The Impact of Adaptation on the Stability of International Environmental Agreements

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Abstract

We examine the stability of international environmental agreements that include clauses pertaining to both adaptation and mitigation measures. 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 amount of pollution.

Using a stylized model, we show that adaptive measures can be used strategically and that their inclusion in environmental agreements enhances agreement stability and can even lead to full cooperation. We examine the robustness of agreements including both adaptation and mitigation measures against renegotiation. Finally, we evaluate how including adaptive measures for climate change in international environmental agreements affects welfare and overall pollution.

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

1 Introduction

It is increasingly recognized that there are two different ways of responding to climate change and its impacts: reducing greenhouse gas (GHG) emissions and investing in adaptive measures.[1] At the international level, this has been acknowledged at several United Nations conferences on climate change (Cancun 2010, Durban 2011, Doha 2012, Paris 2015) and in the series of Intergovernmental Panel on Climate Change (IPCC) assessment reports published over time (Third Assessment Report 2001, Fourth Assessment Report 2007, Fifth Assessment Report 2014). However, in the discussions on climate change, the ambiguous effects of adaptation are often raised.

Following on the statement in the Third Assessment Report, "Adaptation is a necessary strategy at all scales to complement climate change mitigation efforts,"[2] 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 GHG emissions. In particular, we investigate the case of adaptive measures involving long-term planning, long-lived investments, and some degree of irreversibility. For this kind of investments, countries need to act in anticipation of mitigation policies. Examples of such adaptive measures are infrastructures for water management (dams, reservoirs, dykes, storm surge barriers) or transportation (ports or bridges), urbanization plans

[1] Adaptation is defined in the Glossary of the IPCC (2014, p.118) by "The process of adjustment to actual or expected climate and its effects."

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

(urban density, parks), the development of resistant crops, etc. (Hallegatte, 2009). The sequential relation between adaptation and mitigation decisions also stems from the fact that humans have been constantly adapting to climate, climate variability, and extreme weather events, and adaptive measures have always been decided individualistically.[3]

In this context, we analyze three types (M, A and C) of agreements, differing in the scope of the cooperation.[4] The motivation for analyzing various agreement types lies in the evolution of the focus of international negotiations on climate change. With the exception of a few articles referring to the need of adaptation to climate change (Art. 4.1(b) and (e)[5]), the main aim of the UNFCCC (Rio, 1992) was to stabilize the emissions of GHGs. During the 1990s, most of the negotiations focused solely on mitigation and they resulted in the Kyoto Protocol (1997). This is the rationale behind the first type of agreement, the *M-agreement*, where signatory countries agree to coordinate only their mitigation policies, while each country decides on its adaptation policy individually. Over time, countries realized the importance of including the issue of adaptation in the international negotiations on climate change; the first sign of this appeared in 2001 with the Marrakech Accords, followed, in 2002, by the Delhi Declaration, up to the Paris Agreement in 2015. This motivates the analysis of a second type of agreement, the *C-agreement*, where signatory countries agree to coordinate both their adaptation and mitigation policies. Finally, in light of the difficulties of reaching a large participation of countries to coordinate their mitigation levels, we propose a third type of agreement, not observed in reality yet, but hypothetical and worthy of consideration. In an *A-agreement*, signatory countries agree to coordinate only their adaptation policies, while each country decides on its mitigation policy individually.

The problem contemplated here is modelled as a multi-stage game in the context of pollution emissions and vulnerability to climate change. However, the basic model is general and could apply to any agreement involving a reduction in economic activity (mitigation) and/or private measures decreasing vulnerability (adaptation) that require a prior irreversible investment. The same model has been used in Breton & Sbragia (2017) to examine, in a C-agreement setting with and without signatory leadership, how different timings of decisions about adaptation and mitigation impact on environmental costs and levels of effort. The analysis is developed for any number of parties to the agreement, without addressing the issue of membership stability. One of the main results of that paper is that adaptive measures can play a strategic role so that countries can increase adaptation to reduce their mitigation effort, which is shown to be globally inefficient.[6]

The contribution of this paper is twofold. First, we study the impact of including adaptive measures on IEA stability. Second, we assess the economic and environmental consequences of including such measures in IEAs. In both cases, we specifically consider adaptive measures that require prior commitments and are decided before mitigation levels.

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[3]Examples of countries that invested in adaptive measures before deciding on their mitigation levels are: Bangladesh and its investment in coastal forest afforestation as a way to reduce its vulnerability to cyclones and storm surges since 1966 (Islam & Rahman 2015); the Netherlands with the Delta Works (1954 -1997) as a response to the 1953 North Sea flood (VanKoningsveld et al. 2008); the Egyptian Aswan High Dam (1960-1970) to protect from floods and droughts like the ones in 1972–73 and 1983–87 that devastated East and West Africa (Goldenman 1990).

[4]A similar setting is considered in Zehaie (2009) and in Bayramoglu et al. (2016), where two possibilities are analyzed, a M-agreement (called semi-cooperation in Zehaie 2009) and a M+A- (or C-) agreement.

[5]Article 4.1 (e) of the UNFCCC states that "All parties... shall cooperate in preparing for adaptation to the impacts of climate change; develop and elaborate appropriate and integrated plans for coastal zone management, water resources and agriculture, and for the protection and rehabilitation of areas, particularly in Africa, affected by drought and desertification, as well as floods."

[6]A similar result is obtained in Heuson et al. (2015) in a non-cooperative setting.

With respect to our first contribution, other publications that have considered the effects of adaptive investments on membership in IEAs include Marrouch and Chaudhuri (2011), Masoudi & Zaccour (2016), Lazkano et al. (2016), Masoudi & Zaccour (2017), Benchekroun et al. (2017), and Bayramoglu et al. (2018). With the exception of Masoudi & Zaccour (2017), all assume that adaptive measures are decided simultaneously with mitigation decisions.

Marrouch and Chaudhuri (2011) considers an environmental damage cost that is bilinear in total emissions and adaptation; by assuming that signatory countries act as leaders, the authors show that large stable coalitions can be reached and that the level of total emissions can be below the non-cooperative level. Bayramoglu et al. (2018) assumes that adaptation contributes to the welfare both directly and in relation to the level of total emissions; the authors show that in that case adaptation can make countries' mitigation levels strategic complements and this allows countries to form larger stable agreements. Lazkano et al. (2016) studies the stability of an IEA in a generic model where countries are assumed to be asymmetric in adaptation cost parameters. The authors show that when the environmental damage cost is linear, asymmetry does not change the standard small-size coalition result for stable IEAs. However, when damage cost is quadratic, cross-country differences in adaptation may encourage participation in an IEA. In a quadratic environmental cost context, the main feature of Masoudi & Zaccour (2016) is that adaptation has a "public good flavour," in that the benefits of adaptive measures are shared by the signatory countries and can spill over to all countries. The authors find that for some parameter values, stable IEAs can form with a significant number of countries. Finally, Benchekroun et al. (2017) also uses a quadratic model for the environmental cost, where it is assumed that the welfare of non-signatory countries is reduced by an extra fixed cost as a penalty for not signing the agreement. The presence of this fixed cost drives the result of possible large coalitions.

These publications indicate that, when adaptation is decided simultaneously with mitigation levels, it may have a positive effect on the stability of IEAs; however, all the above-mentioned papers make use of specific features that enhance coalition stability, such as leadership, punishments, asymmetry or spillovers.

Compared to the cited literature, in this paper, we adopt a different timing of decisions between adaptation and mitigation: we consider situations where adaptation requires a prior commitment, so that we focus exclusively on the impact of the strategic role of private investments on coalition stability. This approach is similar to the one presented in Masoudi & Zaccour (2017), which considers an A-agreement where adaptation with a public good flavour requires a commitment prior to mitigation decisions. In this setting, the authors find that for some parameter values, large stable IEAs can form. Our private-adaptation version of an A-agreement confirms the results found in Masoudi & Zaccour (2017), implying that knowledge spillovers are not necessary for a large coalition on adaptation to form.

Moreover, we are able to conclude that, in terms of participation size, the M-agreement is the one that performs worst, while the C- and the A-agreements can reach any size, including full cooperation. Furthermore, we show that a C-agreement is however not renegotiation-proof.

Another consequence of the prior-commitment assumption is the fact that, because expenditures on environmental policies differ among signatory and non-signatory countries, countries may differ in their level of adaptation in the last stage of the game wherein mitigation levels are decided. This asymmetrical feature links our paper to another stream of the literature on IEAs that analyzes the impact of some sort of asymmetry among countries on the size of a stable agreement. Examples of such investigations are Fuentes-Albero & Rubio (2010), Glanemann (2012), and Pavlova & de Zeeuw (2013). These analyses all find that, in stylized models without transfers, asymmetry in a single aspect is not sufficient to change the usual small-size-coalition result; to achieve large coalitions, countries have to be different in more than one respect, and the asymmetries among countries have to be strong. In our setting, the asymmetry of countries arises from adaptation decisions that are endogenous to the game itself. Our model with endogenous asymmetry confirms the result of the exogenous-asymmetry literature: we find that the pessimistic small-coalition result persists in the mitigation game when countries differ in their adaptation levels.

The second contribution of our paper is its examination of the economic and environmental implications of including adaptive measures in environmental agreement. We find that when adaptation is regulated by an agreement (A- or C-agreement) and a stable coalition size is reached, the total adaptation expenditures, emissions and environmental costs are lower than when there is no agreement and countries adapt in their own individual way (M-agreement). This result has important policy implications as it provides support for the current trend in international negotiations on climate change.

The rest of the paper is organized as follows. Section 2 briefly recalls the prior-commitment model of Breton & Sbragia (2017). Sections 3 and 4 characterize equilibrium environmental policies in the presence of various types of IEAs involving a subset of countries, and Section 5 discusses the membership stability of these agreements. Section 6 reports on the welfare impact of including adaptive measures in IEAs. Section 7 supplies a conclusion.

2 Model

We consider n symmetric countries whose production activities create economic value but also pollution emissions as a by-product. Countries have two mechanisms at their disposal that can be used to respond to the adverse consequences of pollution emissions. The first, called *adaptation*, involves investing in private[7] measures to counterbalance the negative effects of climate change (for instance, developing a crop variety that resists droughts). As indicated in the IPCC (2014) Glossary, "In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities." The effect of adaptation is thus a reduction in the country's vulnerability to pollution, described as

$$v_j = E - a_j$$

where E is the total emissions by countries, and $a_j \in [0, E]$ measures the reduction in vulnerability resulting from adaptive measures.[8] The cost of adaptation for country j is an increasing convex function of a_j, assumed quadratic, that is,

$$A_j(a_j) = \frac{\gamma_A}{2} a_j^2$$

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

[7] This is a common perspective in the literature on climate change-mitigation-adaptation, see for instance Marrouch & Chaudhuri (2011), Lazkano et al. (2016) or Benchekroun et al. (2017). Only Masoudi & Zaccour (2016, 2017) consider adaptation with a "public good flavour". By assuming that adaptation to climate change is essentially private, we imply that the consequences of the adaptive measures can be excluded and enjoyed primarily by their instigator. For example, the sole beneficiary of the decision by a country to build a desalinization plant will be the country itself.

[8] Note that a_j is not a reduction of total pollution; it represents a reduction of the impact of total pollution on country j.

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,

$$M_j(m_j) = \frac{\gamma_M}{2} m_j^2$$

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

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

$$D_j(v_j) = \frac{\gamma_D}{2} v_j^2$$

where $\gamma_D > 0$ is the environmental sensitivity coefficient. Note that, under the restriction $a_j \in [0, E]$, the damage function is increasing in total emissions and decreasing in adaptation.

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

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

We normalize the cost function by dividing it by the constant γ_M, yielding an equivalent cost function involving two parameters

$$c_j = \frac{z_j}{\gamma_M} = \frac{\omega}{2} (E - a_j)^2 + \frac{1}{2} m_j^2 + \frac{\eta}{2} a_j^2$$

where $E \equiv \sum_{i=1}^{n} (1 - m_i)$, $\omega \equiv \frac{\gamma_D}{\gamma_M}$ and $\eta \equiv \frac{\gamma_A}{\gamma_M}$. The objective of country j is to choose the mitigation and adaptation levels that minimize the global environmental cost c_j.

This stylized model includes the three sources of costs commonly used in the climate change literature, and is consistent with the usual assumptions about the behavior of these costs:

$$\begin{array}{ccc} A_j' > 0 & M_j' > 0 & \frac{\partial}{\partial E} D_j > 0, \frac{\partial}{\partial a_j} D_j < 0 \\ A_j'' \geq 0 & M_j'' \geq 0 & \frac{\partial^2}{\partial E^2} D_j > 0, \frac{\partial^2}{\partial a_j^2} D_j \geq 0 \\ & & \frac{\partial^2}{\partial E \partial a_j} D_j = \frac{\partial^2}{\partial a_j \partial E} D_j \leq 0. \end{array}$$

It is straightforward to check that, for this model, the cost function of an individual country, given the environmental strategies of the other countries, is strictly convex. Also note that the restriction $0 \leq a_j \leq E$ is always satisfied in equilibrium, as shown in Breton & Sbragia (2017). This specific form has been used in Breton & Sbragia (2017), Benchekroun et al. (2017) and Masoudi & Zaccour (2016, 2017).[9]

In this paper, we study the effects of including adaptive investments in the negotiation of an IEA aiming to reduce pollution emissions, when commitments to climate-change-adaptive measures are made before emission-mitigation decisions. This is modelled as a multi-stage game and solved by backward recursion. We look for the sub-game perfect Nash equilibrium of the multi-stage game with full information. The sequence of moves is represented in Figure 1.

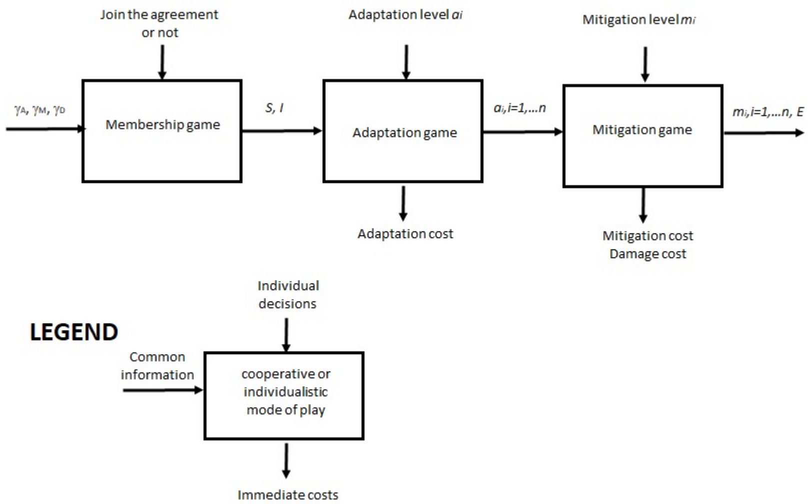

Figure 1: Timeline of the three-stage game.

In the first stage, countries play a "membership" game. Countries that subscribe to the agreement are called *signatories* 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 signatories* or *individualistic countries* and their decisions are driven by their individual interest. We denote by S the set of signatory countries and by I the set of individualistic (non-signatory) countries, where $|S| = N$, $|I| = M$ and $N + M = n$.

In the second stage, countries play an "adaptation" game, that is, they decide 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 how much effort they will dedicate to curtailing their emissions.

We will distinguish between three contrasting cases concerning the scope of the environmental agreement. In the first case (*M-agreement*), signatories only agree to coordinate their mitigation policies; in the second case (*A-agreement*), signatories only agree to coordinate their adaptation policies; in the third case (*C-agreement*), signatories agree to coordinate both their adaptation and

[9] Other papers adopting stylized functional forms in the literature use slightly different assumptions. Buob and Stephan (2011) uses a Cobb-Douglas formulation. Marrouch and Ray Chauduri (2011) and Farnham and Kennedy (2015) use a bilinear damage function, which requires additional conditions on parameter values to ensure convexity of the optimization problems.

mitigation policies.

3 Equilibrium solution of the mitigation game

The mitigation stage is the last stage of the game. To solve it, we make no assumption on the adaptation levels decided on in the preceding stages. Accordingly, we seek an equilibrium solution to a mitigation game involving asymmetric countries, where each country j is characterized by a parameter a_j representing its prior investment in adaptive measures. We denote by m_{Sj} the mitigation effort of a signatory country j, and by m_{Ij} the mitigation effort of a non-signatory country j.

3.1 M-agreement and C-agreement

In both the M-agreement and the C-agreement cases, signatories coordinate their mitigation policies, while non signatories decide individually. A non-signatory country $j \in I$ solves

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

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

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

The non signatories' mitigation policy is a value proportional to their vulnerability $v_j = E - a_j$, where the coefficient ω is the ratio of the damage and mitigation costs parameters.

Signatory countries $j \in S$ jointly solve

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

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

$$m_{Sj} = N\omega \left(E - \bar{a}_S\right) \text{ for all } j \in S,$$

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

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

$$E = n - \sum_{j \in S} N\omega \left(E - \bar{a}_S\right) - \sum_{j \in I} \omega \left(E - a_j\right)$$

yielding

$$\begin{aligned} E &= \frac{n + M\omega\bar{a}_I + N^2\omega\bar{a}_S}{W_1} && (2) \\ W_1 &\equiv \omega\left(M + N^2\right) + 1 \\ m_{Ij} &= \omega\left(E - a_j\right), \quad j \in I && (3) \\ m_{Sj} &= m_S = N\omega\left(E - \bar{a}_S\right), \quad j \in S && (4) \end{aligned}$$

where $\bar{a}_I = \frac{\sum_{i \in I} a_i}{M}$ is the average adaptation level of the non signatories.

3.2 A-agreement

In the A-agreement case, decisions about mitigation levels are not coordinated. All countries solve the optimization problem (1), so that

$$m_j = \omega \left(E - a_j\right) \text{ for } j = 1, \ldots, n. \tag{5}$$

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

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

yielding

$$\begin{aligned} E &= \frac{n + M\omega\bar{a}_I + N\omega\bar{a}_S}{W_2} && (6) \\ W_2 &\equiv n\omega + 1 \\ m_{Ij} &= \omega \left(E - a_j\right), \quad j \in I && (7) \\ m_{Sj} &= \omega \left(E - a_j\right), \quad j \in S. && (8) \end{aligned}$$

3.3 Strategic role of adaptation

Note that in all three types of agreements, adaptation plays a strategic role in the mitigation game: the mitigation level of a given country decreases with its own adaptation level while it increases with the adaptation level of other countries (see Appendix 8.1).

As pointed out in Breton & Sbragia (2017), the strategic complementarity of decisions of different countries is due to the prior commitment assumption, and is not present when adaptation and mitigation decisions are taken simultaneously.

4 Equilibrium solution of the adaptation game

In the adaptation stage, to determine their investment in adaptation, countries take into account the equilibrium solutions found for the mitigation game, i.e. (2)-(4) or (6)-(8).

The impact of a given country j's adaptation on its total environmental cost can be expressed as follows:

$$\frac{dc_j}{da_j} = \omega \left(E - a_j\right) \left(\frac{dE}{da_j} - 1\right) + m_j \frac{dm_j}{da_j} + \eta a_j, \tag{9}$$

where the first term corresponds to the impact on the damage cost and the second and third terms correspond respectively to the impact on the mitigation and adaptation costs.

The mitigation level m_j, the marginal impact of adaptation on total emissions $\frac{dE}{da_j}$ and the marginal impact of adaptation on a country's mitigation level $\frac{dm_j}{da_j}$ differ according to the equilibrium solution of the mitigation game. In all cases, $0 < \frac{dE}{da_j} < 1$ and $\frac{dm_j}{da_j} < 0$ so that the impact of a country's increase in adaptation is a decrease in that country's damage and mitigation costs, and an increase in the total emissions.

Note also that m_j, $\frac{dE}{da_j}$ and $\frac{dm_j}{da_j}$ differ according to the status (signatory or non signatory) of countries, but have the same expression among countries of the same status. As a consequence, the solution of the adaptation game is obtained by simultaneously solving

$$\omega \left(E - a_j\right) \left(\frac{dE}{da_j} - 1\right) + m_j \frac{dm_j}{da_j} + \eta a_j = 0, \ \ j = S, I \tag{10}$$

where a_S denotes the level of adaptation of signatory countries and a_I denotes the level of adaptation of non-signatory countries.

Consider a situation, outside of equilibrium, where all countries use the same level of adaptation a, and therefore have the same vulnerability $v = E - a$. We wish to compare the impact of a marginal change in adaptation on the total environmental cost of signatories and non signatories in that situation. Call Δ the difference in the marginal overall cost of adaptation between non signatories and signatories, that is

$$\Delta = \frac{dc_I}{da_I} - \frac{dc_S}{da_S}.$$

When $a_I = a_S = a$, the value of Δ is given by

$$\Delta = \omega v \left(\frac{dE}{da_I} - \frac{dE}{da_S}\right) + m_I \frac{dm_I}{da_I} - m_S \frac{dm_S}{da_S}. \tag{11}$$

A positive difference Δ means that, when countries use the same level of adaptation, the marginal increase in total environmental cost due to a marginal increase in adaptation is higher for non signatories than for signatories. Therefore, if, for instance, all countries use a level of adaptation that minimizes the environmental cost of non signatories, the marginal impact of an increase in the adaptation level of signatories is negative, a decrease in their total environmental cost, and as a consequence the equilibrium adaptation level $a_S > a_I$. If the difference Δ is negative, the reverse is true and $a_S < a_I$ in equilibrium. When adaptation plays a strategic role, signatories may adapt more or less than non signatories at equilibrium, due to the relative importance of the impact of adaptation on the damage and mitigation costs.

It is interesting to note that, if adaptation decisions were taken simultaneously with or after mitigation decisions, the impact of adaptation on total emissions and on a country's mitigation level would be null, so that Equation (10) would become

$$-\omega E + a_j \left(\eta + \omega\right) = 0 \ , \ j = I, S,$$

and Δ would vanish. In equilibrium, all countries would then choose the same adaptation level, proportional to the total pollution, in all types of agreements.

In what follows we compute the difference Δ and the equilibrium solution of the adaptation game for the three kinds of agreements. Furthermore, for comparison purposes, we also compute the equilibrium solution of the adaptation game in the non-cooperative case when there exists no environmental agreement, in the full-cooperation case, and in the case where adaptation and mitigation decisions are taken simultaneously.

4.1 M-agreement

The M-agreement corresponds to the classical situation where signatories agree to coordinate their mitigation levels, with the additional feature that all countries individually decide on their level of adaptation. The difference in the impact of adaptation on the environmental costs is explained by the fact that signatories mitigate N times more than non signatories with the same vulnerability.

After replacing in (11) the corresponding expressions,[10] we have

$$\begin{aligned}
\Delta &= \omega v\left(\frac{dE}{da_I}-\frac{dE}{da_S}\right)+m_I\frac{dm_I}{da_I}-m_S\frac{dm_S}{da_S}\\
&= \omega v\left(\frac{\omega}{W_1}-\frac{N\omega}{W_1}\right)-v\omega^2\frac{W_1-\omega}{W_1}+v\omega^2N^2\frac{W_1-N\omega}{W_1}\\
&= -v\omega^2\frac{N-1}{W_1}+v\omega^2\left(N-1\right)\left(\frac{N+1+\omega\left(\left(N+1\right)\left(M-1\right)+N^3\right)}{W_1}\right)\\
&= v\omega^2\left(N-1\right)\frac{N+\omega\left(\left(N+1\right)\left(M-1\right)+N^3\right)}{W_1}>0.
\end{aligned}$$

It is immediate to see that $0<\frac{dE}{da_I}<\frac{dE}{da_S}$, that is, an increase in adaptation increases the total emissions of signatories more than those of the non signatories. In the same way, $0>m_I\frac{dm_I}{da_I}>m_S\frac{dm_S}{da_S}$, that is, an increase in adaptation decreases the mitigation cost of signatories more than that of non signatories. Since $\Delta>0$, in the M-agreement case, signatory countries will adapt more than non signatories in equilibrium. Adaptation is more valuable for the signatory countries because an increase in adaptation is able to reduce the signatory mitigation effort at a level that offsets the greater increase in total emissions compared to non signatories. The term that drives the result is $m_S\frac{dm_S}{da_S}$.

The reaction function and equilibrium solutions solving (10) are then given by:

$$\begin{aligned}
a_I(\bar{a}_S) &= \frac{\omega\left(W_1-\omega\right)\left(\omega+1\right)\left(n+N^2\omega\bar{a}_S\right)}{K_1}\\
a_S(\bar{a}_I) &= \frac{\omega\left(N^2\omega+1\right)\left(n+M\omega\bar{a}_I\right)\left(W_1-N\omega\right)}{K_2}\\
a_I &= \frac{n\omega W_1\left(\omega+1\right)\left(\omega-W_1\right)\left(N\omega^2\left(N^2\omega+1\right)-W_1\left(\eta+\omega+N^2\omega^2\right)\right)}{K_1K_2-MN^2\omega^4\left(N^2\omega+1\right)\left(\omega+1\right)\left(W_1-\omega\right)\left(W_1-N\omega\right)} \qquad (12)\\
a_S &= \frac{n\omega\left(N^2\omega+1\right)\left(W_1-N\omega\right)W_1\left(W_1\left(\eta+\omega+\omega^2\right)-\omega^2\left(\omega+1\right)\right)}{K_1K_2-MN^2\omega^4\left(N^2\omega+1\right)\left(\omega+1\right)\left(W_1-\omega\right)\left(W_1-N\omega\right)} \qquad (13)\\
K_1 &= W_1^2\left(\eta+\omega+\omega^2\right)+\omega^2\left(\omega+1\right)\left(M\omega-W_1\left(M+1\right)\right)\\
K_2 &= W_1^2\left(\eta+\omega+N^2\omega^2\right)+\omega^2N\left(N^2\omega+1\right)\left(N^2\omega-W_1\left(N+1\right)\right)
\end{aligned}$$

$$a_S-a_I=\frac{n\omega^2\eta W_1^2\left(N-1\right)\left(N+\omega\left(\left(N+1\right)\left(M-1\right)+N^3\right)\right)}{K_1K_2-MN^2\omega^4\left(\omega+1\right)\left(N^2\omega+1\right)\left(W_1-\omega\right)\left(W_1-N\omega\right)}>0.$$

As indicated by the reaction functions, in the M-agreement case, adaptation levels of signatory and non-signatory countries are strategic complements in the adaptation game.

[10] See Appendix 8.2.

4.2 A-agreement

In the case of an agreement exclusively on adaptation measures, the mitigation level of all countries is $m_j = \omega E - \omega a_j$, as indicated in (7)-(8). After replacing in (11) the corresponding expressions,[11] we have

$$\begin{aligned}
\Delta &= \omega v \left(\frac{dE}{da_I} - \frac{dE}{da_S} \right) + m_I \frac{dm_I}{da_I} - m_S \frac{dm_S}{da_S} \\
&= -v\omega^2 \frac{N-1}{W_2} - v\omega^3 \frac{N-1}{W_2} \\
&= -v\omega^2 (\omega + 1) \frac{N-1}{W_2} < 0.
\end{aligned}$$

In the A-agreement case, signatory countries will adapt less than non signatories in equilibrium. The term that drives the result is $\frac{dE}{da_S}$. Because they move collectively, an increase in the adaptation of signatories has a larger impact on total emissions than that of non signatories. As a consequence, at equal vulnerability, an increase in adaptation by signatories results in a higher increase of both their damage and mitigation costs, compared to non signatories.

The reaction function and equilibrium solutions solving (10) are given by:

$$\begin{aligned}
a_I(\bar{a}_S) &= \frac{\omega (\omega + 1) (n + N\omega \bar{a}_S) (W_2 - \omega)}{K_3} \\
a_S(\bar{a}_I) &= \frac{\omega (\omega + 1) (n + M\omega \bar{a}_I) (W_2 - N\omega)}{K_4} \\
a_I &= \frac{n\omega W_2 (\omega + 1) (W_2 - \omega) \left(\omega^2 (-N + M\omega + 1) + W_2 (\eta + \omega) \right)}{K_3 K_4 - MN\omega^4 (\omega + 1)^2 (M\omega + 1) (W_2 - \omega)} \qquad (14) \\
a_S &= \frac{n\omega W_2 (\omega + 1) \left(\omega^3 (n - 1) + W_2 (\eta + \omega) \right) (M\omega + 1)}{K_3 K_4 - MN\omega^4 (\omega + 1)^2 (W_2 - \omega) (M\omega + 1)} \qquad (15) \\
K_3 &= W_2^2 \left(\eta + \omega + \omega^2 \right) - \omega^2 (\omega + 1) (W_2 (M + 1) - M\omega) \\
K_4 &= W_2^2 \left(\eta + \omega + \omega^2 \right) - \omega^2 N (\omega + 1) (2W_2 - N\omega).
\end{aligned}$$

$$a_S - a_I = -\frac{n\omega^2 (\omega + 1) W_2^2 \eta (N - 1)}{K_3 K_4 - MN (\omega + 1)^2 (M\omega + 1) (W_2 - \omega)} < 0.$$

In the A-agreement case, adaptation levels of signatory and non-signatory countries are strategic complements in the adaptation game.

4.3 C-agreement

In the case of a C-agreement, non signatories individually decide on their level of adaptation, while signatories coordinate their decision. Moreover, in the emission-game equilibrium, signatories mitigate N times more than non signatories for the same level of vulnerability. Replacing in (11)

[11] See Appendix 8.2.

the corresponding expressions,[12] we then have

$$\begin{aligned}\Delta &= \omega v\left(\frac{\omega}{W_1}-\frac{\omega N^2}{W_1}\right)+\omega v\omega\frac{\omega-W_1}{W_1}-N\omega vN\omega\frac{-W_1+N^2\omega}{W_1}\\ &= -v\omega^2\left(N-1\right)\frac{N+1}{W_1}+v\omega^2\left(N-1\right)\left(N+1\right)\frac{\omega\left(M-1\right)+1}{W_1}\\ &= v\omega^3\left(N-1\right)\left(N+1\right)\frac{M-1}{W_1}>0.\end{aligned}$$

In the C-agreement case, signatory countries will adapt more than non signatories in equilibrium. As in the M-agreement case, this is due to the large impact of adaptation on the mitigation cost, $m_S\frac{dm_S}{da_S}$. Adaptation is more valuable for the signatory countries because, at the same adaptation level, an increase in adaptation reduces the signatories' mitigation cost at a level that offsets the greater increase in damage cost compared to non signatories.

The reaction function and equilibrium solution solving (10) are given by:

$$\begin{aligned}a_I(\bar{a}_S) &= \frac{\omega\left(\omega+1\right)\left(n+N^2\omega\bar{a}_S\right)\left(W_1-\omega\right)}{K_5}\\ a_S(\bar{a}_I) &= \frac{\omega\left(N^2\omega+1\right)\left(M\omega+1\right)\left(n+M\omega\bar{a}_I\right)}{K_6}\\ a_I &= \frac{n\omega W_1\left(\omega+1\right)\left(W_1\left(\eta+\omega\right)+MN^2\omega^3\right)\left(W_1-\omega\right)}{K_5K_6-MN^2\omega^4\left(\omega+1\right)\left(N^2\omega+1\right)\left(W_1-\omega\right)\left(M\omega+1\right)} \qquad (16)\\ a_S &= \frac{n\omega W_1\left(N^2\omega+1\right)\left(M\omega+1\right)\left(\omega^3\left(M+N^2-1\right)+W_1\left(\eta+\omega\right)\right)}{K_5K_6-MN^2\omega^4\left(\omega+1\right)\left(N^2\omega+1\right)\left(W_1-\omega\right)\left(M\omega+1\right)} \qquad (17)\\ K_5 &= W_1^2\left(\eta+\omega+\omega^2\right)-\omega^2\left(\omega+1\right)\left(W_1\left(M+1\right)-M\omega\right)\\ K_6 &= W_1^2\left(\eta+\omega+N^2\omega^2\right)-N^2\omega^2\left(N^2\omega+1\right)\left(2M\omega+N^2\omega+2\right).\end{aligned}$$

$$a_S-a_I=\frac{n\eta\omega^3W_1^2\left(N-1\right)\left(N+1\right)\left(M-1\right)}{K_5K_6-MN^2\omega^4\left(\omega+1\right)\left(N^2\omega+1\right)\left(W_1-\omega\right)\left(M\omega+1\right)}>0.$$

In the C-agreement case, as in the two other cases, adaptation levels of signatory and non-signatory countries are strategic complements in the adaptation game.

4.4 Comparison cases

In this section, we develop three more cases that are useful for subsequent comparisons. The first one is the no-cooperation case, that corresponds to the situation where all countries decide individualistically on both their adaptation and mitigation efforts. The equilibrium solution of the adaptation game is obtained by setting $N=1$ and $M=n-1$ in the solution of the A-agreement. The equilibrium adaptation level is then given by:

$$a_j=\frac{n\omega\left(\omega+1\right)\left(-\omega+n\omega+1\right)}{W_2^2\left(\eta+\omega\right)-n\omega^2W_2+\omega^3\left(n-1\right)}\ ,\ j=1,\ldots,n. \qquad (18)$$

[12] See Appendix 8.2.

The second case is full-cooperation, where all countries jointly decide on both their adaptation and mitigation effort. The solution of the adaptation game is retrieved by using $N = n$ countries in the C-agreement equilibrium. The equilibrium adaptation level is then given by:

$$a_j = \frac{n\omega}{\eta + \omega + n^2\eta\omega}\ , j = 1, \ldots, n. \tag{19}$$

Finally, we report the equilibrium solution of the adaptation game for a C-agreement when decisions about adaptation and mitigation are made simultaneously. This is taken from Breton and Sbragia (2017):

$$\begin{aligned}
a_S &= a_I = \omega \frac{E}{\eta + \omega} \\
m_S &= N\omega E \frac{\eta}{\eta + \omega} \\
m_I &= \omega E \frac{\eta}{\eta + \omega} \\
E &= n \frac{\eta + \omega}{W_3} \\
W_3 &= \eta + \omega + \eta\omega \left(M + N^2\right).
\end{aligned}$$

5 Solution of the 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 $c^S(N)$ and $c^I(N)$ represent the equilibrium costs for a signatory and a non-signatory country, respectively, when the number of signatories is N:

$$\begin{aligned}
c^S(N) &= \frac{1}{2}\omega (E - a_S)^2 + \frac{1}{2}m_S^2 + \frac{1}{2}\eta a_S^2 \\
c^I(N) &= \frac{1}{2}\omega (E - a_I)^2 + \frac{1}{2}m_I^2 + \frac{1}{2}\eta a_I^2
\end{aligned}$$

where E, a_S, a_I, m_S and m_I are given, as a function of N, by the equilibrium solutions in the subsequent stages of the game. The internal and external stability conditions defining the equilibrium of the membership game are then, respectively,

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

5.1 M-agreement

We first consider the general problem of the stability of an agreement between N countries to cooperate on mitigation policies, without any assumption on their respective adaptation levels.

The equilibrium solution of the mitigation game involving N signatories where each country is characterized by a level a_j of adaptation is, according to (2)-(4),

$$
\begin{aligned}
E_1 &= \frac{n + M\omega\bar{a}_I + N^2\omega\bar{a}_S}{\omega N^2 + M\omega + 1} \\
m_{Ij_1} &= \omega\left(E_1 - a_j\right), \;\; j \in I \\
m_{Sj_1} &= N\omega\left(E_1 - \bar{a}_S\right), \;\; j \in S.
\end{aligned}
$$

The equilibrium solution of the mitigation game involving $N-1$ signatories where Country i defects from the agreement then corresponds to

$$
\begin{aligned}
E_2 &= \frac{n + M\omega\bar{a}_I + \omega a_i + (N-1)\,\omega\left(Na_S - a_i\right)}{\omega\left(N-1\right)^2 + (M+1)\,\omega + 1} \\
m_i &= \omega\left(E_2 - a_i\right) \\
m_{Ij_2} &= \omega\left(E_2 - a_j\right), \;\; j \in I \\
m_{Sj_2} &= N\omega\left(E_2 - \frac{N\bar{a}_S - a_i}{N-1}\right), \;\; j \in S\backslash i.
\end{aligned}
$$

According to its decision to defect or not, the total environmental cost for Country i is then, as a function of N,

$$
\begin{aligned}
c_i^S\left(N\right) &= \frac{1}{2}\omega\left(E_1 - a_i\right)^2 + \frac{1}{2}N^2\omega^2\left(E_1 - \bar{a}_S\right)^2 + \frac{1}{2}\eta a_i^2 && (20) \\
c_i^I\left(N-1\right) &= \frac{1}{2}\omega\left(E_2 - a_i\right)^2 + \frac{1}{2}\omega^2\left(E_2 - a_i\right)^2 + \frac{1}{2}\eta a_i^2 && (21)
\end{aligned}
$$

and the internal stability condition for a given N is then $c_i^S\left(N\right) - c_i^I\left(N-1\right) \leq 0$ for all $i \in S$.

Proposition 1 *When adaptation levels of all countries are arbitrary, the maximum size of a stable coalition of signatory countries in the mitigation game is two.*

Proof. See Appendix 8.3. ■

When $a_j = 0$ for all countries, i.e. nobody adapts, we retrieve the well known "pessimistic" result for agreements on mitigation policies involving symmetrical countries.

Proposition 1 indicates that neither adaptation nor asymmetry in countries' vulnerability to global pollution help in achieving coordination in mitigation policies: for arbitrary adaptation levels, the small-coalition result for agreements on mitigation policies holds.

According to the sequence presented in Figure 1, the M-agreement is signed before countries decide on their adaptation levels, that is, the membership game is played by countries anticipating the equilibrium solution of the adaptation game (12)-(13). Proposition 1 establishes that the maximum number of signatories of a M-agreement is then two.[13]

Note that Proposition 1 also applies to a M-agreement when adaptation is decided simultaneously with, or after mitigation. This is the result found in Benchekroun et al. (2017) when the fixed cost paid by countries for not participating in the agreement is set to 0.

[13]Proposition 1 would also apply to a case where countries invest in adaptive measures and then sign an agreement to cooperate on their mitigation levels, that is, the membership game is played by countries having already invested in adaptation at arbitrary levels. Again, the maximum coalition size would be 2.

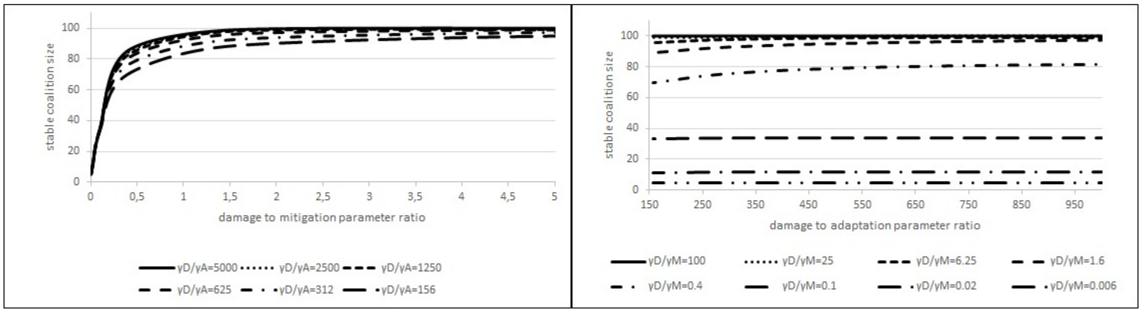

Figure 2: Size of the stable coalition for an A-agreement as a function of $\frac{\gamma_D}{\gamma_M}$ (left panel) and $\frac{\gamma_D}{\gamma_A}$ (right panel). The total number of countries is $n = 100$.

5.2 A-agreement

On the other hand, for A-agreements, stable equilibrium solutions with a significant number of signatories may be obtained. As an illustration, Figures 2 and 3 report the solutions of the membership game when adaptation levels are given by (14)-(15) and mitigation levels by (7)-(8), for a variety of parameter values, for $n = 100$ and for $n = 50$.[14] Numerical experiments show that equilibrium total cost functions of both types of countries are decreasing and concave with respect to the number of signatories, so that when an internally and externally stable coalition exists, it is unique. Figures 2 and 3 plot the size of the stable coalition as a function of $\frac{\gamma_D}{\gamma_M} = \omega$ and $\frac{\gamma_D}{\gamma_A} = \frac{\omega}{\eta}$ (the corresponding numerical results are provided in Appendix 8.4). We observe that the behavior of the solutions of the membership game is qualitatively similar for $n = 100$ and $n = 50$. We find that full cooperation can be achieved for some parameter values, and that the size of the stable coalition is increasing with ω and decreasing with η. We conclude that A-agreements, where signatories agree to coordinate their adaptation levels, are likely to include a large number of countries when the environmental damage cost is relatively high with respect to the cost of adaptation and of mitigation.

It is interesting to point out that, while cooperation on mitigation can not be achieved due to the fact that mitigation levels are strategic substitutes, this is not the case for adaptation decisions, which are strategic complements in the adaptation game when adaptation plays a strategic role in the subsequent mitigation game. When countries agree to coordinate their adaptation levels, cooperation is possible, and full cooperation can even be achieved.

5.3 C-agreement

Figures 4 and 5 report the solutions of the membership game for a C-agreement, that is, when adaptation levels are given by (16)-(17) and mitigation levels by (3)-(4), for the same set of parameter values as those used in the preceding section (corresponding numerical results are provided in Appendix 8.4). As for the A-agreement case, large coalitions can form, and full cooperation can be achieved for some sets of parameter values. We observe that the size of a stable coalition in a

[14] The combinations of values used in our numerical experiments span the space of parameter values yielding interior solutions. Extensive simulations show that reported results are robust to n and to the range for ω and η.

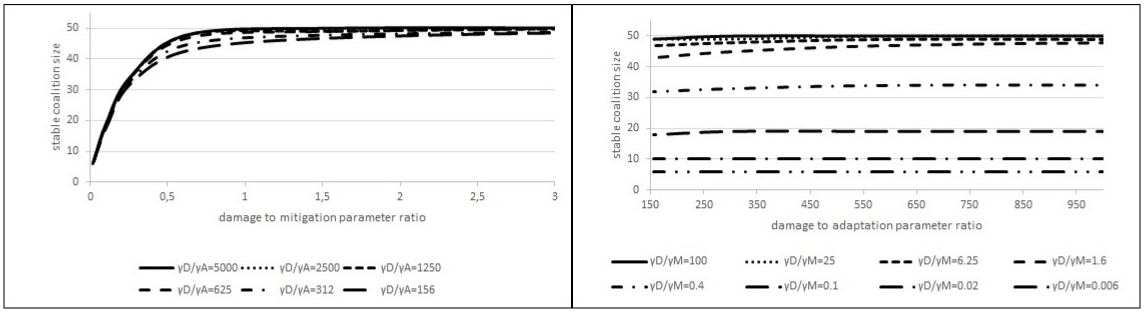

Figure 3: Size of the stable coalition for an A-agreement as a function of $\frac{\gamma_D}{\gamma_M}$ (left panel) and $\frac{\gamma_D}{\gamma_A}$ (right panel). The total number of countries is $n = 50$.

C-agreement is increasing with ω and decreasing with η, but is never larger than in an A-agreement for a given set of parameter values.

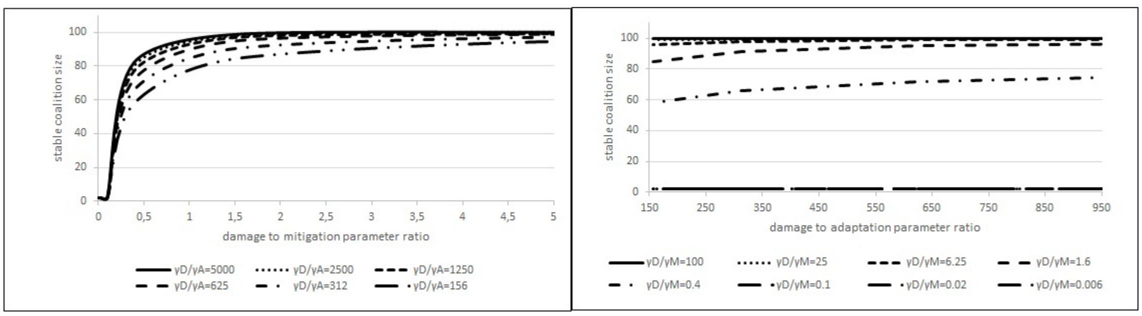

Figure 4: Size of the stable coalition for a C-agreement as a function of $\frac{\gamma_D}{\gamma_M}$ (left panel) and $\frac{\gamma_D}{\gamma_A}$ (right panel). The total number of countries is $n = 100$.

However, when adaptation investments are made before mitigation decisions, a drawback of the C-agreement is that it is not renegotiation-proof. To show that this is the case, consider the time line presented in Figure 6, where signatory players can reconsider their participation to the agreement after investments in adaptive measures have become irreversible.

Corollary 2 *When commitments to adaptive measures are made before mitigation decisions, agreements to coordinate both adaptation and mitigation policies are not renegotiation-proof.*

Proof. Assume that the set of parameter values is such that a coalition of $N \geq 3$ countries is internally and externally stable when costs are computed using the equilibrium solution (16)-(17) and (3)-(4) corresponding to the C-agreement. Using Proposition 1, if a membership game were played in the renegotiation step, the maximum size of a stable coalition would be $2 < N$. As a

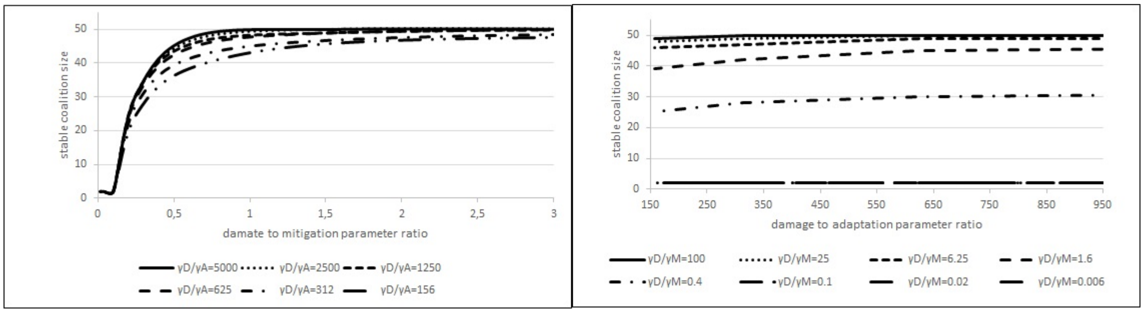

Figure 5: Size of the stable coalition for a C-agreement as a function of $\frac{\gamma_D}{\gamma_M}$ (left panel) and $\frac{\gamma_D}{\gamma_A}$ (right panel). The total number of countries is $n = 50$.

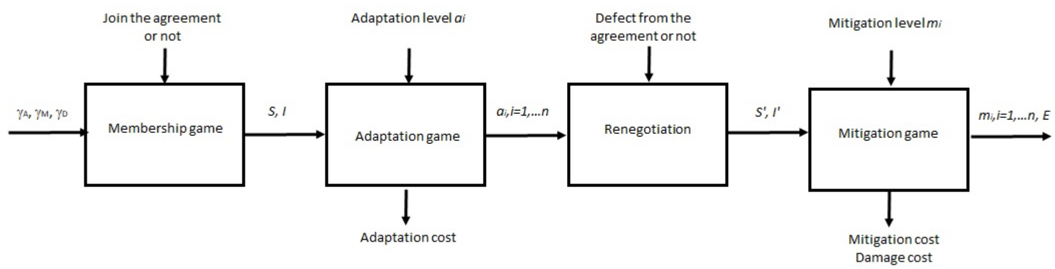

Figure 6: Sequence of decisions when players can defect from an agreement after adaptive measures have been implemented.

consequence, at least one signatory country will have an incentive to defect from the coalition in the renegotiation step. ■

Knowing that a C-agreement is not renegotiation-proof, farsighted players solving the four-stage game depicted in Figure 6 by backward induction should expect the agreement to break down after investment in adaptive measures have become irreversible. If one assumes that the equilibrium solution of the renegotiation step is $N' = 1$, the equilibrium solution of the four-stage game corresponds to the solution obtained under an A-agreement.

Note that when adaptation and mitigation decisions are taken simultaneously, the issue of renegotiation does not apply. The solution of the membership game in the C-agreement scenario is then obtained by using Proposition 1, showing that the maximum size of a stable coalition is two. In this case the arbitrary levels of adaptation are replaced by a common level for all players, proportional to the total emissions. This is an interesting result, as it shows that when (private) adaptive measures to the adverse 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 cannot form.

6 Economic and environmental implications of adaptive measures in IEAs

In this section, we evaluate the implications of incorporating adaptive policies into IEAs, by comparing the outcomes of various agreement types using two benchmark cases:

- the case where there is no agreement on environmental policies, where adaptation levels are given by (18) and mitigation levels by (5);
- the full-cooperation case, where adaptation and mitigation levels are given respectively by (19) and (4), with $N = n$.

6.1 Benefits of cooperation

We first provide an assessment of how far apart are the no-cooperation and the full cooperation solutions for a variety of parameter values. Table 1 reports on the average adaptation level, total emission and average total costs in the full-cooperation case, expressed as a percentage of the corresponding values in the no-agreement case.

$\frac{\gamma_D}{\gamma_M}$	0.02	0.39	6.25	100	0.02	0.39	6.25	100	0.02	0.39	6.25	100
$\frac{\gamma_D}{\gamma_A}$	Average adaptation level				Total emissions				Average total cost			
312.5	57	8.1	0.64	0.04	57	8.1	0.64	0.04	57	8.8	0.81	0.05
1250	84	24.8	2.10	0.13	84	24.8	2.10	0.13	84	25.4	2.24	0.15
5000	95	56.5	7.54	0.51	95	56.5	7.54	0.51	95	56.8	7.67	0.52

Table 1: Ratio of full-cooperation over no-cooperation outcomes (in %) for various parameter values, where $n = 100$.

As expected, adaptation levels, emissions and costs are all lower in the full-cooperation case than in the no-cooperation case. Small reported values indicate that the no-cooperation outcomes are far from the full-cooperation ones. We observe that the distance between these two solutions increases with $\frac{\gamma_D}{\gamma_M}$ and decreases with $\frac{\gamma_D}{\gamma_A}$.[15] In other words, for a given value of the damage cost parameter γ_D, the benefit from cooperation increases when the mitigation cost parameter γ_M decreases and/or the adaptation cost parameter γ_A increases. It is interesting to observe by comparing these results with those of Figures (2)-(5) that stable agreements involving adaptive measures (A-agreements and C-agreements) are more likely to include a large number of countries when the benefit from cooperation is high.

6.2 Three-stage game equilibrium outcome comparisons

Table 2 compares the equilibrium solutions against the benchmark solutions, for different parameter values in the various types of agreements considered in this paper. It also includes the equilibrium solution of a C-agreement when adaptation and mitigation decisions are taken simultaneously. The comparison is made by evaluating, for each agreement type, the position λ of the solution (in

[15] Results obtained by varying the total number of countries n are qualitatively similar.

terms of average adaptation level, total emissions and average cost) in the range separating the cooperative and non-cooperative values, that is, the value of λ solving

$$V^k = \lambda V^{FC} + (1 - \lambda) V^{NC},$$

where V^k is the value of the outcome for scenario k and V^{FC} and V^{NC} are the values of the outcome in the full-cooperation and no-cooperation solutions, respectively. A value of λ close to 1 means that the outcome is close to the full-cooperation solution. For all types of agreements, outcomes are computed using the size of the stable coalition in the first-stage membership game. For the C-agreement, we also report the outcome obtained when the coalition breaks down after the investment in adaptive measures (C-agreement with defection). In all cases, $\lambda \in [0, 1]$, that is, average adaptation, total emissions and total environmental costs are never higher than what is achieved when there is no agreement, nor lower than under full cooperation.

Examination of Table 2 shows that a M-agreement, or a C-agreement with simultaneous decisions, do not help in significantly reducing emissions and environmental costs due to the impossibility of achieving stability in coalitions with a significant size. However, agreements including resolutions on adaptive measures can have a significant number of signatories, and this happens specifically in cases where the non-cooperative and cooperative outcomes are very far apart. In such cases, even a modest value of λ may represent a substantial improvement with respect to the non-cooperative solution. This is illustrated in Figures 7 and 8 comparing the total environment costs and the total pollution under the A- and C- agreements to the no-agreement case, and in Figure 9 comparing the total pollution under the A- and C- agreements, for various combinations of parameter values.

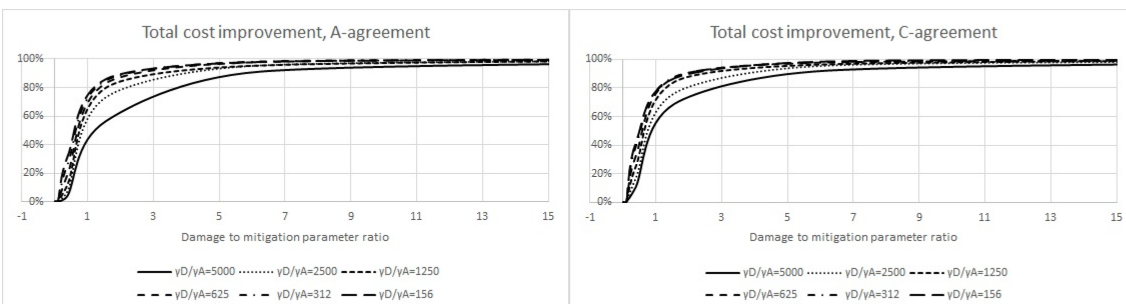

Figure 7: Reduction in total environmental cost, as a percentage of the no-cooperation solution outcome, for various parameter values and $n = 100$.

6.3 Agreement design

From both an environmental and an economic standpoint, the results illustrated in Table 2 and Figures 7-9 indicate that including adaptive measures in the scope of environmental agreements may be advisable when these measures require irreversible investments prior to the implementation of mitigation policies. In fact, the M-agreement does little better than no cooperation since the largest possible size of a stable coalition is 2, and even such a small coalition can only be formed when the damage costs are small relatively to the mitigation costs and the benefits of cooperation

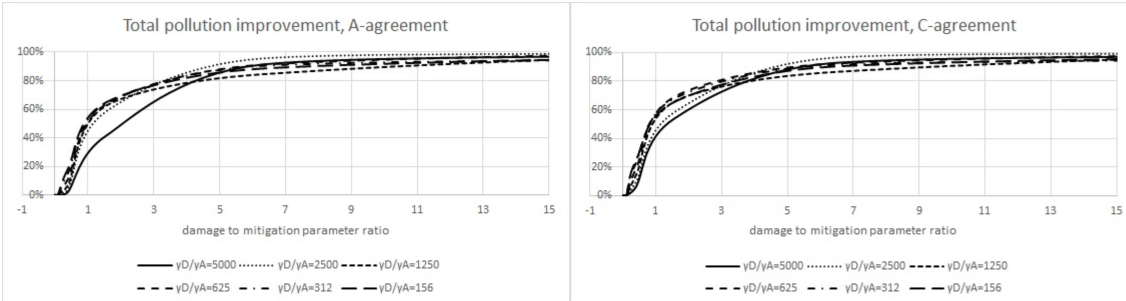

Figure 8: Reduction in total pollution, as a percentage of the no-cooperation solution outcome, for various parameter values and $n = 100$.

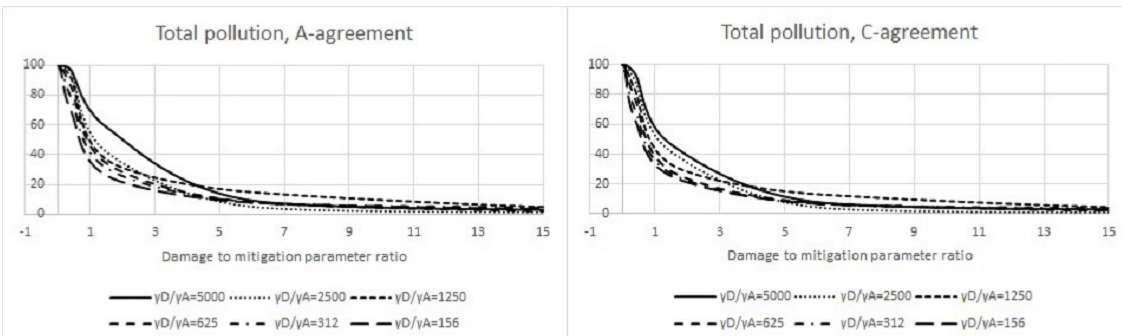

Figure 9: Total pollution for various parameter values and $n = 100$.

are small. On the other hand, both the A- and the C- agreements can support large coalitions, up to full cooperation. We find that including adaptation provisions in environmental agreements is more likely to achieve important reductions in environmental costs and in total emissions when the damage cost is relatively high with respect to the adaptation and mitigation costs. We also find that, while the number of signatory countries of a stable C-agreement is never larger than that of an A-agreement, a C-agreement still generally results in better outcomes in terms of total cost and pollution than an A-agreement, even when the agreement breaks down after investment in adaptive measures become irreversible. This is an important result since it shows that, from both the economic and environmental points of view, including resolutions on adaptive measures in an IEA is better than letting countries decide on adaptation policies in their own individual way. Finally, since C-agreements are not renegotiation proof, designing agreements pertaining exclusively to adaptive measures (A-agreements) may be worth considering since their effectiveness is close to that of C-agreements. Recall that the equilibrium solution of the A-agreement game can be interpreted as the solution of a game involving farsighted signatory players who account for the fact that all signatory countries should defect from the agreement and fail to coordinate their mitigation policies.

6.4 Illustrative example

As an illustration, Table 3 provides a detailed comparison of the outcomes under various types of agreements for a specific set of parameters.

In this particular scenario, the M-agreement coincides with the no-cooperation solution since no stable coalition can form in the mitigation game. We observe that the no-cooperation and the full-cooperation solutions differ significantly (emissions, adaptation levels and total cost under co-operation are between 8% and 9% of the corresponding outcomes when countries do not coordinate their policies). Adaptation plays an important role in that difference: while the cost of adaptation represents 7.4% of the total environmental cost in the full-cooperation solution, it represents 99.8% of the total cost in the no-cooperation solution.

An A-agreement involving 76 countries is stable. Under the A-agreement, signatories' adaptation levels are lower than those of non signatories; as a result, their adaptation cost is lower, but they are more vulnerable to the total emissions and suffer a higher damage cost than non signatories. Signatories' mitigation level is 3.8 times that of non signatories. Even if the λ values are relatively small at 0.168 (adaptation), 0.163 (emissions) and 0.293 (costs), with respect to the no-cooperation case, an A-agreement results in a reduction of 15% of the average adaptation level and of the total pollution, and in a reduction of 27% of the total environmental costs.

The number of signatories of a C-agreement is 66. Under the C-agreement, signatories' adaptation levels are higher than those of non signatories; as a result, their adaptation cost is higher, but their damage cost is lower than that of non signatories. In the C-agreement, signatories' mitigation level is 6.5 times that of non signatories. The total environmental cost of all countries is lower in a C-agreement than in an A-agreement. A C-agreement results in a reduction of 23% of the average adaptation level and of the total pollution, and in a reduction of 39% of the total environmental costs with respect to the no-cooperation case.

However, the C-agreement is not renegotiation-proof, and since coordination of mitigation policies in an IEA cannot be enforced, one should expect countries to defect after investments in adaptive measures are committed to. In that case (C-agreement with defection), countries do not coordinate their mitigation decisions, but since (former) signatories are less vulnerable to total pollution than non signatories, their mitigation level is 80% of the non signatories' mitigation level. As a result, the total environmental cost of all countries is lower than under an A-agreement, but higher than under a C-agreement where players do not defect. A C-agreement with defection results in a reduction of 23% of the average adaptation level, a reduction of 22% of the total pollution, and in a reduction of 38% of the total environmental costs with respect to the no-cooperation case.

Finally, as pointed out by Benchekroun et al. (2017), the inclusion of adaptive measures into an IEA does increase the incentive to cooperate when adaptation and mitigation are decided simultaneously; however, as shown in Proposition 1, the maximum size of a stable coalition in that case is two, so that the impact of introducing adaptive measures into an IEA is limited. This is illustrated by the results provided in Table 3: for the set of parameters used in this example, there is no stable M-agreement, but in the simultaneous case, a C-agreement between two countries would be stable, where the two signatories' mitigation level would be twice that of non signatories. We observe that the outcome in terms of adaptation levels, total emissions and average costs is close to the no-cooperation solution, resulting in a reduction of 2% of the average adaptation level and total pollution, and in a reduction of 4% of the total environmental costs.

$\frac{\gamma_D}{\gamma_M}$	Average adaptation level				Total emissions				Average total cost				Coalition size			
$\frac{\gamma_D}{\gamma_A}$	0.024	0.39	6.25	100	0.024	0.39	6.25	100	0.024	0.39	6.25	100	0.024	0.39	6.25	100
	M-agreement															
312.5	.030	-	-	-	.031	-	-	-	061	-	-	-	2	0	0	0
1250	.020	-	-	-	.021	-	-	-	.041	-	-	-	2	0	0	0
5000	.018	-	-	-	.018	-	-	-	.036	-	-	-	2	0	0	0
	A-agreement															
312.5	.025	16.8	91.1	100	.018	16.3	91.0	100	.035	29.3	99.1	100	12	76	98	100
1250	.017	9.1	86.3	100	.012	8.9	86.2	100	.024	16.4	97.8	100	12	82	99	100
5000	.015	5.3	98.8	100	.011	5.1	98.7	100	.021	9.6	98.8	100	12	85	100	100
	C-agreement															
312.5	.031	24.8	92.2	100	.032	24.9	92.2	100	.063	43.3	99.4	100	2	66	98	100
1250	.021	18.8	88.1	100	.021	18.8	88.1	100	.042	33.8	98.6	100	2	77	99	100
5000	.018	13.1	100	100	.019	13.1	100	100	.037	24.3	100	100	2	82	100	100
	C-agreement with defection															
312.5					.022	24.1	92.0	100	.044	41.4	99.3	100	before defection,			
1250	same as C-agreement				.015	18.3	87.9	100	.030	31.3	98.3	100	same as C-agreement			
5000					.013	12.8	99.8	100	.026	21.7	98.8	100				
	C-agreement with simultaneous decisions															
312.5	.036	2	-	-	.036	.2	-	-	.071	.5	-	-	2	2	0	0
1250	.024	1	-	-	.024	.1	-	-	.048	.2	-	-	2	2	0	0
5000	.021	0	2	-	.021	0	.2	-	.042	.1	.5	-	2	2	2	0

Table 2: Coalition sizes and position λ in percentage points of the outcomes for various scenarios with respect to the corresponding ones in the full-cooperation and no-cooperation soution. A value of λ close to 100 means that the outcome is close to the full-cooperation solution. Results are computed for various parameter values, with $n = 100$.

	Full cooperation	M-agreement	A-agreement	C-agreement	Defection	Simultaneous
	100	0	76	66		2
(a_S, a_I)	2.9	35.7	$(30.2, 30.4)$	$(27.6, 27.6)$	$(27.6, 27.6)$	34.6
Average adaptation	2.9	35.7	30.2	27.6	27.6	34.6
$m_S; m_I$ ×100	93	8	27; 7	41; 6	27; 32	22; 11
E	7.4	91.7	77.9	70.7	71.4	88.7
Damage cost×100	0.05	4.41	46; 0.2	.02; 2.6	45.6; 67.3	7.8
Mitigation cost×100	214	1.72	18; 1.3	42.3; 1	17.8; 26.3	12.2; 3.1
Adaptation cost	0.17	26.15	18.7; 19	15.6; 15.5	15.6; 15.5	24.4
Total cost	2.3	26.2	19.3; 18.9	16.0; 15.6	16.2; 16.5	24.6; 25.5
Average cost	2.3	26.2	19.2	15.9	16.3	24.6

Table 3: Comparison of the outcomes of various types of agreements. Parameter values are $n = 100$, $\gamma_M = 5$, $\gamma_D = 1.95$, $\gamma_A = 0.00625$. This corresponds to $\omega = 312.5 \eta = 0.39$.

7 Conclusion

The objective of the paper was to study the consequences of introducing resolutions on adaptive measures into an IEA. We focused on the case of private adaptive solutions that require a prior commitment with respect to emission-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 signatories can be obtained, which is not the case when adaptation and mitigation are decided simultaneously.
- The number of signatories in a stable agreement depends on the relative values of three cost parameters. It is likely to be high when the adaptation and mitigation costs are relatively low with respect to the environmental damage cost.
- Such combinations of cost parameters correspond to cases where the no-cooperation solution is very far from the full-cooperation solution, so that the inclusion of adaptive measures in IEAs in these cases can significantly enhance welfare.
- An IEA including private adaptive investment clauses results in less adaptive effort, less global pollution and a smaller environmental cost, as compared to a situation where there is no agreement on adaptation or mitigation.
- Stable A-agreements involve more signatories than C-agreements, but can nonetheless result in outcomes that are further away from the full-cooperation solution. C-agreements are not renegotiation-proof; a C-agreement with defection results in outcomes that are between the outcomes of an A-agreement and a C-agreement.
- The number of signatories of an IEA involving only mitigation clauses cannot be larger than two, irrespective of the adaptation levels of participating countries, and of the timing of the adaptation decisions.

It is important to stress that the economic and environmental impact of including resolutions on adaptive measures in IEAs is beneficial only in the case where adaptation requires a prior commitment. When adaptation and mitigation measures are decided simultaneously, large coalitions of more than two players cannot form.

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

The major conclusion that we can draw from our results is that private adaptive investments to counteract the adverse consequences of climate change should be incorporated into 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.

8 Appendix

8.1 Impact of a player's adaptation on the mitigation game solution

1. M-agreement and C-agreement

   (a) Impact of a non-signatory country's adaptation

      i. on total emission:

$$\frac{d}{da_j}\left(\frac{n+\omega A_I+\omega a_j+N^2\omega\bar{a}_S}{W_1}\right)=\frac{\omega}{W_1}$$

      ii. on its own mitigation level:

$$\frac{d}{da_j}\omega\left(E-a_j\right)=\frac{\omega}{W_1}\left(\omega-W_1\right)<0$$

      iii. on other non-signatories' mitigation level:

$$\frac{d}{da_j}\omega\left(E-a_i\right)=\frac{\omega^2}{W_1}>0$$

      iv. on signatories' mitigation level:

$$\frac{d}{da_j}N\omega\left(E-a_i\right)=N\frac{\omega^2}{W_1}>0.$$

   (b) Impact of a signatory country's adaptation

      i. on total emissions:

$$\frac{d}{da_j}\left(\frac{n+M\omega\bar{a}_I+N\omega\left(A_S+a_j\right)}{W_1}\right)=\frac{N\omega}{W_1}$$

      ii. on its own mitigation level:

$$\frac{d}{da_j}\left(N\omega\left(E-a_j\right)\right)=N\omega\frac{N\omega-W_1}{W_1}<0$$

      iii. on other signatories' mitigation level:

$$\frac{d}{da_j}N\omega\left(E-a_i\right)=N^2\frac{\omega^2}{W_1}>0$$

      iv. on non-signatories' mitigation level:

$$\frac{d}{da_j}\omega\left(E-a_i\right)=N\frac{\omega^2}{W_1}>0.$$

2. A-agreement

(a) For both signatories and non signatories, the impact of a single country's adaptation on total emission is $\frac{\omega}{W_2}$.

(b) Impact of a signatory or non-signatory country's adaptation

i. on its own mitigation level:

$$\frac{d}{da_j}\omega\left(E - a_j\right) = \omega\frac{\omega - W_2}{W_2} < 0$$

ii. on other countries' mitigation level:

$$\frac{d}{da_j}\omega\left(E - a_i\right) = \frac{\omega^2}{W_2} > 0.$$

8.2 Summary results

This table summarizes the impact of adaptation on total emissions and on mitigation levels for both kind of countries and for three possible agreements when $v_I = v_S = v$.

Non signatories	Signatories
M-agreement	
$\frac{dE}{da_I} = \frac{\omega}{W_1}$	$\frac{dE}{da_S} = \frac{N\omega}{W_1}$
$m_I = \omega v$	$m_S = N\omega v$
$\frac{dm_I}{da_I} = \omega\frac{\omega - W_1}{W_1}$	$\frac{dm_S}{da_S} = N\omega\frac{N\omega - W_1}{W_1}$
A-agreement	
$\frac{dE}{da_I} = \frac{\omega}{W_2}$	$\frac{dE}{da_S} = \frac{N\omega}{W_2}$
$m_I = \omega v$	$m_S = \omega v$
$\frac{dm_I}{da_I} = \omega\frac{\omega - W_2}{W_2}$	$\frac{dm_S}{da_S} = \omega\frac{N\omega - W_2}{W_2}$
C-agreement	
$\frac{dE}{da_I} = \frac{\omega}{W_1}$	$\frac{dE}{da_S} = \frac{\omega N^2}{W_1}$
$m_I = \omega v$	$m_S = N\omega v$
$\frac{dm_I}{da_I} = \omega\frac{\omega - W_1}{W_1}$	$\frac{dm_S}{da_S} = N\omega\frac{-W_1 + N^2\omega}{W_1}$

8.3 Proof of Proposition 1

For a given player $i \in S$, define $\theta_i \equiv \bar{a}_S - a_i$ and

$$\begin{aligned}
\Psi_i &= c_i^S\left(N\right) - c_i^I\left(N-1\right) \\
&= \frac{1}{2}\omega\left(E_1 - a_i\right)^2 - \frac{1}{2}\omega\left(E_2 - a_i\right)^2 + \frac{1}{2}N^2\omega^2\left(E_1 - \bar{a}_S\right)^2 - \frac{1}{2}\omega^2\left(E_2 - a_i\right)^2.
\end{aligned}$$

The internal stability condition for a given coalition of size N is then $\Psi_i \leq 0$ for all $i \in S$. We then have

$$\begin{aligned}
E_1 &= \frac{n + M\omega\bar{a}_I + N^2\omega\bar{a}_S}{\omega N^2 + M\omega + 1} \\
E_2 &= \frac{W_1 E_1 - \omega a_i (N-2) - N\omega(\theta_i + a_i)}{W_1 - 2\omega(N-1)} \\
\Psi_i &= \frac{1}{2}\omega(E_1 - a_i)^2 \\
&\quad - \frac{1}{2}\omega\left(\frac{W_1 E_1 - \omega a_i (N-2) - N\omega(\theta_i + a_i)}{W_1 - 2\omega(N-1)} - a_i\right)^2 \\
&\quad + \frac{1}{2}N^2\omega^2(E_1 - (\theta_i + a_i))^2 \\
&\quad - \frac{1}{2}\omega^2\left(\frac{W_1 E_1 - \omega a_i (N-2) - N\omega(\theta_i + a_i)}{W_1 - 2\omega(N-1)} - a_i\right)^2. \qquad (22)
\end{aligned}$$

Rearranging Equation (22) yields

$$\begin{aligned}
\Psi_i &= \frac{N^2\omega^2}{2(W_1 - 2\omega(N-1))^2}K_7\theta_i^2 \\
&\quad - \frac{N\omega^2(E_1 - a_i)}{(W_1 - 2\omega(N-1))^2}K_8\theta_i \\
&\quad + \frac{\omega^2(E_1 - a_i)^2(N-1)}{2(W_1 - 2\omega(N-1))^2}K_9
\end{aligned}$$

where

$$\begin{aligned}
K_7 &= \omega^2(M + N(N-2) + 1)(M + N(N-2) + 3) \\
&\quad + \omega(2M + 2N(N-2) + 3) + 1 \\
K_8 &= \omega^2\left(NM^2 + M\left(4N + 2N^2(N-2) - 1\right) + N(N-1)\left(5N + N^2(N-3) - 4\right)\right) \\
&\quad + \omega(2N-1)\left(M + (N-1)^2\right) + (N-1) \\
K_9 &= \omega^2(M + N(N-2))\left(M + N(M+2) + N^2(N-1)\right) \\
&\quad + 2\omega\left((N-1)(M+2) + N^2(N-3)\right) + (N-3).
\end{aligned}$$

Note that the three constants K_7, K_8 and K_9 are strictly positive for $N \geq 3$. Ψ_i is a convex quadratic function of θ_i that is decreasing and positive at $\theta_i = 0$. As a consequence, for $N \geq 3$, $\Psi_i > 0$ when $\theta_i \leq 0$. Recall that the stability condition requires that $\Psi_i \leq 0$ for all $i \in S$. As a consequence, for a coalition of $N \geq 3$ players, it suffices to show that there exists at least one $i \in S$ for which $\theta_i \leq 0$ to obtain that the coalition is not stable. We distinguish two cases:

i) If all signatories have the same adaptation level (symmetric case), $\theta_i = 0$ and $\Psi_i > 0$ for all $i \in S$ when $N \geq 3$. All signatories would benefit from leaving the agreement, and we conclude that no coalition of $N \geq 3$ countries is stable when they have the same adaptation level.

ii) If signatories have different adaptation levels (asymmetric case), then there exists at least one signatory country adapting more than the average $\overline{a}_S$, say country j. For that country, $\theta_j < 0$ and, if $N \geq 3$, $\Psi_j > 0$. Country j would benefit from leaving the agreement and we conclude that no coalition of $N \geq 3$ countries is stable when they have different adaptation levels.

8.4 Numerical values used in figures

Figure 2

A-agreement, $n = 100$

$\frac{\gamma_D}{\gamma_M}$	0.006	0.02	0.1	0.39	1.6	6.25	25	100
$\frac{\gamma_D}{\gamma_A}$	Stable coalition size							
156	5	11	33	70	89	96	99	100
312	5	11	34	76	93	98	99	100
625	5	12	34	80	96	99	100	100
1250	5	12	34	82	98	99	100	100
2500	5	12	34	84	99	100	100	100
5000	5	12	34	85	99	100	100	100

Figure 3

A-agreement, $n = 50$

$\frac{\gamma_D}{\gamma_M}$	0.006	0.02	0.1	0.39	1.6	6.25	25	100
$\frac{\gamma_D}{\gamma_A}$	Stable coalition size							
156	6	10	18	32	43	47	49	49
312	6	10	19	33	45	48	49	50
625	6	10	19	34	47	49	50	50
1250	6	10	19	34	48	49	50	50
2500	6	10	19	34	48	50	50	50
5000	6	10	19	34	48	50	50	50

Figure 4

C-agreement, $n = 100$

$\frac{\gamma_D}{\gamma_M}$	0.006	0.02	0.1	0.39	1.6	6.25	25	100
$\frac{\gamma_D}{\gamma_A}$	Stable coalition size							
156	2	2	2	58	85	96	99	100
312	2	2	2	66	91	98	99	100
625	2	2	2	72	95	99	100	100
1250	2	2	2	77	97	99	100	100
2500	2	2	2	80	98	100	100	100
5000	2	2	2	82	99	100	100	100

Figure 5

C-agreement, $n = 50$								
$\frac{\gamma_D}{\gamma_M}$	0.006	0.02	0.1	0.39	1.6	6.25	25	100
$\frac{\gamma_D}{\gamma_A}$	Stable coalition size							
156	2	2	2	25	39	46	48	49
312	2	2	2	28	42	47	49	50
625	2	2	2	30	45	49	50	50
1250	2	2	2	31	46	49	50	50
2500	2	2	2	31	47	50	50	50
5000	2	2	2	31	48	50	50	50

Figure 7

A-agreement, $n = 100$								
$\frac{\gamma_D}{\gamma_M}$	0.006	0.02	0.1	0.39	1.6	6.25	25	100
$\frac{\gamma_D}{\gamma_A}$	% reduction in total cost w.r.t. no-cooperation							
156	0.000	0.000	0.014	0.323	0.862	0.981	0.998	1.000
312	0.000	0.000	0.008	0.268	0.852	0.983	0.996	0.999
625	0.000	0.000	0.004	0.195	0.833	0.979	0.997	0.999
1250	0.000	0.000	0.002	0.122	0.802	0.956	0.994	0.999
2500	0.000	0.000	0.001	0.075	0.732	0.953	0.989	0.997
5000	0.000	0.000	0.001	0.042	0.566	0.912	0.979	0.995
C-agreement, $n = 100$								
$\frac{\gamma_D}{\gamma_M}$	0.006	0.02	0.1	0.39	1.6	6.25	25	100
$\frac{\gamma_D}{\gamma_A}$	% reduction in total cost w.r.t. no-cooperation							
156	0.000	0.001	0.001	0.420	0.867	0.984	0.998	1.000
312	0.000	0.000	0.001	0.394	0.882	0.986	0.996	0.999
625	0.000	0.000	0.000	0.327	0.879	0.982	0.997	0.999
1250	0.000	0.000	0.000	0.252	0.842	0.963	0.994	0.999
2500	0.000	0.000	0.000	0.170	0.766	0.959	0.989	0.997
5000	0.000	0.000	0.000	0.105	0.689	0.923	0.980	0.995

Figure 8

A-agreement, $n = 100$								
$\frac{\gamma_D}{\gamma_M}$	0.006	0.02	0.1	0.39	1.6	6.25	25	100
$\frac{\gamma_D}{\gamma_A}$	% reduction in total pollution w.r.t. no-cooperation							
156	0.000	0.000	0.007	0.183	0.650	0.885	0.972	1.000
312	0.000	0.000	0.004	0.150	0.644	0.904	0.956	0.999
625	0.000	0.000	0.002	0.108	0.635	0.909	0.997	0.999
1250	0.000	0.000	0.001	0.067	0.626	0.844	0.994	0.999
2500	0.000	0.000	0.001	0.040	0.585	0.953	0.989	0.997
5000	0.000	0.000	0.000	0.022	0.417	0.912	0.979	0.995

C-agreement, $n = 100$								
$\frac{\gamma_D}{\gamma_M}$	0.006	0.02	0.1	0.39	1.6	6.25	25	100
$\frac{\gamma_D}{\gamma_A}$	% reduction in total pollution w.r.t. no-cooperation							
156	0.000	0.000	0.001	0.245	0.653	0.898	0.974	1.000
312	0.000	0.000	0.000	0.229	0.682	0.916	0.958	1.000
625	0.000	0.000	0.000	0.187	0.692	0.922	0.997	0.999
1250	0.000	0.000	0.000	0.142	0.658	0.862	0.995	0.999
2500	0.000	0.000	0.000	0.094	0.583	0.960	0.990	0.997
5000	0.000	0.000	0.000	0.057	0.539	0.925	0.980	0.995

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