dismal result is obtained even when the static model is extended to a dynamic framework, which approximates climate change much closer since it introduces stock instead of flow pollutants (Calvo and Rubio, 2013). It is only when coalition formation is modelled as an infinitely repeated game allowing defectors' punishment that could sustain full cooperation (Barrett, 1999), especially if multiple coalitions are considered (Asheim et al., 2006). Departing from the assumptions of the non-cooperative games, another part of the IEAs' literature applies the core concept of stability to examine coalition formation (Chander and Tulkens, 1995 and 1997). The cooperative approach asserts the formation of the grand coalition and the attainment of efficiency, assuming that when a country deviates it expects that the agreement collapses. The concept of farsighted stability has been used to bridge the gap between these two polar approaches. It assumes that when a country defects from an agreement it does not make any assumption regarding the behavior of the coalition's remaining members. Instead, it foresees what their reaction will be, and which equilibrium agreement will result from such a deviation. Diamantoudi and Sartzetakis (2002) formally define the concept of farsighted stability and provide the complete characterization of the farsighted stable set, permitting renegotiation among countries if an IEA collapses. Diamantoudi and Sartzetakis (2015) and (2017) examine respectively the case in which groups of countries may coordinate their actions or act independently, in either joining or withdrawing from an agreement, and in both cases find, using general functional forms, that by not restricting countries to a myopic behavior, increases the set of possible stable coalitions. The above results have been verified in a dynamic setting (de Zeeuw, 2008; Biancardi, 2010) and by using a multi-regional computable general equilibrium model (Lise and Tol, 2004).

One of the most restrictive and unrealistic assumptions of the above mentioned literature is the homogeneity of countries' damages suffered from the global pollutant and benefits (related to production and consumption) derived from emitting the pollutant. A number of papers have tried to address the issue by introducing heterogeneity. Assuming two types of countries, Barrett (1997) finds no substantial difference in the size of the stable coalition relative to the homogeneous case. On the contrary, McGinty (2007), allowing for transfer payments through a permit system among n asymmetric nations, finds that asymmetries can increase the coalition size. Moreover, Chou and Sylla (2008), Osmani and Tol (2010) and Biancardi and Villani (2010) examine stability considering also two types of countries. In particular, Chou and Sylla (2008) explain theoretically why it is more likely that some developed countries can form a small stable coalition first and then engage in monetary transfers to form the grand coalition. Osmani and Tol (2010) allow the formation of two separate coalitions and demonstrate that with high environmental damages, forming two coalitions yields higher welfare and better environmental quality relative to a unique coalition. Biancardi and Villani (2010) find that stability depends on the level of the asymmetry and the grand coalition can be obtained only by transfers.

Moreover, Fuentes-Albero and Rubio (2010) introduce also two types of countries differing either in abatement costs or environmental damages (which are assumed to be linear on emissions) and find that heterogeneity has no important effect without transfers, but if transfers are allowed the level of cooperation increases with the degree of heterogeneity. On the other hand, Pavlova and Zeeuw (2013) assuming differences in both emission-related benefits and environmental damages (which are assumed to be linear on emissions), find that large stable coalitions are possible without transfers if the asymmetries are sufficiently large, however, the gains of cooperation are very low, and that transfers could improve the gains of cooperation. Using transfers, Weikard (2009) shows that under asymmetry large coalitions may be stable. In most of the aforementioned papers, transfers are implemented using the optimal transfer scheme. That is, when the coalition's payoff equals or exceeds the sum of the outside option payoffs then every coalition member receives at least his free-rider payoff plus a share of the remaining surplus (Eyckmans and Finus, 2004).

As the above review indicates, results of the theoretical literature are mixed. Some papers support the idea that allowing for heterogeneity yields larger stable coalitions, with and without transfers, while some other claim that transfers are necessary to induce cooperation (Petrakis and Xepapadeas, 1996; Botteon and Carraro, 1997 and 2001). Diamantoudi et al. (2017) expand the standard, quadratic cost and benefit functions, simultaneous decision, model by assuming two types of countries that differ in their sensitivity towards the global pollutant. They prove analytically that introducing heterogeneity does not enhance the size of a coalition. On the contrary, under heterogeneity, when stable coalitions exist, their size is very small. In addition, heterogeneity can reduce the scope of cooperation relative to the homogeneous case. In other words, introducing asymmetry into a stable, under symmetry, agreement can disturb stability.

The present paper, employs a model similar to Diamantoudi et al. (2017) and introduces transfers to examine the stability of self-enforcing IEAs. Our results indicate that transfers can increase cooperation incentives, yielding larger coalition sizes. However, reductions in emissions and thus welfare improvements are small. Furthermore, the inducement of larger coalitions can be achieved only with the help of the countries that suffer the higher damages. That is, stable agreements consist of two, at the maximum, countries of the type with the higher environmental damages and many countries of the type with the lower environmental damages. Strong free-riding incentives persist among the type of countries that suffer the higher damages, thus only few of them join the coalition. Using transfers, a small number of this type of countries can convince a large number of countries from the other type to join the coalition, but their contribution has small effect on emissions and welfare. Our findings confirm the persistent result in the literature, first noted in Barrett (1994) and recently noted as the "paradox of cooperation", that even when a large stable coalition is achieved, the associated welfare benefits are minimal.

It should be stressed that the main difference between our model and most of the literature is the functional form of the environmental damages. While most papers (Fuentes-Albero and Rubio, 2010; Pavlova and Zeeuw, 2013) use a linear damage function, we employ a quadratic one[1]. With a quadratic environmental damage function, we can capture the interaction effects between heterogeneous countries, which seems to play an important role in the results. Thus, in contrast to Pavlova and Zeeuw (2013), we find that large stable coalitions are possible only with transfers, but when transfers are used we confirm that cooperation requires strong asymmetry. Furthermore, we show that the results obtained by Fuentes-Albero and Rubio (2010) hold also for the case of quadratic environmental damages, but heterogeneity should be stronger to improve cooperation.

The rest of the paper is structured as follows. Section 2 describes the model and presents the coalition formation. Section 3 solves for the choice of emissions of the countries. Section 4 analyses the existence and stability of an agreement when countries are heterogeneous in environmental damages and transfers are used to increase cooperation incentives. Section 5 presents the aggregate emissions and welfare with and without transfers for stable agreements of different sizes. Section 6 concludes the paper.

2 The model

We consider two types of countries, $j \in \{A, B\}$. We assume that for each type j there exists a set of N^j countries, $N^j = \{1, 2, 3, \ldots, n^j\}$, each of which generates emissions $e_i^j > 0$[2] as a result of its economic activity. The set of all countries is defined by N, where $N = N^A \cup N^B$. Each country i of type j derives benefits from the economic activity, expressed as function of its emissions, $B_i^j(e_i^j)$, which are assumed to be strictly concave, $B_i^j(0) = 0$, $B_i^{j\prime} \geq 0$ and $B_i^{j\prime\prime} < 0$. It also suffers damages from the aggregate emissions of the global pollutant, $D_i^j(E)$, which are

[1] We employ the damage functional form, $D_i^j(E) = \frac{1}{2}c^j E^2$. To be consistent with the analysis derived in Fuentes-Albero and Rubio (2010) and Pavlova and Zeeuw (2013) our damage function should be simplified to $D_i^j(E) = c^j E$.

[2] The superscript j denotes the type of the country and the subscript i denotes a particular country belonging to type j.

assumed to be strictly convex, $D_i^j(0) = 0$, $D_i^{j\prime} \geq 0$ and $D_i^{j\prime\prime} > 0$. In particular, we use the following functional forms,

$$B_i^j(e_i^j) = b^j(a^j e_i^j - \frac{1}{2}(e_i^j)^2) \text{ and } D_i^j(E) = \frac{1}{2}c^j E^2, \tag{1}$$

where a^j, b^j and c^j are type specific, positive parameters, and $E = \sum_j \sum_{i=1}^{n^j} e_i^j$ are the aggregate emissions, where $j \in \{A, B\}$. That is,

$$E = \sum_{i=1}^{n^A} e_i^A + \sum_{i=1}^{n^B} e_i^B. \tag{2}$$

In addition, we incorporate into the model the possibility of welfare transfers T_i^j, as well as some form of commitment for those countries that decide to pay the transfers. Transfers T_i^j can be either positive, i.e. $T_i^j > 0$, when a country i of type j receives a payment, or negative, i.e. $T_i^j < 0$, when a country i of type j submits a payment. We make also the standard assumption that transfers balance.

2.1 Country's welfare function

The social welfare of each country i of type j, W_i^j, is defined as total benefits from its own emissions minus environmental damages from aggregate emissions,

$$W_i^j = B_i^j\left(e_i^j\right) - D_i^j(E). \tag{3}$$

Substituting the specific functional forms, country i's of type j social welfare is,

$$W_i^j = b^j\left(a^j e_i^j - \frac{1}{2}\left(e_i^j\right)^2\right) - \frac{1}{2}c^j\left(\sum_j \sum_{i=1}^{n^j} e_i^j\right)^2, \tag{4}$$

where $j \in \{A, B\}$ and $i \in N^j = \{1, 2, 3, \ldots, n^j\}$.

2.2 Coalition formation

We model the process of the heterogeneous countries' decision as a non-cooperative two stage game and examine the existence and stability of a self-enforcing coalition aiming at controlling emissions. In the first stage, each country i of type j decides whether or not to join the coalition, while in the second stage, emissions are chosen by all countries simultaneously. In addition, in the first stage those countries that decide to join the coalition agree to share the gains from cooperation among its members. Furthermore, we assume that once the agreement is signed, signatories acting as a unique player, maximize the joint welfare, while non-signatories acting in a non-cooperative way, maximize their own welfare. In particular, for each type $j \in \{A, B\}$ a set of countries $S^j \subset N^j$ signs an agreement to reduce the emissions of the global pollutant and the remaining $N^j \backslash S^j$ do not. The game is solved by backward induction. Once emissions have been chosen and welfare levels have been realized, transfers are implemented.

Following D'Aspremont et al. (1983), we define a stable coalition as a coalition which is both internally and externally stable. Stable agreements are those from which no signatory country has incentives to leave (internal stability) and no country outside the agreement has incentives to join (external stability), assuming that the rest of the countries do not change their membership decision. Thus, the stability conditions, for type A and B countries respectively, take the following forms:
internal stability conditions,

$$\begin{aligned} \mathcal{W}_s^A(s^A, s^B) &\geq \mathcal{W}_{ns}^A(s^A - 1, s^B) \text{ and} \\ \mathcal{W}_s^B(s^A, s^B) &\geq \mathcal{W}_{ns}^B(s^A, s^B - 1), \end{aligned} \tag{5}$$

external stability conditions,

$$\begin{aligned} \mathcal{W}_s^A(s^A + 1, s^B) &\leq \mathcal{W}_{ns}^A(s^A, s^B) \text{ and} \\ \mathcal{W}_s^B(s^A, s^B + 1) &\leq \mathcal{W}_{ns}^B(s^A, s^B), \end{aligned} \tag{6}$$

where $s^j = |S^j|$ denotes the number of type $j \in \{A, B\}$ countries that sign the agreement, $\mathcal{W}_s^j$ is the welfare of a signatory country and $\mathcal{W}_{ns}^j$ is the welfare of a non-signatory country.

To explore the scope of cooperation when countries use transfers, we apply the Potentially Internally Stability (PIS) condition as defined in Eyckmans and Finus (2004). This condition implies that the aggregate net benefits of the coalition must exceed the aggregate of the outside net-benefit options of all coalition members. Hence, countries can redistribute payoffs within the coalition such that the coalition is internally stable. The following condition should be satisfied to ensure that a coalition is potentially internally stable,

$$\sum_{j\in\{A,B\}} s^j \mathcal{W}_s^j(s^j, s^{-j}) \geq \sum_{j\in\{A,B\}} s^j \mathcal{W}_{ns}^j(s^j-1, s^{-j}). \tag{7}$$

That is, the aggregate welfare of all coalition members should be at least larger than the aggregate welfare they receive deciding to free-ride. In other words, the above condition states that the sum of the internal stability conditions should be non-negative.

It follows that the sum of the internal stability conditions in the case of transfers is the sum of the internal stability conditions for the case without transfers, since transfers add up to zero. Recall that, we make the standard assumption that transfers balance, i.e. $\sum_j \sum_{i=1}^{s^j} T_i^j = 0$, where $j \in \{A, B\}$. That is, $\sum_{i=1}^{s^A} T_i^A + \sum_{i=1}^{s^B} T_i^B = s^A T_s^A + s^B T_s^B = 0$. This leads to the following internal stability condition,

$$\begin{aligned} PIS(s^A, s^B) &= s^A[\mathcal{W}_s^A(s^A, s^B) - \mathcal{W}_{ns}^A(s^A-1, s^B)] + \\ & \quad s^B[\mathcal{W}_s^B(s^A, s^B) - \mathcal{W}_{ns}^B(s^A, s^B-1)] \geq 0. \end{aligned} \tag{8}$$

The option of transfers may allow coalition members to allocate their net benefits in such a way that a larger number of countries will have no incentives to leave the coalition. Thus, there could be a self-financed transfer T_i^j from the i cooperating countries of type j to the other non-cooperating countries that can successfully enlarge the original coalition. The potential internal stability is a sufficient condition for internal stability in the presence of transfers, provided that transfers are optimally designed. According to Eyckmans and Finus (2004), under an optimal transfer scheme every coalition member receives at least its free-rider payoff and there may be an extra share of the surplus $PIS(s^A, s^B)$.

When transfers are used to increase cooperation, the stability conditions, for each type of country, are modified as follows:
internal stability conditions,

$$\begin{aligned} \mathcal{W}_s^A(s^A, s^B) + T_s^A(s^A, s^B) &\geq \mathcal{W}_{ns}^A(s^A-1, s^B) \text{ and} \\ \mathcal{W}_s^B(s^A, s^B) + T_s^B(s^A, s^B) &\geq \mathcal{W}_{ns}^B(s^A, s^B-1), \end{aligned} \tag{9}$$

external stability conditions,

$$\begin{aligned} \mathcal{W}_s^A(s^A+1, s^B) + T_s^A(s^A+1, s^B) &\leq \mathcal{W}_{ns}^A(s^A, s^B) \text{ and} \\ \mathcal{W}_s^B(s^A, s^B+1) + T_s^B(s^A, s^B+1) &\leq \mathcal{W}_{ns}^B(s^A, s^B). \end{aligned} \tag{10}$$

In other words, internal stability holds when the welfare of a signatory country net of the transfer, which could be positive or negative, is larger than its welfare under the free-riding option. On the other hand, external stability holds when a non-signatory country's welfare exceeds the welfare it earns when it is part of the agreement, taking into account the transfer payment.

3 Choice of emissions

We solve the game using backward induction. Thus, once emissions have been chosen and welfare levels have been realized, transfers are implemented to examine their effect on the game. Each signatory of type j emits e_s^j, such that $E_{s^j} = s^j e_s^j$, where $s^j = |S^j|$, and thus the coalition's total emissions are $E_s = E_{s^A} + E_{s^B}$. Similarly, each non-signatory of type j emits e_{ns}^j, such that $E_{ns^j} = (n^j - s^j)e_{ns}^j$, yielding aggregate emissions of non-signatories $E_{ns} = E_{ns^A} + E_{ns^B}$. Therefore, global emissions are given by,

$$E = E_s + E_{ns} = s^A e_s^A + s^B e_s^B + (n^A - s^A)e_{ns}^A + (n^B - s^B)e_{ns}^B. \tag{11}$$

Before we proceed to the solutions regarding countries' emissions and welfare levels, we define the following parameters in order to simplify the presentation. Namely, parameter γ^j indicates the relationship between environmental damages and benefits due to emissions for all countries i in type $j \in \{A, B\}$. Thus,

$$\gamma^j = \frac{c^j}{b^j}. \tag{12}$$

Moreover, parameters c and b are defined as follows,

$$c = \frac{c^A}{c^B} \text{ and } b = \frac{b^A}{b^B}, \tag{13}$$

where c is the ratio of the slopes of the marginal environmental damages and b is the ratio of the slopes of the marginal benefits, of type A over type B countries.

Finally, we define the expression Ψ,

$$\Psi = 1 + \gamma^A(n^A - s^A) + \gamma^B(n^B - s^B) + \gamma^A(s^A)^2 + \gamma^B(s^B)^2 + (\frac{c^B}{b^A} + \frac{c^A}{b^B})s^A s^B, \tag{14}$$

which can also be written as,

$$\Psi = 1+\gamma^A(n^A-s^A)+\gamma^B(n^B-s^B)+\gamma^A(s^A)^2+\gamma^B(s^B)^2+(\gamma^A c^{-1}+\gamma^B c)s^A s^B. \quad (15)$$

Note that Ψ is always positive since $s^A \leq n^A$, $s^B \leq n^B$ and $\gamma^j > 0$.

The payoff function for each country i of type j, is given by equation (4). Each country receives benefits from its economic activity while it suffers damages from global emissions. Signatories maximize the coalition's welfare given by $W_s = \sum_j s^j W_s^j$, where $j \in \{A, B\}$, that is, $W_s = s^A W_s^A + s^B W_s^B$. Therefore, signatories choose e_s^j by solving the following maximization problem,

$$\max_{e_s^j} \left[s^A \left(B_s^A(e_s^A) - D_s^A(E) \right) + s^B \left(B_s^B(e_s^B) - D_s^B(E) \right) \right], \quad (16)$$

where aggregate emissions E are given by equation (11).

The first order conditions of the signatories' maximization problem (16) yield the equilibrium emissions,

$$e_s^A = a^A - \frac{\gamma^A(a^A n^A + a^B n^B)(s^A + c^{-1}s^B)}{\Psi}, \quad (17)$$

$$e_s^B = a^B - \frac{\gamma^B(a^A n^A + a^B n^B)(cs^A + s^B)}{\Psi}. \quad (18)$$

Non-signatories choose their emissions e_{ns}^j, by maximizing their own welfare given by W_{ns}^j, where $j \in \{A, B\}$. Hence, they solve the following maximization problem,

$$\max_{e_{ns}^j} \left[B_{ns}^j(e_{ns}^j) - D_{ns}^j(E) \right], \quad (19)$$

where aggregate emissions E are given by equation (11).

The first order conditions of the non-signatories' maximization problem (19) yield the equilibrium emissions,

$$e_{ns}^A = a^A - \frac{\gamma^A(a^A n^A + a^B n^B)}{\Psi}, \quad (20)$$

$$e_{ns}^B = a^B - \frac{\gamma^B(a^A n^A + a^B n^B)}{\Psi}. \quad (21)$$

Substituting the equilibrium values of the choice variables from (17), (18), (20) and (21) into equation (11), we derive the aggregate emissions,

$$E = \frac{(a^A n^A + a^B n^B)}{\Psi}. \tag{22}$$

We continue by substituting the equilibrium values of the choice variables from (17), (18), (20) and (21) into equation (4), to derive the indirect welfare functions of signatories ($\mathcal{W}_s^A$ and $\mathcal{W}_s^B$) and non-signatories ($\mathcal{W}_{ns}^A$ and $\mathcal{W}_{ns}^B$) for both types of countries.

The welfare functions of signatories, $\mathcal{W}_s^A$ and $\mathcal{W}_s^B$, are,

$$\mathcal{W}_s^A = \frac{1}{2} b^A \left[(a^A)^2 - \frac{\gamma^A (a^A n^A + a^B n^B)^2 (1 + \gamma^A (s^A + c^{-1} s^B)^2)}{\Psi^2} \right], \tag{23}$$

$$\mathcal{W}_s^B = \frac{1}{2} b^B \left[(a^B)^2 - \frac{\gamma^B (a^A n^A + a^B n^B)^2 (1 + \gamma^B (c s^A + s^B)^2)}{\Psi^2} \right]. \tag{24}$$

The welfare functions of non-signatories, $\mathcal{W}_{ns}^A$ and $\mathcal{W}_{ns}^B$ are,

$$\mathcal{W}_{ns}^A = \frac{1}{2} b^A \left[(a^A)^2 - \frac{\gamma^A (a^A n^A + a^B n^B)^2 (1 + \gamma^A)}{\Psi^2} \right], \tag{25}$$

$$\mathcal{W}_{ns}^B = \frac{1}{2} b^B \left[(a^B)^2 - \frac{\gamma^B (a^A n^A + a^B n^B)^2 (1 + \gamma^B)}{\Psi^2} \right]. \tag{26}$$

4 Stable coalitions with transfers

Without permitting transfers, Diamantoudi et al. (2017) have shown that under heterogeneity the size of stable coalitions remains small and in some cases smaller than in the case of homogeneity. That is, heterogeneity could exacerbate rather than reduce free-riding incentives. In this section, we examine whether transfers can be used to increase participation in an IEA.

We focus on internal stability and recall that potential internal stability is given in condition (8). Substituting the values of the indirect welfare functions from (23), (24), (25) and (26), into condition (8) yields,

$$PIS(s^A, s^B) = \frac{\left(a^A n^A + a^B n^B\right)^2}{2} \left\{ \begin{array}{l} s^A \gamma^A b^A \left[\frac{1+\gamma^A}{(\Psi - 2\gamma^A (s^A - 1) - \gamma^A (b + c^{-1}) s^B)^2} - \frac{1 + \gamma^A \left(s^A + c^{-1} s^B\right)^2}{\Psi^2} \right] \\ + s^B \gamma^B b^B \left[\frac{1+\gamma^B}{(\Psi - 2\gamma^B (s^B - 1) - \gamma^B (b^{-1} + c) s^A)^2} - \frac{1 + \gamma^B \left(c s^A + s^B\right)^2}{\Psi^2} \right] \end{array} \right\} \geq 0, \tag{27}$$

where, as previously defined, $b = \frac{b^A}{b^B}$, $c = \frac{c^A}{c^B}$, $\gamma^j = \frac{c^j}{b^j}$ with $j \in \{A, B\}$, and $\Psi = 1 + \gamma^A (n^A - s^A) + \gamma^B (n^B - s^B) + \gamma^A (s^A)^2 + \gamma^B (s^B)^2 + (\gamma^A c^{-1} + \gamma^B c) s^A s^B$.

4.1 Heterogeneity in environmental damages

In order to derive analytical results Diamantoudi et al. (2017) restrict heterogeneity among countries. In order to compare results, we make the same assumption, that is, countries are assumed to be heterogeneous in the environmental damages, while they have the same benefit function. Given that we have to restrict heterogeneity, the choice of keeping heterogeneity of countries' damages seems more appropriate since the strongest part of countries' strategic interactions is captured, in the model, through global pollution. That is, we consider $c^A \neq c^B$ while $a^A = a^B = a^I$ and $b^A = b^B = b^I$[3]. Furthermore, without any loss of generality, we assume that $c > 1$, implying that $c^A > c^B$, and since $b = \frac{b^A}{b^B} = 1$, we have $\gamma^A > \gamma^B$. Therefore, in this context, type A countries have a steeper marginal environmental damage function compared to type B countries. That is, type A countries suffer higher marginal environmental damages at any level of global pollution, which implies that they are more sensitive to environmental pollution. For simplicity and without any loss of generality we set $n^A = n^B = n$.

Under these assumptions, the PIS condition can be written as follows,

$$PIS(s^A, s^B) = \frac{b^I(a^I n)^2}{2} \left\{ \begin{array}{l} s^A\gamma^A \left[\frac{1+\gamma^A}{(\Psi-2\gamma^A(s^A-1)-\Gamma s^B)^2} - \frac{1+\gamma^A\left(s^A+c^{-1}s^B\right)^2}{\Psi^2} \right] \\ +s^B\gamma^B \left[\frac{1+\gamma^B}{(\Psi-2\gamma^B(s^B-1)-\Gamma s^A)^2} - \frac{1+\gamma^B\left(cs^A+s^B\right)^2}{\Psi^2} \right] \end{array} \right\} \geq 0. \tag{28}$$

Based on the above assumptions regarding the parameters, the expression Ψ can be written as $\Psi = 1 + \gamma^A(n - s^A) + \gamma^B(n - s^B) + \gamma^A(s^A)^2 + \gamma^B(s^B)^2 + \Gamma s^A s^B$, where $\Gamma = (\gamma^A + \gamma^B)$. Note that $c = \frac{\gamma^A}{\gamma^B}$ since $b = 1$.

Given the higher sensitivity of type A countries ($c > 1$), they benefit from cooperation that yields lower levels of global pollution and are willing to provide side payments to less sensitive type B countries, in order to support a large stable coalition. We are interested in finding the number of type A countries, i.e. s^A, that sign the agreement and commit to share the gains from cooperation as well as the maximum number of type B countries, i.e. s^B, that are lured into signing the agreement by transfers at a level at least equal to their free-riding gains.

Assuming the same type of heterogeneity but without transfers, Diamantoudi

[3]The superscript I in parameters a and b, i.e. a^I and b^I, is used to define that countries are identical with respect to benefits.

et al. (2017) prove analytically that the largest possible stable coalition that can be achieved includes only two countries and the membership of the coalition is mainly driven by the degree of heterogeneity in environmental damages. In particular, there are three possible cases: a mixed coalition that includes one country of each type, i.e. ($s^A = 1$, $s^B = 1$), when heterogeneity is small, a coalition with two type B countries, i.e. ($s^A = 0$, $s^B = 2$), when heterogeneity is moderate, and a coalition with two type A countries, i.e. ($s^A = 2$, $s^B = 0$), when heterogeneity is strong. Moreover, when heterogeneity exceeds a certain level, a stable coalition does not exist.

Unfortunately, it is not possible to derive analytical results when transfers are introduced. Thus, we resort to simulations. The following Remark summarizes the results obtained using simulations.

Remark 1 *Allowing for transfers among heterogeneous countries increases cooperation. However, the increase in the coalition size does not come from countries belonging to the type suffering the higher damages (type A), but only from countries of type B, drawn into the coalition by the transfers offered.*

It is evident that the introduction of transfers cannot not induce more type A countries to cooperate, since these countries have to provide the necessary transfers to type B countries. Thus, we can have a coalition with either $s^A = 1$ or $s^A = 2$ type A countries. For any $s^A \geq 3$ the internal stability condition for type A countries is not satisfied. This result was expected since the need to provide transfer payments exacerbates the existing free-riding incentives. The number of type B countries that are willing to join the coalition, under the condition that they receive transfers, varies depending on the degree of heterogeneity. Our simulations demonstrate that as the degree of heterogeneity increases, the size of the coalition under transfers increases as well. Without loss of generality we set $s^B = n$ assuming that all type B countries participate in the agreement and we try to find the degree of heterogeneity needed to support coalitions of different sizes, i.e. either ($s^A = 1, s^B = n$) or ($s^A = 2, s^B = n$), for any number of countries $n \geq 3$.

Setting $s^B = n$ and rearranging terms, the PIS condition (28) can be written as follows,

$$PIS(s^A,n)=\frac{b^I(a^In)^2}{2}\left\{\begin{array}{l} s^A\gamma^A\left[\frac{1+\gamma^A}{(\Psi-2\gamma^A(s^A-1)-\Gamma n)^2}-\frac{1+\gamma^A\left(s^A+c^{-1}n\right)^2}{\Psi^2}\right] \\ +n\gamma^B\left[\frac{1+\gamma^B}{(\Psi-2\gamma^B(n-1)-\Gamma s^A)^2}-\frac{1+\gamma^B\left(cs^A+n\right)^2}{\Psi^2}\right]\end{array}\right\}\geq 0. \tag{29}$$

Given the assumption, $s^B=n$, the value of Ψ can be written as $\Psi=1+\gamma^A(n-s^A)+\gamma^A(s^A)^2+\gamma^Bn^2+\Gamma s^An$.

Condition (29) is satisfied, only if $s^A\in\{1,2\}$ while $s^B=n$ for any value of $n\geq 3$. Moreover, in all cases presented in our numerical analysis, if condition (29) holds, meaning that an enlarged coalition is internally stable, the external stability condition for type A countries (first condition in (10)) holds as well.

In the following table, Table 1, we summarize all possible stable coalitions that can be achieved for $n\in\{3,4,...,10\}$ and $s^A\in\{1,2\}$ presenting the threshold values of parameters γ^A and γ^B that support each one of them[4].

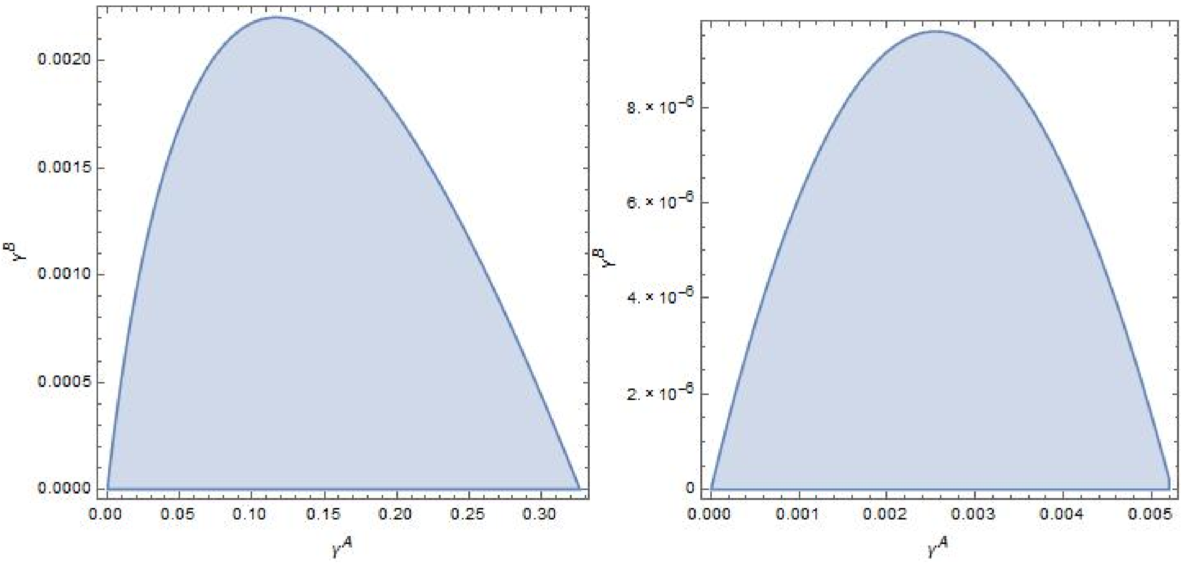
Table 1: Possible stable agreements

	Agreement $(1,n)$		Agreement $(2,n)$	
n	$\gamma^A\leq$	$\gamma^B\leq$	$\gamma^A\leq$	$\gamma^B\leq$
3	∇	0.0520	0.0429	$4.85*10^{-4}$
4	1.6513	0.0133	0.0223	$1.51*10^{-4}$
5	0.8216	0.0070	0.0138	$6.19*10^{-5}$
6	0.5461	0.0044	0.0094	$2.99*10^{-5}$
7	0.4087	0.0030	0.0068	$1.62*10^{-5}$
8	0.3265	0.0022	0.0052	$9.58*10^{-6}$
9	0.2718	0.0017	0.0041	$6.01*10^{-6}$
10	0.2327	0.0013	0.0033	$3.95*10^{-6}$

Note that, as indicated from the expression in (29), the relationship between γ^A and γ^B is not linear. When, for instance, parameter γ^B takes its maximum value, condition (29) specifies the maximum value parameter γ^A can take such that the corresponding coalition is stable. According to the analysis, a larger coalition requires stricter constraints for the parameters of the model, i.e. γ^A and γ^B.

[4] Values are rounded off such that they do not exceed their corresponding thresholds.

To visualize the results, we consider the two coalitions $(1, 8)$ and $(2, 8)$ and present the corresponding regions, see Figure 1, in which the PIS condition (29) is satisfied respectively. The X axis shows the parameter γ^A while the Y axis shows the parameter γ^B. The first graph, Figure 1a, plots the region where the PIS condition is satisfied such that the agreement $(1, 8)$ is stable (blue area), while the second graph, Figure 1b, plots the region where the PIS condition is satisfied such that the agreement $(2, 8)$ is stable (blue area)[5].



(a) Region where $PIS > 0$, agreement $(1, 8)$ (b) Region where $PIS > 0$, agreement $(2, 8)$

Figure 1: Regions where PIS > 0

Regarding coalition $(1, 8)$, if parameter γ^B takes its maximum value, i.e. $\gamma^B = 0.0022$, the corresponding maximum value that parameter γ^A can take, based on condition (29), such that the agreement is stable, is $\gamma^A = 0.1256$. Similarly for the coalition $(2, 8)$, if parameter γ^B takes its maximum value, i.e. $\gamma^B = 9.58 * 10^{-6}$, the corresponding maximum value that parameter γ^A can take, such that the agreement is stable, is $\gamma^A = 2.58 * 10^{-3}$. Obviously, when the agreement $(2, 8)$ is stable, the agreement $(1, 8)$ is stable as well since we need stricter constraints for the parameters γ^A and γ^B in order to have a stable coalition with 2 instead of 1 type A countries. We can present similar graphs for all cases displayed in Table

[5] Note that the vertical axis' scale is different between the two figures.

1. The regions where the PIS condition is satisfied take always the same semi-oval form and shrink as we move to larger stable agreements. This is also obvious by comparing the region where the agreement $(1, 8)$ is stable, Figure 1a, to the region where the agreement $(2, 8)$ is stable, Figure 1b.

Taking the peak points of all curves, like the ones presented in Figure 1, for any coalition size, we generate Table 2. The table includes the values of the parameters γ^A and γ^B at the peak points[6] and their ratio, parameter $\gamma = \frac{\gamma^A}{\gamma^B}$, which captures the degree of heterogeneity among the two types of countries ($\gamma = \frac{c^A}{c^B}$, given that $b^A = b^B$) for any possible stable coalition[7].

Table 2: Stable agreements for different degrees of heterogeneity

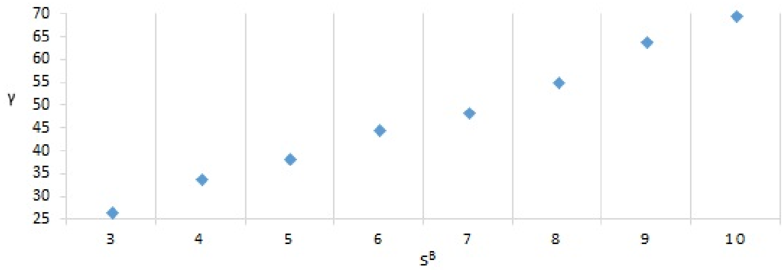
	Agreement $(1, n)$			Agreement $(2, n)$		
n	γ^A	$max\ \gamma^B$	γ	γ^A	$max\ \gamma^B$	γ
3	0.9999	0.0375	26.62	0.01989	$4.85 * 10^{-4}$	40.97
4	0.4557	0.0133	34.13	0.01093	$1.51 * 10^{-4}$	72.32
5	0.2719	0.0070	38.53	0.00679	$6.19 * 10^{-5}$	109.65
6	0.1978	0.0044	44.85	0.00473	$2.99 * 10^{-5}$	157.98
7	0.1468	0.0030	48.53	0.00341	$1.62 * 10^{-5}$	209.84
8	0.1218	0.0022	55.24	0.00263	$9.58 * 10^{-6}$	275.38
9	0.1071	0.0017	63.92	0.00208	$6.01 * 10^{-6}$	347.24
10	0.0920	0.0013	69.65	0.00183	$3.95 * 10^{-6}$	463.15

In all cases, the derived values for the parameters γ^A and γ^B satisfy the following conditions, $0 < \gamma^A < 1$ and $0 < \gamma^B < 1$, except for the agreement $(1, 3)$ where parameter γ^A takes a value higher than 1 when parameter γ^B takes its maximum value. Thus, for this coalition, we restrict $\gamma^A < 1$ and so the corresponding maximum value for γ^B, based on condition (29), is $\gamma^B = 0.0375$. The intuition of having $\gamma^j < 1$ is that the slope of the marginal environmental damages (c^j) is smaller than the slope of the marginal benefits (b^j). Therefore, the relative impact of damages to benefits is not very high. In the homogeneous case, the literature has shown that a stable agreement exists, though small, only when

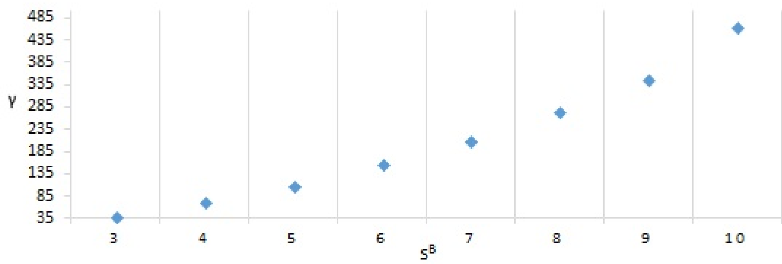
[6] Values are rounded off such that they do not exceed their corresponding maximum points.
[7] Values are rounded to two decimal places.

the above-mentioned restriction holds (i.e. the impact of damages to benefits is low). The analysis indicates that larger coalitions require stricter constraints for the parameters of the model and a stronger degree of heterogeneity (captured by the parameter γ). Thus, to increase cooperation we have to increase heterogeneity among the two types of countries (higher value for γ) while decreasing the effect of the global environmental damages on their welfare levels (lower values for γ^A and γ^B).

Using the data from Table 2, we plot in Figure 2 the degree of heterogeneity γ against the number of type B signatory countries. We display two graphs for the two cases, $(1, n)$ and $(2, n)$ for $n \in \{3, 4, ..., 10\}$. The X axis shows the number of type B signatory countries (i.e. $s^B = n$) and the Y axis shows the parameter γ.



(a) Stable agreements with 1 type A country



(b) Stable agreements with 2 type A countries

Figure 2: Stable agreements for different degrees of heterogeneity

Figure 2a depicts the results for the case with 1 type A country and Figure 2b depicts the results for the case with 2 type A countries. As indicated, the larger is the degree of heterogeneity, the larger is the coalition size.

We can demonstrate the fact that larger coalitions are stable only when the degree of heterogeneity increases, by choosing a specific value for the parameter

$\gamma^A = 0.0015$ and calculate the required degree of heterogeneity to support different sizes of stable agreement. Table 3 presents the degree of heterogeneity, $\gamma = \gamma^A/\gamma^B$, required, by the PIS condition (29), to support stable coalitions consisting of one or two type A countries (first and second column respectively) and $n \in \{3, 4, ..., 10\}$ type B countries[8].

Table 3: Stable agreements when $\gamma^A = 0.0015$

		Agreement $(1, n)$	Agreement $(2, n)$
		$\gamma^A = 0.0015$	
n		γ	γ
3		4.31	19.14
4		6.85	35.46
5		9.36	58.16
6		11.87	88.97
7		14.36	130.66
8		16.89	187.25
9		19.40	266.40
10		21.93	381.47

The example clearly illustrates that the greater the heterogeneity, the greater the cooperation incentives. For instance, in order to reach the stable agreement with four type B countries and one type A country $(1, 4)$, we need a relatively low level of heterogeneity $\gamma = 6.85$, but in order to have two type A signatories $(2, 4)$, the level of heterogeneity has to be $\gamma = 35.46$. It is worth mentioning that, the degree of heterogeneity required to sustain stable agreements with one type A country increases at a smaller rate as the number of type B signatories increases, relative to the case of an agreement with two type A countries. The above discussion is summarized in Corollary 1.

Corollary 1 *A higher degree of heterogeneity is required in order to achieve larger stable agreements. The rate of the required increase in heterogeneity is higher if*

[8] Parameter γ is calculated by using the maximum value that parameter γ^B can take, given that $\gamma^A = 0.0015$, such that the PIS condition (29) is satisfied. Values are rounded to two decimal places.

there are two relative to only one type A signatories.

The above results extent to any number of countries. The maximum number of type A countries that will join an agreement is two, regardless of their number. Type A signatories, by offering transfers, can attract into the agreement a large number of type B countries, that is increasing with the degree of heterogeneity. In what follows we extent the above results to $n \in \{10, 20, ..., 100\}$.

Following the same process as before, we present in Table 4 the values of the parameters γ^A and γ^B (at the peak points of the corresponding curves)[9] and the parameter γ[10], necessary to support possible stable coalitions, such that $s^A \in \{1, 2\}$ and $n \in \{10, 20, ..., 100\}$.

Table 4: Larger stable agreements for different degrees of heterogeneity

		Agreement $(1, n)$				Agreement $(2, n)$		
n		γ^A	$max\ \gamma^B$	γ		γ^A	$max\ \gamma^B$	γ
10		0.0870	$1.32 * 10^{-3}$	65.72		$1.66 * 10^{-3}$	$3.96 * 10^{-6}$	418.71
20		0.0378	$2.93 * 10^{-4}$	128.85		$4.16 * 10^{-4}$	$2.53 * 10^{-7}$	$1,647.26$
30		0.0241	$1.25 * 10^{-4}$	191.93		$1.87 * 10^{-4}$	$5.04 * 10^{-8}$	$3,705.38$
40		0.0177	$6.94 * 10^{-5}$	254.92		$1.04 * 10^{-4}$	$1.60 * 10^{-8}$	$6,473.00$
50		0.0141	$4.39 * 10^{-5}$	321.05		$6.73 * 10^{-5}$	$6.58 * 10^{-9}$	$10,221.68$
60		0.0115	$3.03 * 10^{-5}$	379.86		$4.66 * 10^{-5}$	$3.18 * 10^{-9}$	$14,661.68$
70		0.0100	$2.21 * 10^{-5}$	449.21		$3.47 * 10^{-5}$	$1.72 * 10^{-9}$	$20,197.90$
80		0.0087	$1.68 * 10^{-5}$	517.25		$2.67 * 10^{-5}$	$1.01 * 10^{-9}$	$26,519.84$
90		0.0077	$1.33 * 10^{-5}$	575.62		$2.10 * 10^{-5}$	$6.30 * 10^{-10}$	$33,392.52$
100		0.0070	$1.07 * 10^{-5}$	649.54		$1.74 * 10^{-5}$	$4.13 * 10^{-10}$	$42,104.80$

Comparing the results presented in Table 4 with those in Table 2, we observe that the required degree of heterogeneity should be higher in order to induce cooperation of a larger number of type B countries.

In order to clearly demonstrate the requirement of increasing heterogeneity in order to support larger coalitions, we choose a particular value $\gamma^A = 1.50 * 10^{-5}$

[9] Values are rounded off such that they do not exceed their corresponding maximum points.
[10] Values are rounded to two decimal places.

and calculate the value of the parameter γ necessary to support different coalition sizes[11]. Table 5 presents the results of this exercise.

Table 5: Larger stable agreements when $\gamma^A = 1.50 * 10^{-5}$

		Agreement $(1, n)$	Agreement $(2, n)$
		$\gamma^A = 1.50 * 10^{-5}$	
n		γ	γ
10		21.33	202.95
20		45.52	819.85
30		69.70	1,885.46
40		93.88	3,463.97
50		118.08	5,658.65
60		142.28	8,630.26
70		166.50	12,630.73
80		190.73	18,066.61
90		214.97	25,628.41
100		239.22	36,578.32

Summarizing the above discussion, we first find that in order to achieve a larger coalition, a higher degree of heterogeneity is required. Second, the degree of heterogeneity required to sustain stable agreements with one type A country increases at a smaller rate as the number of type B signatories increases, relative to the case of an agreement with two type A countries.

4.2 Transfer rules

We now turn to the design of transfers. Under the optimal transfer rule every coalition member receives at least his free-rider payoff plus a share of the remaining surplus (Eyckmans and Finus, 2004). Therefore, no resources are wasted.

We define the share as $\mu_i^j \geq 0$ such that $\mu = \sum_j \sum_{i=1}^{s^j} \mu_i^j = 1$, where $j \in \{A, B\}$. That is,

[11] Parameter γ is calculated by using the maximum value that parameter γ^B can take, given that $\gamma^A = 1.50 * 10^{-5}$, such that the PIS condition (29) is satisfied. Values are rounded to two decimal places.

$$\mu = \sum_{i=1}^{s^A} \mu_i^A + \sum_{i=1}^{s^B} \mu_i^B = s^A \mu_s^A + s^B \mu_s^B = 1. \tag{30}$$

Thus, shares can be different between the two types of countries, however, countries belonging to the same type receive an equal share. This rule is reasonable since countries that benefit from participating in the agreement can induce cooperation without transferring all of their gains to those countries that require compensation for their losses from joining the agreement.

The surplus is defined by the potential stability condition in (8). Thus, each signatory country receives a share μ_s^j of the surplus,

$$\begin{aligned} PIS(s^A, s^B) \;\; = \;\; & s^A[\mathcal{W}_s^A(s^A, s^B) - \mathcal{W}_{ns}^A(s^A - 1, s^B)] + \\ & s^B[\mathcal{W}_s^B(s^A, s^B) - \mathcal{W}_{ns}^B(s^A, s^B - 1)] \geq 0. \end{aligned} \tag{31}$$

Every type A coalition member receives final welfare $\mathcal{W}_s^{A^{final}}(s^A, s^B)$,

$$\mathcal{W}_s^{A^{final}}(s^A, s^B) = \mathcal{W}_{ns}^A(s^A - 1, s^B) + \mu_s^A PIS(s^A, s^B), \tag{32}$$

and every type B coalition member receives final welfare $\mathcal{W}_s^{B^{final}}(s^A, s^B)$,

$$\mathcal{W}_s^{B^{final}}(s^A, s^B) = \mathcal{W}_{ns}^B(s^A, s^B - 1) + \mu_s^B PIS(s^A, s^B). \tag{33}$$

Since type A countries benefit from cooperation, they submit payments, while type B countries receive payments. That is, we have welfare transfers from type A to type B countries, meaning that the first term inside the brackets in condition (31) is positive (internal stability is satisfied for type A countries) while the second term is negative (internal stability is not satisfied for type B countries) for any $s^A \in \{1, 2\}$ and $s^B = n$ with $n \geq 3$. According to the optimal transfer scheme, type A countries should provide each type B signatory its free-rider payoff plus its share of the surplus. Each type A country will also receive its free-rider payoff plus its share of the surplus.

Hence, transfers from type A to type B countries take the following form,

$$T_s(s^A, s^B) = \mathcal{W}_{ns}^B(s^A, s^B - 1) - \mathcal{W}_s^B(s^A, s^B) + \mu_s^B PIS(s^A, s^B). \tag{34}$$

At the extreme, type A countries could provide type B countries with just their free-rider payoff, without sharing the surplus. Thus, in this case, $\mu_s^B = 0$, transfers are,

$$T_s(s^A, s^B) = \mathcal{W}_{ns}^B(s^A, s^B - 1) - \mathcal{W}_s^B(s^A, s^B). \tag{35}$$

Given the above assumption regarding the transfer rule, the coalition member's welfare after the transfers, is defined in the following Remark.

Remark 2 *After the transfers, the welfare level of type A coalition member is,* $\mathcal{W}_s^{A^{final}}(s^A, s^B) = \mathcal{W}_s^A(s^A, s^B) - \frac{s^B}{s^A} T_s(s^A, s^B)$*, and of type B coalition member is,* $\mathcal{W}_s^{B^{final}}(s^A, s^B) = \mathcal{W}_s^B(s^A, s^B) + T_s(s^A, s^B)$.

Proof. See appendix A. ■

5 Emissions and welfare levels

The aggregate emissions are given by equation (22). Recall that,

$$E = \frac{(a^A n^A + a^B n^B)}{\Psi}. \tag{36}$$

Setting $a^A = a^B = a^I$, $b^A = b^B = b^I$[12], $n^A = n^B = n$ and $s^B = n$, global emissions can be written as,

$$E = \frac{2a^I n}{\Psi}, \tag{37}$$

where $\Psi = 1 + \gamma^A(n - s^A) + \gamma^A(s^A)^2 + \gamma^B n^2 + \Gamma s^A n$, $\Gamma = (\gamma^A + \gamma^B)$ and $\gamma^j = \frac{c^j}{b^I}$ with $j \in \{A, B\}$.

Remark 3 *Aggregate emissions decrease in the number of type A signatory countries and in the value of the parameter* γ^j*, where* $j \in \{A, B\}$*.*

Proof. See appendix B. ■

As expected, when $s^A = 2$ aggregate emissions are lower relative to the case when $s^A = 1$. Moreover, a higher value for the parameter γ^j implies that countries suffer more due to environmental damages and thus tend to emit less.

[12] The superscript I is used to denote that countries are identical with respect to benefits.

Proposition 1 *With transfers, large stable agreements emit less. However, the reduction in aggregate emissions achieved by the enlarged agreements is very small relative to the case without transfers.*

Proof. Under the coalition ($s^A = 1, s^B = n$), global emissions are[13],

$$E(s^A = 1, s^B = n) = \frac{2a^I n}{1 + n^2\gamma^B + (\Gamma + \gamma^A)n}. \quad (38)$$

Under the coalition ($s^A = 2, s^B = n$), global emissions are[14],

$$E(s^A = 2, s^B = n) = \frac{2a^I n}{1 + n^2\gamma^B + (\Gamma + \gamma^A)n + 2\gamma^A + \Gamma n}. \quad (39)$$

Without transfers, as long as γ^A and γ^B satisfy the necessary conditions (see Diamantoudi et al., 2017), a stable agreement exists such that ($s^A = 2, s^B = 0$). In this case, global emissions are[15],

$$E(s^A = 2, s^B = 0) = \frac{2a^I n}{1 + \Gamma n + 2\gamma^A}. \quad (40)$$

Clearly, for $n \geq 2$,

$$1 + n^2\gamma^B + (\Gamma + \gamma^A)n + 2\gamma^A + \Gamma n > 1 + n^2\gamma^B + (\Gamma + \gamma^A)n > 1 + \Gamma n + 2\gamma^A. \quad (41)$$

Therefore,

$$E(s^A = 2, s^B = n) < E(s^A = 1, s^B = n) < E(s^A = 2, s^B = 0). \quad (42)$$

■

Table 6 presents the global emissions (i.e. E) for the case where $s^A \in \{1, 2\}$ and $n \in \{10, 20, ..., 100\}$[16]. We fix the values for the parameters a, γ^A and γ^B such that $a = 1$, $\gamma^A = 1.50 * 10^{-5}$ and $\gamma^B = 4.10 * 10^{-10}$. Given these values for the parameters γ^A and γ^B, all the agreements presented in Table 4 are stable. To facilitate comparison the last column of Table 6 presents aggregate emissions in the case that no transfers are used and a stable agreement exists such that ($s^A = 2, s^B = 0$).

[13] Global emissions are calculated using (37) and setting $s^A = 1$ and $s^B = n$.
[14] Global emissions are calculated using (37) and setting $s^A = 2$ and $s^B = n$.
[15] Global emissions are calculated using (22) and setting $s^A = 2$ and $s^B = 0$.
[16] Values are rounded to three decimal places.

Table 6: Global emissions

		Transfers			No Transfers
		Agreement $(1, n)$	Agreement $(2, n)$		Agreement $(2, 0)$
n		E	E		E
10		19.994	19.990		19.996
20		39.976	39.963		39.987
30		59.946	59.917		59.971
40		79.904	79.854		79.950
50		99.850	99.772		99.922
60		119.784	119.673		119.889
70		139.706	139.556		139.849
80		159.616	159.421		159.803
90		179.515	179.268		179.752
100		199.401	199.097		199.694

Comparing the first two columns of Table 6 it is evident that total emissions are slightly lower with the large agreements $(2, n)$ compared to the agreements $(1, n)$ for any corresponding number of n. Comparing the first two with the third column, it is clear that total emissions are slightly higher in the case without transfers, however, reductions are very small. Thus, even though the presence of transfers increases cooperation, the reduction in aggregate emissions achieved by the enlarged coalitions is very small and consequently the welfare improvement is also small. Table 7 includes the global welfare levels (i.e. W_T) for the cases presented above[17].

The increase in the coalition size, relative to the case that transfers are not available, comes only from countries belonging to the type with the lower environmental damages (i.e. type B countries), which are drawn into the coalition by the transfers offered. The number of coalition members belonging to the type suffering the higher damages (i.e. type A countries) does not increase. Thus, the fact that stable agreements consist of a few countries with high environmental damages and many countries with low environmental damages, confirms the persistent result in

[17] Values are rounded to three decimal places.

Table 7: Global welfare levels

	Transfers		No Transfers
	Agreement $(1, n)$	Agreement $(2, n)$	Agreement $(2, 0)$
n	W_T	W_T	W_T
10	249.250	249.251	249.250
20	494.007	494.011	494.004
30	729.785	729.804	729.769
40	952.112	952.170	952.058
50	1156.530	1156.670	1156.390
60	1338.570	1338.860	1338.290
70	1493.810	1494.350	1493.290
80	1617.820	1618.740	1616.930
90	1706.160	1707.630	1704.730
100	1754.440	1756.680	1752.260

the IEAs' literature that large stable coalitions are associated with low gains of cooperation.

6 Conclusions

The present paper examines the existence and stability of international environmental coalitions in a two stage, non-cooperative game among heterogeneous countries while allowing transfers. In particular, we introduce two types of countries differing in their sensitivity to the global pollutant. In order to introduce transfers, the concept of the stability conditions requiring that none of the coalition's members wish to withdraw from and no country outside the coalition wishes to join the coalition, needs to be modified. We do this by introducing the concept of potential internal stability that allows coalition members to redistribute payoffs among them so that the coalition is internally stable.

We use the usual two-stage emission game where in the first stage each country decides whether or not to join the agreement, while in the second stage the quantity of emissions is chosen simultaneously by all countries. In addition, in the first stage those countries that decide to join the agreement agree also to share the gains from cooperation. We apply the following optimal transfer rule: type A countries give every type B country, member of the coalition, his free-rider payoff and they share the remaining gains among either all members or themselves.

Our results show that allowing for transfers can increase cooperation among heterogeneous countries. Although the increase in the coalition size can be considerable, the coalition's expansion is based only on countries of type B drawn into the coalition by the incentive of the transfers offered by countries of type A which suffer the higher environmental damages. Type A countries' free-riding incentives are strong and thus, the coalition does not expand by including more of them. Since the coalition contains more type B countries, that they do not have strong incentives to decrease emissions, the reduction in aggregate emissions due to the enlargement of the coalition is small, leading to dismal improvement in welfare.

Consequently, based on our analysis, using simulations, we can conclude that a stable with transfers agreement can have either one or two type A countries and any number n of type B countries. The level of cooperation that can be achieved using transfers increases with the degree of heterogeneity, meaning that the higher the heterogeneity in environmental damages, the higher the level of cooperation. Furthermore, with transfers large stable coalitions can perform only slightly better in terms of reductions in emissions.

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8 Appendices

In what follows we present the proofs of Remark 2 and Remark 3.

8.1 Appendix A

Under the optimal transfer rule, every coalition member receives at least his free-rider payoff plus a share of the remaining surplus. Based on our analysis, type A countries should give each type B country - member of the coalition - his free-rider payoff. They will each receive also their free-rider payoffs and then share the remaining gains among all members.

Recall that,

$$\begin{aligned} PIS(s^A, s^B) &= s^A[\mathcal{W}_s^A(s^A, s^B) - \mathcal{W}_{ns}^A(s^A - 1, s^B)] + \\ &\quad s^B[\mathcal{W}_s^B(s^A, s^B) - \mathcal{W}_{ns}^B(s^A, s^B - 1)] \geq 0. \end{aligned} \tag{43}$$

Thus, every type A coalition member receives final welfare $\mathcal{W}_s^{A^{final}}(s^A, s^B)$,

$$\mathcal{W}_s^{A^{final}}(s^A, s^B) = \mathcal{W}_{ns}^A(s^A - 1, s^B) + \mu_s^A PIS(s^A, s^B), \tag{44}$$

and every type B coalition member receives final welfare $\mathcal{W}_s^{B^{final}}(s^A, s^B)$,

$$\mathcal{W}_s^{B^{final}}(s^A, s^B) = \mathcal{W}_{ns}^B(s^A, s^B - 1) + \mu_s^B PIS(s^A, s^B). \tag{45}$$

Transfers can take the following form,

$$T_s(s^A, s^B) = \mathcal{W}_{ns}^B(s^A, s^B - 1) - \mathcal{W}_s^B(s^A, s^B) + \mu_s^B PIS(s^A, s^B). \tag{46}$$

The total transfers that should be paid to type B coalition members are,

$$\begin{aligned} T_s^{total}(s^A, s^B) &= s^B \left[\mathcal{W}_{ns}^B(s^A, s^B - 1) - \mathcal{W}_s^B(s^A, s^B) + \mu_s^B PIS(s^A, s^B)\right] \\ &= s^B \left[\mathcal{W}_{ns}^B(s^A, s^B - 1) - \mathcal{W}_s^B(s^A, s^B)\right] + s^B \mu_s^B PIS(s^A, s^B) \\ &= -s^B \left[\mathcal{W}_s^B(s^A, s^B) - \mathcal{W}_{ns}^B(s^A, s^B - 1)\right] + (1 - s^A \mu_s^A) PIS(s^A, s^B) \\ &= s^A \left[\mathcal{W}_s^A(s^A, s^B) - \mathcal{W}_{ns}^A(s^A - 1, s^B)\right] - s^A \mu_s^A PIS(s^A, s^B). \end{aligned} \tag{47}$$

Each type A country should pay,

$$\frac{T_s^{total}(s^A, s^B)}{s^A} = \mathcal{W}_s^A(s^A, s^B) - \mathcal{W}_{ns}^A(s^A - 1, s^B) - \mu_s^A PIS(s^A, s^B). \tag{48}$$

Therefore, the final welfare for each type A country is,

$$\begin{aligned} \mathcal{W}_s^{A^{final}}(s^A, s^B) &= \mathcal{W}_s^A(s^A, s^B) - \frac{T_s^{total}(s^A, s^B)}{s^A} \\ &= \mathcal{W}_{ns}^A(s^A - 1, s^B) + \mu_s^A PIS(s^A, s^B). \end{aligned} \tag{49}$$

Moreover, the final welfare for each type B country is,

$$\begin{aligned} \mathcal{W}_s^{B^{final}}(s^A, s^B) &= \mathcal{W}_s^B(s^A, s^B) + T_s(s^A, s^B) \\ &= \mathcal{W}_s^B(s^A, s^B) + \mathcal{W}_{ns}^B(s^A, s^B - 1) - \mathcal{W}_s^B(s^A, s^B) + \mu_s^B PIS(s^A, s^B) \\ &= \mathcal{W}_{ns}^B(s^A, s^B - 1) + \mu_s^B PIS(s^A, s^B). \end{aligned} \tag{50}$$

In the extreme case where type A countries decide to give every type B country only his free-rider payoff without any share of the remaining surplus, parameters

μ_s^B should be equal to zero, i.e. $\mu_s^B = 0$. Thus, transfers can be simplified as follows,

$$T_s(s^A, s^B) = \mathcal{W}_{ns}^B(s^A, s^B - 1) - \mathcal{W}_s^B(s^A, s^B). \tag{51}$$

Furthermore, $\mu_s^A = \frac{1}{s^A}$ since gains are distributed only among type A countries. That is, $\mu = \sum_{i=1}^{s^A} \mu_i^A = s^A \mu_s^A = 1$. Therefore, every type A coalition member receives final welfare,

$$\begin{aligned}
\mathcal{W}_s^{A^{final}}(s^A, s^B) &= \mathcal{W}_{ns}^A(s^A - 1, s^B) + \frac{1}{s^A} PIS(s^A, s^B) \\
&= \mathcal{W}_{ns}^A(s^A - 1, s^B) + \frac{1}{s^A}[s^A(\mathcal{W}_s^A(s^A, s^B) - \mathcal{W}_{ns}^A(s^A - 1, s^B)) + \\
&\quad s^B(\mathcal{W}_s^B(s^A, s^B) - \mathcal{W}_{ns}^B(s^A, s^B - 1))] \\
&= \mathcal{W}_s^A(s^A, s^B) + \frac{s^B}{s^A}\left[\mathcal{W}_s^B(s^A, s^B) - \mathcal{W}_{ns}^B(s^A, s^B - 1)\right] \\
&= \mathcal{W}_s^A(s^A, s^B) - \frac{s^B}{s^A} T_s(s^A, s^B). \qquad (52)
\end{aligned}$$

Every type B coalition member receives final welfare,

$$\begin{aligned}
\mathcal{W}_s^{B^{final}}(s^A, s^B) &= \mathcal{W}_{ns}^B(s^A, s^B - 1) \\
&= \mathcal{W}_s^B(s^A, s^B) + T_s(s^A, s^B). \qquad (53)
\end{aligned}$$

8.2 Appendix B

The aggregate emissions can be written as,

$$E = \frac{2a^I n}{\Psi}. \tag{54}$$

where $\Psi = 1 + \gamma^A(n - s^A) + \gamma^A(s^A)^2 + \gamma^B n^2 + \Gamma s^A n$, $\Gamma = (\gamma^A + \gamma^B)$ and $\gamma^j = \frac{c^j}{b^I}$ with $j \in \{A, B\}$.

The derivative of the aggregate emissions with respect to the number of type A signatory countries, i.e. s^A, is negative meaning that global emissions decrease in the number of type A signatory countries.

$$D_{s^A} = -2a^I n \frac{\gamma^A(2s^A - 1) + \Gamma n}{\Psi^2}. \tag{55}$$

The derivative of the aggregate emissions with respect to the parameter γ^A is negative. When parameter γ^A increases, type A countries suffer more due to environmental pollution and thus tend to emit less.

$$D_{\gamma^A} = -2a^I n \frac{n + s^A(s^A + n - 1)}{\Psi^2}. \tag{56}$$

The derivative of the aggregate emissions with respect to the parameter γ^B is negative. When parameter γ^B increases, type B countries suffer more due to environmental pollution and thus tend to emit less.

$$D_{\gamma^B} = -2a^I n \frac{n(s^A + n)}{\Psi^2}. \tag{57}$$

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