The impact of adaptation on the stability of International Environmental Agreements

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Abstract

We examine the stability of international environmental agreements when they include both adaptation and mitigation policies. We assume that adaptation requires a prior irreversible investment and presents the characteristics of a private good by reducing a country's vulnerability to the impact of pollution, while mitigation policies produce a public good by reducing the total pollution.

Using a stylized model, we show that adaptive measures can be used strategically and that their inclusion in environmental agreements enhances their stability and can even lead to full cooperation. However, adaptation does not help cooperation on mitigation policies. Finally, we evaluate how including adaptive measures to climate change in international environmental agreements affect welfare and total pollution.

Keywords: Adaptation, Climate change, Mitigation, Strategy, Stability.

1 Introduction

It is increasingly recognized that the response to climate change and its consequences lies in two different types of actions, namely, the reduction of greenhouse gases (GHGs) emissions and the investment in adaptive measures. At the international level, this has been acknowledged in several United Nations conferences on climate change (Cancun 2010, Durban 2011, Doha 2012, Paris 2015) and in the series of the Intergovernmental Panel on Climate Change (IPCC) assessments reports published over time (Third Assessment Report 2001, Fourth Assessment Report 2007, Fifth Assessment Report 2014). However, in discussions about climate change, the ambiguous effects of adaptation are often raised.

Given the statement in the Third Assessment Report "*Adaptation is a necessary strategy at all scales to complement climate change mitigation efforts,*"[1] our aim in this paper is to study the consequences of including resolutions on adaptive measures in the negotiation of an International Environmental Agreement (IEA) aiming at reducing GHGs emissions. In particular, we investigate the case where commitments to adaptive solutions are made before those related to mitigation efforts. The problem is modelled as a three-stage game. In the

[1] https://www.ipcc.ch/ipccreports/tar/wg2/index.php?idp=10

first stage, countries decide whether or not to be party to the agreement; in the second stage, countries choose their investment in adaptive measures according to their membership status; and in the third stage, countries play a mitigation game, where decisions are dependent on membership and adaptation choices made in the previous stages. The analysis is carried out for two distinct cases representing two different types of agreement. The first type is called *full agreement,* and it requires signatory countries to coordinate both their adaptation and mitigation policies; the second type is called *partial agreement*; in this case, signatory countries agree to coordinate only their adaptation policies (with mitigation policies decided by all countries individualistically). The games are solved by backward recursion. Our study extends and completes part of the work developed in Breton and Sbragia (2016), who examine the consequences of different types of adaptive measures on environmental costs and levels of efforts, for any number of parties to the agreement, both when signatory countries act as leaders or not in responding to climate change. However, the paper does not address the issue of membership stability of such agreements, which is indeed the main objective of the present paper.

Other works interested in the effects of adaptive investments on membership of IEAs are, for example, Marrouch and Chaudhuri (2011), Masoudi and Zaccour (2016), Lazkano, Marrouch and Nkuiya (2016), and Masoudi and Zaccour (2017). Under the assumption of a bilinear damage cost, where signatory countries act as leaders, and emissions and adaptation efforts are decided simultaneously by the players, Marrouch and Chaudhuri (2011) show that large stable coalitions can be reached and the level of total emissions can be below the non-cooperative level. Under the assumption of a quadratic damage cost, the main feature of Masoudi and Zaccour (2016) and Masoudi and Zaccour (2017) is that adaptation has a "public good flavour," in that the benefits of adaptive measures are shared by the signatory countries and can spillover to all players. In a setting where countries decide on their environmental policies simultaneously, Masoudi and Zaccour (2016) find that the adaptation effort of signatory countries is higher than that of non-signatories, and that for some parameter values, stable IEAS can form with a significant number of players.

In Lazkano, Marrouch and Nkuiya (2016), the stability of an IEA is studied for countries that are asymmetric in adaptation cost parameters and simultaneously choose emission and adaptation levels. The authors show that when the environmental damage cost is linear, asymmetry in adaptation cost parameters does not change the standard result on the size of a stable IEA, which is three signatories. However, when damage cost is quadratic, cross-country differences in adaptation may encourage participation in an IEA. The asymmetrical feature of the model by Lazkano, Marrouch and Nkuiya (2016) relates their paper to another literature on IEAs, namely the one studying the impact of some sort of asymmetry among countries on the size of a stable agreement. Examples of these investigations are Fuentes-Albero and Rubio (2010), Glanemann (2012) and Pavlova and de Zeeuw (2013). The common result of these analyzes is that, in stylized models without transfers, asymmetry in a single aspect is not sufficient to change the usual small-size-coalition result (coalition size not greater than three); to achieve large coalitions, countries have to be different in more than one aspect, and the asymmetries among countries have to be strong.

This asymmetric aspect also comes into play in our model, but in a different way. In our model, countries are identical at the start of the game, when their first decision is about their membership to the IEA. Being a member means that expenditures on environmental policies (that is, adaptation and emissions reduction) differ from those of non-signatory countries. Since these decisions are made in two stages, with countries first investing in adaptive measures, and then complying with their emissions reduction, countries differ in their level of adaptation in the last stage of the game where emissions are decided. Thus, in our setting, the asymmetry of countries arises from adaptation decisions that are endogenous to the game itself. Nevertheless in our paper with endogenous asymmetry, we confirm the result of the exogenous asymmetry literature: the pessimistic small-size-coalition result persists in the mitigation game when countries differ in their adaptation levels.

An important difference in our model compared to the above-mentioned literature on the stability of IEAs is that we assume that countries commit to adaptive investments prior to mitigation decisions, instead of simultaneously. This is an important aspect, as adaptive measures can then have a strategic role, as shown in Breton and Sbragia (2016). A similar approach is taken in Masoudi and Zaccour (2017), where the focus is on the stability of an IEA that concerns only adaptation. There the authors show that a large IEA on adaptation is achievable, including full participation. Their model is similar to our partial agreement case, the main difference lying in the private good nature of adaptation. In Masoudi and Zaccour (2017), benefits from investing in adaptation may not be fully appropriable, and are voluntarily shared among the signatories, whereas in our model, adaptation is an investment that has the properties of a private good. Our private adaptation version of partial agreement exclusive to adaptive measures confirms the results found in Masoudi and Zaccour (2017). This implies that knowledge spillovers are not necessary for a large size coalition on adaptation. The result extends to the full agreement case, where we also find that incorporating adaptation in the negotiation of an IEA improves the stability of the agreement.

An important issue raised by the prior commitment assumption in an agreement including both adaptive and mitigation measures is its dynamic stability. In the full agreement case, players could revise their membership decision, and opt to leave the agreement, after implementing agreed adaptation measures. In this case, we show that it is not possible to maintain cooperation in mitigation policies, and any agreement that includes both types of actions will break down after the initial investment in adaptation measures.

Another important contribution of our paper is the examination of the economic and environmental implications of including adaptive measures in environmental agreements. This is done by comparing the outcomes achieved by all countries when a stable coalition of players forms, with the outcomes when countries decide individualistically on both their levels of adaptation and mitigation, for both the partial and the full agreement cases. This is justified by the fact that, regardless of the existence of an agreement, countries are investing increasingly in adaptive measures to counteract climate change consequences. The interesting result is that when adaptation is regulated by agreement, and a stable coalition size is reached, total adaptation expenditures, emissions and environmental costs are lower than when there is no agreement and countries adapt in their own individual way.

The rest of the paper is organized as follows. Section 2 briefly recalls the prior commitment model of Breton and Sbragia (2016). Section 3 characterizes equilibrium environmental policies in the presence of an IEA involving a subset of countries. Section 4 investigates the dynamic stability of IEAs when players can revise their membership decisions after their investment in adaptive measures. Section 5 reports on the welfare impact of including adaptive measures in IEAs. Section 6 supplies a conclusion.

2 Model

The model is the same as in Breton an Sbragia (2016). We consider n symmetric countries whose production activity creates economic value but also pollution emissions as a by-product.

Countries have two instruments that can be used to respond to the adverse consequenses of pollution emissions. The first instrument, called *adaptation*, is to invest in some private measures that balance the negative effects of climate change (for instance, developing some crop variety that resists to frequent droughts). The effect of adaptation is a reduction in the countries vulnerability to pollution, described as

$$v_j = E - b_j$$

where E is the total emissions by countries and $b_j \in [0, E]$ measures the reduction in vulnerability resulting from adaptive measures. The cost of adaptation for country j is an increasing convex function of b_j, assumed quadratic, that is,

$$\mathcal{A}_j(b_j) = \frac{\gamma_A}{2} b_j^2$$

where $\gamma_A > 0$ is the adaptation cost coefficient.

The second environmental policy is called *mitigation* and it consists of any means (e.g., filters) aimed at curtailing the pollution emissions of country j, denoted by e_j; we normalize the production technology in such a way that the optimal emissions of country j when there is no environmental concern is equal to 1, so that mitigation is represented by the variable

$$m_j = 1 - e_j,$$

where $m_j \in [0, 1]$ is the reduction in the country's emissions with respect to the base level of 1. The total pollution from all countries is then given by

$$E = \sum_{j=1}^{n} (1 - m_j).$$

The cost of mitigation for country j is an increasing convex function of m_j, assumed quadratic, that is,

$$\mathcal{M}_j(m_j) = \frac{\gamma_M}{2} m_j^2$$

where $\gamma_M > 0$ is the mitigation cost coefficient.

Global pollution reduces the welfare (e.g., losses in productivity) of each country, and this environmental cost is increasing and convex in the country's environmental vulnerability, that is,

$$\mathcal{D}_j(v_j) = \frac{\gamma_E}{2} v_j^2$$

where $\gamma_E > 0$ is the environmental sensitivity coefficient.

The overall environmental cost for a representative country j is thus given by

$$z_j = \frac{\gamma_E}{2} (E - b_j)^2 + \frac{\gamma_M}{2} m_j^2 + \frac{\gamma_A}{2} b_j^2.$$

As in Breton and Sbragia (2016), we normalize the cost by setting $\gamma_M = 1$ and we use $a_j \equiv \gamma_E b_j$, yielding an equivalent cost function involving two parameters

$$c_j = \frac{\omega}{2}E^2 - Ea_j + \frac{1}{2}m_j^2 + \frac{\theta}{2}a_j^2$$

where $E \equiv \sum_{i=1}^{n}(1 - m_i)$, $\omega \equiv \frac{\gamma_E}{\gamma_M} > 0$ is the environmental sensitivity parameter and $\theta \equiv \gamma_M \frac{\gamma_A + \gamma_E}{\gamma_E^2} > 0$ is a parameter accounting for the impact of adaptive measures on both the adaptation and environmental costs. The objective of country j is to choose the mitigation and adaptation levels that minimize the environmental cost c_j. Note that $\theta\omega = \frac{\gamma_A + \gamma_E}{\gamma_E} > 1$, which ensures that the cost function of an individual country, given the environmental strategies of the other countries, is strictly convex. Notice also that the restriction $0 \leq b_j \leq E$ is always satisfied in equilibrium.

3 The game

In this section we study the effects of including adaptive investments in the negotiation of an IEA aiming at reducing pollution emissions, when commitments to climate change adaptive measures are made before emissions mitigation decisions. This is modelled as a three-stage game.

In the first stage, countries play a "membership" game. Countries that subscribe to the agreement are called *signatory* countries and their decisions are made in the interest of all members, that is, they minimize their aggregate total environmental cost. Countries that do not subscribe to the agreement are called *non-signatory* countries and their decisions are driven by their individual interest. We denote by C the set of (cooperating) signatory countries and by I the set of (individualistic) non-signatory countries, where $|C| = N$, $|I| = M$ and $N + M = n$.

In the second stage, countries play an "adaptation" game, that, is they decide on how much they will invest in measures to counteract the adverse effects of climate change.

In the third stage, countries play a "mitigation" game, that is, they decide on how much effort they will put in curtailing their emissions.

We will distinguish between two contrasting cases concerning the scope of the environmental agreement. In the first case (*full agreement*), signatory countries agree to coordinate both their adaptation and their mitigation policies; in the second case (*partial agreement*), signatory countries only agree to coordinate their adaptation policies. The game is solved by backward recursion.

3.1 Equilibrium solution of the mitigation game

To solve the mitigation game, we make no assumption on the adaptation levels decided on in the preceding stage of the game. Accordingly, each country j is characterized by a parameter a_j representing its prior investment in adaptive measures. We denote by m_{Cj} the mitigation effort of a signatory country j and by m_{Ij} the mitigation effort of a non-signatory country j.

3.1.1 Full agreement

In this case, the agreement regulates both environmental policies. A non-cooperating country $j \in I$ solves

$$\min_{m_j \in [0,1]} \left\{ \frac{\omega}{2} (O_j - m_j)^2 - (O_j - m_j) a_j + \frac{1}{2} m_j^2 + \frac{\theta}{2} a_j^2 \right\} \tag{1}$$

where $O_j = n - \sum_{i \neq j} m_i$. Assuming an interior solution, the first order conditions for all $j \in I$ yield:

$$m_{Ij} = \omega E - a_j \text{ for all } j \in I.$$

Non-cooperating countries mitigation policy is a value proportional to total emissions reduced by their individual level of adaptation.

Cooperating countries $j \in C$ jointly solve

$$\min_{m_j \in [0,1],\ j \in C} \left\{ \sum_{j \in C} \frac{\omega}{2} \left(O_C - \sum_{i \in C} m_i \right)^2 - \left(O_C - \sum_{i \in C} m_i \right) a_j + \frac{1}{2} m_j^2 + \frac{\theta}{2} a_j^2 \right\}$$

where $O_C = n - \sum_{i \notin C} m_i$. Assuming an interior solution, the first order conditions yield

$$m_{Cj} = N (\omega E - \overline{a}_C) \text{ for all } j \in C,$$

where $\overline{a}_C = \frac{\sum_{i \in C} a_i}{N}$ is the average adaptation level of the cooperating countries. We observe that the mitigation efforts of all cooperating countries are the same, irrespective of their adaptation levels; moreover, cooperating countries' mitigation effort would be N times higher than that of non-cooperating countries with an adaptation level equal to $\overline{a}_C$.

The equilibrium solution of the mitigation game is readily obtained by solving for the total emissions:

$$E = n - \sum_{j \in C} N (\omega E - \overline{a}_C) - \sum_{j \in I} (\omega E - a_j)$$

yielding

$$\begin{aligned} E &= \frac{n + M\overline{a}_I + N^2 \overline{a}_C}{\omega N^2 + M\omega + 1} && (2) \\ m_{Ij} &= \omega E - a_j,\ j \in I && (3) \\ m_{Cj} &= m_C = N (\omega E - \overline{a}_C),\ j \in C && (4) \end{aligned}$$

where $\overline{a}_I = \frac{\sum_{i \in I} a_i}{M}$ is the average adaptation level of the non-cooperating countries.

3.1.2 Partial agreement

In the case where the agreement does not include coordination of mitigation policies, all players solve the optimization problem (1), so that

$$m_j = \omega E - a_j \text{ for } j = 1, ..., n.$$

The equilibrium solution of the mitigation game is then obtained by solving for the total emissions:

$$E = n - \sum_{j \in C} (\omega E - a_j) - \sum_{j \in I} (\omega E - a_j)$$

yielding

$$E = \frac{n + M\overline{a}_I + N\overline{a}_C}{n\omega + 1} \quad (5)$$

$$m_{Ij} = \omega E - a_j, \; j \in I \quad (6)$$

$$m_{Cj} = \omega E - a_j, \; j \in C. \quad (7)$$

3.2 Equilibrium solution of the adaptation game

In the adaptation game, players take into account the equilibrium solution (2)-(4) or (5)-(7) to determine their investment in adaptation. We denote by a_{Cj} the level of adaptation collectively chosen for a signatory country j, and by a_{Ij} the individual level of adaptation selected by a non-signatory country j.

3.2.1 Full agreement

In the case of a full agreement, the solution of the adaptation game is the same as in Breton and Sbragia (2016) and is obtained by solving, for non-cooperating countries:

$$\min_{a_j} \left\{ \frac{\omega}{2} \left(\frac{n + A^{-j} + a_j + N^2\overline{a}_C}{\omega N^2 + M\omega + 1} \right)^2 - \left(\frac{n + A^{-j} + a_j + N^2\overline{a}_C}{\omega N^2 + M\omega + 1} \right) a_j \right.$$
$$\left. + \frac{1}{2} \left(\omega \left(\frac{n + A^{-j} + a_j + N^2\overline{a}_C}{\omega N^2 + M\omega + 1} \right) - a_j \right)^2 + \frac{\theta}{2} a_j^2 \right\}$$

where $A^{-j} = \sum_{i \in I, i \neq j} a_i$, and, for cooperating countries:

$$\min_{a_j} \left\{ \frac{\omega}{2} \left(\frac{n + M\overline{a}_I + N^2 a_j}{\omega N^2 + M\omega + 1} \right)^2 - \left(\frac{n + M\overline{a}_I + N^2 a_j}{\omega N^2 + M\omega + 1} \right) a_j \right.$$
$$\left. + \frac{1}{2} \left(N \left(\omega \left(\frac{n + M\overline{a}_I + N^2 a_j}{\omega N^2 + M\omega + 1} \right) - a_j \right) \right)^2 + \frac{\theta}{2} a_j^2 \right\},$$

yielding the equilibrium solution:

$$a_{Ij} = a_I = \frac{nW_1(\omega + 1)(W_1 - \omega)(\theta W_1 + MN^2\omega)}{K_1 + MN^2(N^2\omega + 1)(\omega + 1)(M\omega + 1)(\omega - W_1)}, \; j \in I \quad (8)$$

$$a_{Cj} = a_C = \frac{nW_1(N^2\omega + 1)(M\omega + 1)(\theta W_1 + \omega(M + N^2 - 1))}{K_1 + MN^2(N^2\omega + 1)(\omega + 1)(M\omega + 1)(\omega - W_1)}, \; j \in C \quad (9)$$

where

$$W_1 \equiv \omega\left(M + N^2\right) + 1$$
$$K_1 = \left(\theta W_1^2 + N^2\left(\omega\left(M^2\omega - N^2\right) - 1\right)\right)\left(\theta W_1^2 - M^2\omega + \left(N^2\omega + 1\right)(W_1 - M - \omega - 1)\right)$$

and $a_C > a_I$.

3.2.2 Partial agreement

In the case of a partial agreement, a non-cooperating country solves

$$\min_{a_j}\left\{\frac{\omega}{2}\left(\frac{n+A^{-j}+N\overline{a}_C+a_j}{\omega n+1}\right)^2-\left(\frac{n+A^{-j}+N\overline{a}_C+a_j}{\omega n+1}\right)a_j\right.$$
$$\left.+\frac{1}{2}\left(\omega\frac{n+A^{-j}+N\overline{a}_C+a_j}{\omega n+1}-a_j\right)^2+\frac{\theta}{2}a_j^2\right\}.$$

Since countries are symmetrical, the equilibrium reaction of non-cooperating countries to $\overline{a}_C$ is then

$$a_{Ij}=\frac{(\omega+1)(-\omega+\omega n+1)(n+N\overline{a}_C)}{\theta(n\omega+1)^2-M(n\omega+1)+\omega(n-1)(N\omega+1)},\ j\in I.$$

Symmetrical cooperating countries jointly solve:

$$\min_{a_j}\left\{\frac{\omega}{2}\left(\frac{n+M\overline{a}_I+Na_j}{\omega n+1}\right)^2-\left(\frac{n+M\overline{a}_I+Na_j}{\omega n+1}\right)a_j+\frac{1}{2}\left(\omega\frac{n+M\overline{a}_I+Na_C}{\omega n+1}-a_j\right)^2+\frac{\theta}{2}a_j^2\right\}.$$

Their reaction to $\overline{a}_I$ is

$$a_{Cj}=\frac{(\omega+1)(M\omega+1)(n+M\overline{a}_I)}{\theta(n\omega+1)^2+(M\omega+1)^2-N(2M\omega+N\omega+2)},\ j\in C.$$

The equilibrium solution of the adaptation game is then

$$a_{Ij}=a_I=nW_2(\omega+1)\frac{(W_2-\omega)(\theta W_2-N+M\omega+1)}{K_2K_3-MN(\omega+1)^2(M\omega+1)(W_2-\omega)},\ j\in I \tag{10}$$
$$a_{Cj}=a_C=nW_2(\omega+1)\frac{(M\omega+1)(\theta W_2+\omega(n-1))}{K_2K_3-MN(\omega+1)^2(M\omega+1)(W_2-\omega)},\ j\in C \tag{11}$$

where

$$\begin{aligned}W_2&\equiv n\omega+1\\K_2&=\theta W_2^2+(M\omega+1)^2-N(W_2+M\omega+1)\\K_3&=\theta W_2^2-MW_2+\omega(n-1)(N\omega+1).\end{aligned}$$

Notice that, in partial agreements, the adaptation level of signatory countries is lower than that of non-signatories:

$$a_C-a_I=-\frac{n(\omega+1)W_2^2(\theta\omega-1)(N-1)}{K_2K_3-MN(\omega+1)^2(M\omega+1)(W_2-\omega)}<0,$$

which is the reverse of what is obtained in full agreements.

3.3 Membership game

To solve the membership game, we adopt the non-cooperative point of view, which assumes that agreements must be self-enforcing. Accordingly, following d'Aspremont et al. (1983), an equilibrium is defined by two conditions: the internal stability, which implies that signatories have no incentive to leave the agreement, and the external stability, which implies that non-signatories have no incentive to join the agreement.

Let $C^C(N)$ and $C^I(N)$ represent the equilibrium costs, for a signatory and a non-signatory player respectively, when the number of signatory countries is N:

$$\begin{aligned} C^C(N) &= \frac{\omega}{2}E^2 - Ea_C + \frac{1}{2}(m_C)^2 + \frac{\theta}{2}(a_C)^2 \\ C^I(N) &= \frac{\omega}{2}E^2 - Ea_I + \frac{1}{2}(m_I)^2 + \frac{\theta}{2}(a_I)^2 \end{aligned}$$

where E, a_C, a_I, m_C and m_I are given, as a function of N, by (2)-(4) and (8)-(9) for a full agreement, or by (5)-(7) and (10)-(11) for a partial agreement. The internal and external stability conditions defining the equilibrium of the membership game are then respectively:

$$\begin{aligned} C^C(N) - C^I(N-1) &\leq 0 \\ C^C(N+1) - C^I(N) &\geq 0. \end{aligned}$$

3.3.1 No adaptation

First notice that the equilibrium solution obtained using (2)-(4) with $a_C = a_I = 0$ corresponds to an agreement, among symmetrical countries, involving mitigation policies only. In this case,

$$\begin{aligned} C^C(N) &= \frac{1}{2}n^2\omega\frac{N^2\omega+1}{(M\omega+N^2\omega+1)^2} \\ C^I(N-1) &= \frac{1}{2}n^2\omega\frac{\omega+1}{\left((M+1)\omega+(N-1)^2\omega+1\right)^2} \end{aligned}$$

and the internal stability condition is

$$C^C(N) - C^I(N-1) = \frac{K_4 n^2\omega^2(N-1)}{2\left((M+1)\omega+(N-1)^2\omega+1\right)^2(M\omega+N^2\omega+1)^2} \leq 0$$

where

$$\begin{aligned} K_4 &= \omega^2(M+N(N-2))\left(M+2N+MN+N^2(N-1)\right) \\ &\quad +2\omega\left(M(N-1)+2(N-1)+N^2(N-3)\right) \\ &\quad +(N-3). \end{aligned}$$

It is easy to verify that $K_4 > 0$ for any $N \geq 3$, which means that the maximum size of an equilibrium coalition in the membership game is two. This is a well known result for agreements on mitigation policies involving symmetrical players.

3.3.2 Adaptation with a prior commitment

On the other hand, when adaptation is included in the agreement, stable equilibrium solutions with a significant number of signatories may be obtained for both a full and a partial agreement. As an illustration, Table 1 reports the solutions of the membership game, for both the partial and the full agreement cases, and for a variety of parameter values when $n = 50$. The table shows examples where full cooperation is reached in both types of agreements. It also contains instances where a coalition is formed under a partial agreement but not under a full agreement. Moreover, in all numerical experiments, the size of the stable coalition in the full agreement case is smaller or equal to that in the partial agreement case.

γ_A	$\omega = \gamma_E$	$\theta = \frac{\gamma_A + \gamma_E}{\gamma_E^2}$	Partial	Full
0.001	0.01	110	4	2
0.001	0.1	10.1	18	2
0.001	1	1.001	50	48
0.002	0.2	5.05	27	0
0.002	0.3	3.356	34	28
0.01	0.3	3.444	28	0
0.01	0.4	2.563	32	22
0.01	0.8	1.266	42	38
0.01	1	1.01	44	41
0.01	1.2	0.84	45	43
0.01	1.5	0.671	47	45
0.01	2	0.503	48	47
0.01	3	0.334	50	50
1	0.001	10^6	3	2
1	50	0.0204	50	50
2	0.001	2×10^6	2	2

Table 1: This table reports the size of stable coaltions in the membership game for various parameter values when the total number of countries is $n = 50$ and $\gamma_M = 1$. Values are reported for both the full and the partial agreement cases.

3.3.3 Adaptation with simultaneous decisions

It is interesting to compare the above results with the case where adaptation and mitigation decisions are taken simultaneously. The solution of the adaptation game is the same as in Breton and Sbragia (2016) and is obtained by solving

$$\min_{a_j} \left\{ \frac{\omega}{2} E^2 - E a_j + \frac{1}{2} m_j^2 + \frac{\theta}{2} a_j^2 \right\},$$

yielding:

$$a_j = \frac{E}{\theta} \text{ for } j = 1, ..., n.$$

It it then straightforward to retrieve the full and the partial agreement equilibrium solutions using (2)-(4) or (5)-(7) respectively.

The full agreement solution[2] is then

$$\begin{aligned} a_j &= \frac{E}{\theta} \\ m_{Ij} &= \omega E - a_j = E\phi \\ m_{Cj} &= N\left(\omega E - \overline{a}_C\right) = NE\phi \\ E &= n - N\left(NE\phi\right) - M\left(E\phi\right) \\ &= \frac{n}{\phi\left(M+N^2\right)+1} \end{aligned}$$

where $\phi \equiv \frac{\theta\omega-1}{\theta}$. The total cost for signatory and non-signatory countries respectively is then

$$\begin{aligned} C^C\left(N\right) &= \frac{\omega}{2}E^2 - E\frac{E}{\theta} + \frac{1}{2}\left(NE\phi\right)^2 + \frac{\theta}{2}\left(\frac{E}{\theta}\right)^2 \\ &= \frac{1}{2}n^2\phi\frac{N^2\phi+1}{\left(\phi\left(M+N^2\right)+1\right)^2} \\ C^I\left(N\right) &= \frac{\omega}{2}E^2 - E\frac{E}{\theta} + \frac{1}{2}\left(E\phi\right)^2 + \frac{\theta}{2}\left(\frac{E}{\theta}\right)^2 \\ &= \frac{1}{2}n^2\phi\frac{\phi+1}{\left(\phi\left(M+N^2\right)+1\right)^2} \end{aligned}$$

and the internal stability condition is

$$C^C\left(N\right) - C^I\left(N-1\right) = \frac{K_5 n^2\phi^2\left(N-1\right)}{2\left(\phi\left(M+1+\left(N-1\right)^2\right)+1\right)^2\left(\phi\left(M+N^2\right)+1\right)^2} \leq 0$$

where

$$\begin{aligned} K_5 &= \phi^2\left(M+N\left(N-2\right)\right)\left(M+2N+MN+N^2\left(N-1\right)\right) \\ &\quad +2\phi\left(\left(N-1\right)\left(M+2\right)+N^2\left(N-3\right)\right) \\ &\quad +\left(N-3\right), \end{aligned}$$

which is strictly positive for $N \geq 3$, meaning that the maximum size of a stable agreement is two. This is an important result as it shows that when (private) adaptive measures to the adverses consequences of climate change are negotiated simultaneously with emissions reduction as part of an IEA, they do not change the well-known pessimistic result that stable large-size coalitions can not form.

[2]There is no point in examining the partial agreement equilibrium when decisions are taken simultaneously. It is straightforward to observe that both signatories and non-signatories of such an agreement would take the exact same decisions.

4 Dynamic stability

Given our assumption that adaptation decisions require a prior commitment and an irreversible investment, it is important to highlight that, in the case of a full agreement, countries could revise their membership decision between the adaptation and mitigation game. In other words, a country that in the first stage has signed the agreement, and has made an investment a_C in adaptation, could defect from the agreement and decide on its mitigation level individualistically. The reverse could also happen: a non-signatory country having made an investment a_I could join the agreement and decide on its mitigation level cooperatively. In this section, we investigate whether a renegotiation-proof agreement involving both mitigation and adaptation policies can be designed.

To this end, we consider the general problem of the stability of an agreement between N players to cooperate on mitigation policies when players differ in their adaptation levels.

The equilibrium solution of the mitigation game involving N cooperating players when players have different adaptation levels is, according to (2)-(4):

$$\begin{aligned} E_1 &= \frac{n + M\overline{a}_I + N^2\overline{a}_C}{\omega N^2 + M\omega + 1} \\ m_{Ij_1} &= \omega E_1 - a_j, \ j \in I \\ m_{Cj_1} &= N\left(\omega E_1 - \overline{a}_C\right), \ j \in C. \end{aligned}$$

The equilibrium solution of the mitigation game with $N-1$ cooperating players, where player i defects from the agreement, corresponds to:

$$\begin{aligned} E_2 &= \frac{n + M\overline{a}_I + a_i + (N-1)\left(N\overline{a}_C - a_i\right)}{\omega\left(N-1\right)^2 + (M+1)\,\omega + 1} \\ m_i &= \omega E_2 - a_i \\ m_{Ij_2} &= \omega E_2 - a_j, \ j \in I \\ m_{Cj_2} &= N\left(\omega E_2 - \frac{N\overline{a}_C - a_i}{N-1}\right), \ j \in C\backslash i. \end{aligned}$$

As players involved in the membership game are not symmetrical, the internal stability condition becomes $C_i^C(N) - C_i^I(N-1) \leq 0$ for all $i \in C$, where

$$\begin{aligned} C_i^C(N) &= \frac{\omega}{2}E_1^2 - E_1 a_i + \frac{1}{2}\left(N\left(\omega E_1 - \overline{a}_C\right)\right)^2 + \frac{\theta}{2}\left(a_i\right)^2 \\ C_i^I(N) &= \frac{\omega}{2}E_2^2 - E_2 a_i + \frac{1}{2}\left(\omega E_2 - a_i\right)^2 + \frac{\theta}{2}\left(a_i\right)^2. \end{aligned}$$

Proposition 1 *When adaptation to climate change is a prior investment to mitigation decisions and players differ in their adaptation levels, no stable coalition exists in the mitigation game.*

Proof. See Appendix. ■

Note that adaptation reduces the vulnerability of a country to the negative effects of global pollution. Proposition 1 indicates that asymmetry in countries' vulnerability to global pollution does not help in achieving coordination in mitigation policies; even the small-coalition-result of the symmetric game does not hold, as coalitions of two players are no longer stable.

When this general result is applied to the full agreement case analyzed in the previous section, we obtain that, even if all coalition members agree on identical levels of adaptation, since the equilibrium (8)-(9) prescribes different adaptation levels for signatory and non-signatory countries, players should expect the agreement to break down between the second and the third stage of the game, that is, a full agreement is not renegotiation-proof.

This justifies why we also studied the stability of a partial agreement in Section 3. When players are farsighted and expect a full agreement to break down after their investments in adaptive measures, the equilibrium solution corresponds to a partial agreement and is given by (5)-(7) and (10)-(11). Our illustrative results in Table 1 show that, depending on parameter values, partial agreements can still involve a significant proportion of countries.

5 Economic and environmental implications of adaptive measures in IEAs

In this section, we evaluate the implications of incorporating adaptive policies in IEAs by comparing the outcomes of the full and the partial agreement cases with the benchmark case where there is no agreement on environmental policies. This benchmark can be readily obtained, from either the full or the partial agreement cases, by setting $N = 1$, yielding

$$\begin{aligned} a &= \frac{n(\omega+1)(\omega(n-1)+1)}{\theta(n\omega+1)^2 - \omega(n(n-1)+1) - n} \\ E &= \frac{n(a+1)}{n\omega+1} \\ m &= \frac{n\omega - a}{n\omega+1}. \end{aligned}$$

Tables 2 and 3 compare the equilibrium solutions of the partial and full agreement cases with the benchmark non-cooperative solution for various parameter values. Results include total adaptive investments by all countries, total emissions, and total environmental costs of all countries, expressed as a percentage of the corresponding result in the benchmark non-cooperative game. For both types of agreements, outcomes are computed using the size of the stable coalition in the first stage membership game. In the case of the full agreement, emissions and costs are computed by assuming that the coalition breaks down after the investment in adaptive measures.

For both the partial and full agreements, and for any coalition size, total adaptation, emissions and environmental cost are smaller than what is achieved when there is no agreement. This is an important result as it shows that, from both an economic and an environmentalist point of view, including resolutions on adaptive measures to counter the negative impact of climate change in an IEA aiming at reducing GHG emission is better than letting countries decide on these two policies in their own individual way. Moreover, this result is true whether the agreement includes only adaptation measures or both adaptation and mitigation measures (with countries withdrawing from their mitigation effort commitments later on).

γ_A	$\omega = \gamma_E$	Number of signatories	Adaptation	Emissions	Costs
0.001	0.01	4	99.98	99.99	99.99
0.001	0.1	18	99.24	99.37	98.81
0.001	1	50	62.64	63.40	51.96
0.002	0.2	27	95.91	96.31	93.13
0.002	0.3	34	91.80	92.35	86.19
0.01	0.3	28	85.19	86.47	75.94
0.01	0.4	32	79.05	80.40	66.29
0.01	0.8	42	55.43	55.95	34.80
0.01	1	44	47.36	48.65	27.50
0.01	1.2	45	43.65	44.78	23.87
0.01	1.5	47	33.15	34.21	16.19
0.01	2	48	27.46	28.30	12.43
0.01	3	50	19.4	20.55	8.69
1	0.001	3	99.99	100.00	100.00
1	50	50	4.15	4.23	0.34
2	0.001	2	99.99	100.00	100.00

Table 2: Partial agreement case. This table reports on the adaptation level, total emissions and total costs for various parameter values when the total number of countries is $n = 50$ and when $\gamma_M = 1$. Adaptation, emissions and costs are computed at the solution of the membership game and are expressed as a percentage of the benchmark non-cooperative results.

6 Conclusion

The objective of the paper was to study the consequences of introducing resolutions on adaptive measures in an IEA. We focused on the case of private adaptive solutions that need a prior commitment with respect to emissions reduction decisions.

The main findings of the paper can be summarized as follows:

- When an IEA includes private adaptive investments settled prior to mitigation decisions, stable coalitions with a significant number of signatory countries can be obtained, no matter how mitigation decisions are made (full agreement vs. partial agreement or non renegotiation-proof full agreement).
  - The size of a stable coalition for an agreement involving only adaptation measures is at least as large as that of an agreement involving both adaptation and mitigation efforts.
  - Full cooperation can be achieved for some parameter values.
  - Unfortunately, these adaptive investments do not change the standard result for the mitigation game.
- Pessimistic results are also obtained when adaptive investments are decided simultaneously with emissions reductions: indeed the maximum size of a stable agreement is then still two.

γ_A	$\omega = \gamma_E$	Number of signatories	Adaptation	Emissions	Costs
0.001	0.01	2	99.83	99.95	99.90
0.001	0.1	2	99.89	99.91	99.83
0.001	1	48	57.97	58.81	48.89
0.002	0.2	0	100.00	100.00	100.00
0.002	0.3	28	86.76	87.65	78.47
0.01	0.3	0	100.00	100.00	100.00
0.01	0.4	22	84.64	85.63	74.15
0.01	0.8	38	52.79	54.26	32.64
0.01	1	41	46.03	47.35	25.98
0.01	1.2	43	41.08	42.27	21.62
0.01	1.5	45	35.39	36.42	17.20
0.01	2	47	28.09	28.93	12.54
0.01	3	50	16.10	16.73	7.51
1	0.001	2	99.81	100.00	100.00
1	50	50	4.16	4.23	0.33
2	0.001	2	99.81	100.00	100.00

Table 3: Full agreement case when the agreement breaks down after the adaptation game. This table reports on the adaptation level, total emissions and total costs for various parameter values when the total number of countries is $n = 50$ and when $\gamma_M = 1$. Values are reported for the full agreement case, when however the agreement breaks down after the adaptation game. Adaptation, emissions and costs are computed at the solution of the membership game and are expressed as a percentage of the benchmark non-cooperative results.

- Finally, an IEA with private adaptive investments is able to generate less adaptive effort, less global pollution and a smaller environmental cost, compared to a situation where there is no agreement on adaptation and mitigation.

Compared to the related literature, we showed that an endogenous asymmetry of the payers provides results in line with the literature on IEA and asymmetric players and that to have some positive effects on the stability of an IEA, we do not need spillovers of adaptation benefits.

The major conclusions that we can draw from our results are that private adaptive investments to counteract the adverse consequences of climate change should be incorporated in IEAs, as this would enhance their stability and improve the overall welfare of all countries, provided that the adaptive measures considered in such agreements require commitments and investments prior to mitigation decisions.

7 Appendix: proof of Proposition 1

Let

$$S_i = \frac{1}{2}\omega\left(E_1^2 - E_2^2\right) - a_i\left(E_1 - E_2\right) + \frac{1}{2}\left(N\left(\omega E_1 - \overline{a}_C\right)\right)^2 + \frac{1}{2}\left(\omega E_2 - a_i\right)^2.$$

The internal stability condition for a given coalition of size N is then $S_i \leq 0$ for all $i \in C$. Define $T \equiv n + M\overline{a}_I + N^2\overline{a}_C$ and $D \equiv \overline{a}_C - a_i$. We then have:

$$\begin{aligned}
E_1 &= \frac{T}{\omega N^2 + M\omega + 1} \\
E_2 &= \frac{T - a_i(N-2) - N(a_i + D)}{\omega N^2 + M\omega + 1 - 2\omega(N-1)} \\
S_i &= \frac{1}{2}\omega\left(\left(\frac{T}{\omega N^2 + M\omega + 1}\right)^2 - \left(\frac{T - a_i(N-2) - N(a_i + D)}{\omega N^2 + M\omega + 1 - 2\omega(N-1)}\right)^2\right) \\
&\quad - a_i\left(\frac{T}{\omega N^2 + M\omega + 1} - \frac{T - a_i(N-2) - N(a_i + D)}{\omega N^2 + M\omega + 1 - 2\omega(N-1)}\right) \\
&\quad + \frac{1}{2}\left(N\left(\omega\left(\frac{T}{\omega N^2 + M\omega + 1}\right) - (a_i + D)\right)\right)^2 \\
&\quad + \frac{1}{2}\left(\omega\frac{T - a_i(N-2) - N(a_i + D)}{\omega N^2 + M\omega + 1 - 2\omega(N-1)} - a_i\right)^2
\end{aligned}$$

where $\omega T \geq \left(\omega N^2 + M\omega + 1\right)a_j$ for all j if the solution is interior.

First assume that all players in C have the same adaptation levels, so that $D = 0$ for all $i \in C$. In that case, S_i reduces to

$$\begin{aligned}
S_i &= \frac{1}{2}\omega\left(\left(\frac{T}{\omega N^2 + M\omega + 1}\right)^2 - \left(\frac{T - 2a_i(N-1)}{\omega N^2 + M\omega + 1 - 2\omega(N-1)}\right)^2\right) \\
&\quad - a_i\left(\frac{T}{\omega N^2 + M\omega + 1} - \frac{T - 2a_i(N-1)}{\omega N^2 + M\omega + 1 - 2\omega(N-1)}\right) \\
&\quad + \frac{1}{2}N^2\left(\frac{T\omega - a_i\left(M\omega + N^2\omega + 1\right)}{M\omega + N^2\omega + 1}\right)^2 \\
&\quad + \frac{1}{2}\left(\frac{T\omega - a_i\left(M\omega + N^2\omega + 1\right)}{2\omega + M\omega - 2N\omega + N^2\omega + 1}\right)^2 \\
&= K_6\frac{\left(T\omega - a_i\left(M\omega + N^2\omega + 1\right)\right)^2}{2\left(2\omega + M\omega - 2N\omega + N^2\omega + 1\right)^2\left(M\omega + N^2\omega + 1\right)^2}
\end{aligned}$$

where

$$\begin{aligned}
K_6 &= \omega^2\left(M\left(M\left(N^2+1\right) + 2N^2\left(N(N-2)+3\right)\right) + N^2\left((N-2)\left(5N + N^2(N-2) + 2\right) + 8\right)\right) \\
&\quad + 2\omega\left(M\left(N(N-2)+3\right) + (N-2)\left(3N + N^2(N-2) + 2\right) + 6\right) \\
&\quad + (N-2)^2 + 1.
\end{aligned}$$

It is straightforward to check that $K_6 > 0$ for $N \geq 2$.We conclude that if all members of C have the same adaptation level, there is no stable coalition.

Now assume that players in C have different adaptation levels. This means that there exists at least one player with an adaptation level higher than the average level of the coalition, say Player i, with $a_i > \overline{a}_C$.

For given values of the other parameters, S_i is a quadratic function of D,

$$S_i = k_1 + k_2 D + k_3 D^2,$$

where

$$\begin{aligned}
k_1 &= \frac{K_6\left(T\omega - a_i\left(M\omega + N^2\omega + 1\right)\right)^2}{2\left(M\omega + N^2\omega + 1\right)^2\left(2\omega + M\omega - 2N\omega + N^2\omega + 1\right)^2} \\
k_2 &= -NK_7\frac{T\omega - a_i\left(M\omega + N^2\omega + 1\right)}{\left(M\omega + N^2\omega + 1\right)\left(2\omega + M\omega + N\omega\left(N-2\right) + 1\right)^2} \\
k_3 &= \frac{N^2 K_8}{2\left(2\omega + M\omega + N\omega\left(N-2\right) + 1\right)^2} \\
K_7 &= \omega^2\left(M\left(MN + 2N\left(N\left(N-2\right)+2\right)+1\right) + N\left(\left(N-1\right)\left(N-2\right)+2\right)\left(N\left(N-1\right)+1\right)\right) \\
&\quad +\omega\left(M\left(2N-1\right) + N\left(\left(2N-1\right)\left(N-2\right)+2\right)+1\right) + \left(N-1\right) \\
K_8 &= \omega^2\left(M\left(M + 2\left(N\left(N-2\right)+2\right)\right) + N\left(N-2\right)\left(N\left(N-2\right)+4\right)+5\right) \\
&\quad +\omega\left(2M + 2N\left(N-2\right)+3\right)+1
\end{aligned}$$

Assuming an interior solution, for $N \geq 2$, $k_3 > 0$, $k_2 < 0$ and $k_1 > 0$. This means that S_i is a strictly convex function of D that is strictly positive and decreasing at $D = 0$. As a consequence, if $a_i > \overline{a}_C$, D is negative and the mimimum value of S_i is strictly positive. We conclude that the internal stability condition cannot be satisfied whenever $N \geq 2$: any player who has adapted more than the average adaptation level of the signatories would benefit from leaving the agreement.

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