Adaptation to Climate Change: How does Heterogeneity in Adaptation Costs Affect Climate Coalitions?*

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Abstract

We examine how adaptation to climate change affects the incentives to ratify international environmental agreements (IEAs). In particular, we study the effects of two aspects of adaptation on the incentives to join a coalition. First, we analyze cross-country differences in adaptation costs. Second, we investigate the role of carbon leakage. We find that cross-country differences in adaptation may discourage countries from joining IEAs when there is no carbon leakage, while these cross-country differences may strengthen the incentives to join IEAs with leakages. Our results emphasize that policies directed at reducing cost differences and carbon leakage may also affect the success and failure of IEAs.

Keywords: adaptation; environmental agreements; cost differences; carbon leakage

JEL Codes: Q50, Q54, C72

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1 Introduction

The United Nations Conference on Climate Change (UNFCCC) in Cancún in 2010 (COP16) and in Durban in 2011 (COP17) adopted a new approach to design international environmental agreements (IEAs) compared to the previous Kyoto framework. The new emerging post-Kyoto framework combines efforts of emissions abatement to adaptation. While most agree that abatement and adaptation are the two main available options to tackle climate change, unfortunately the role of adaptation is largely ignored in the study of IEAs.[1] In this paper, we focus on the role of adaptation in the decision to join a coalition. In particular, we study how cross-country differences in adaptation costs affect the incentives to join an IEA.

The World Bank estimates that an approximate 2°C increase in world temperatures by 2050 may require between $70 - $100 billion a year in adaptation costs from 2010 to 2050.[2] Adaptation refers to any activity with a potential to reduce the damages from climate change. For example, the construction of dams, levees or dikes, changing the types of crops used in agriculture or improving storm predictions and their warnings (Parry, 2007). These adaptation costs, however, differ widely across countries. For instance, empirical studies find evidence of cost differences between developed and developing countries.[3] These cross-country differences yield new challenges in understanding a country's incentives to join climate coalitions.

In this paper, we ask three questions. First, how do cross-country differences in adaptation costs affect emissions? Second, how do cross-country differences in adaptation costs change the incentives to join IEAs? And finally, how do emission leakages, combined with

[1] A few exceptions are Benchekroun et al. (2011) and Marrouch & Chaudhuri (2011).

[2] These findings are from "The Economics of Adaptation to Climate Change (EACC)" study in 2011 by the World Bank. They also find that this amount is comparable to the current annual foreign aid from developed to developing countries.

[3] *Ibid.*

adaptation, influence the incentives to join IEAs? We address these questions within the framework of IEA membership games first introduced by Carraro & Siniscalco (1993) and Barrett (1994). The main difference in our setup is that we explicitly model adaptation as a possibility, in addition to emissions abatement, to reduce environmental damages.

We model a world consisting of many countries, and we introduce three modeling features that differentiate our paper from previous work. First, countries can simultaneously choose emissions and adaptation levels. In our context, the most important feature that distinguishes emissions and adaptation decisions relates to their public and private good nature. While each country's emissions generate a private benefit, their implications have a global public bad nature. Note, however, the distinction from adaptation. While adaptation also generates a private benefit, its implications only benefit the individual country. Therefore, in our setting, a key feature is that emissions abatement has a public good nature while adaptation has a private good nature.[4]

Second, we account for cross-country differences in adaptation costs. Specifically, there are two types of countries: countries with low and high adaptation costs. This feature addresses some of the concerns raised in the recent climatic negotiations in Cancún in 2010 (COP16) and in Durban in 2011 (COP17), where the importance of adaptation differences among developed and developing countries for environmental agreements was highlighted. For example, the Cancún Adaptation Fund, established in 2010, aims at reducing the technological gap that exists between developed (low cost) and developing (high cost) countries.

The third modeling feature that differentiates our work is that we explicitly account for emission leakages. We do so by modeling a general damage function that includes both the linear and quadratic forms. We capture the lack of leakages by assuming linear damages, and the presence of leakages by assuming quadratic damages.

[4]One might argue that adaptation could also have some sort of public nature. See, for example, Mendelsohn (2000) who distinguishes private and public adaptation, and shows that the level of private adaptation is efficient, while joint adaptation may be under-provided.

We define a country's payoff as the difference between benefits from emissions and the sum of environmental damages and adaptation costs. Each country's production activities generate a global pollutant, which benefits each country privately while simultaneously damaging all countries. A country can offset these damages by choosing individual adaptation levels. We capture the expenditure in adaptation with an increasing cost function. Then, countries simultaneously choose emission and adaptation levels to maximize their own payoff given others' strategies.

Within this context, we find several surprising results. In contrast to previous work, our results suggest that cross-country differences in adaptation may discourage countries from joining coalitions when there is no carbon leakage, while these cross-country differences may enhance the incentives to join IEAs with leakages. In the absence of leakages, the puzzle of small coalitions holds and adaptation leaves the participation incentives unchanged. This result implies that, in absence of leakages, policies directed at reducing the cross-country gap in adaptation costs are unconducive to the success of IEAs. When there are leakages, however, the existence of adaptation breaks the puzzle of small coalitions, even when all countries differ in adaptation costs. These results suggest that coalition formation is highly sensitive to the possibility for adaptation and to the existence of leakages. Therefore, policies directed at reducing the gap in adaptation costs, such as the Cancún adaptation fund, and carbon leakage, such as the Clean Development Mechanism, may also affect the success and failure of IEAs.

Our paper closely relates to two main strands of the literature. First, there is a literature that studies the relationship between abatement of emissions and adaptation in climate economics, but ignore IEAs. A main goal of this literature is to better understand the relationship between abatement and adaptation as decisions to tackle environmental damages. For example, Kane & Shogren (2000) examine the optimal mix of the two measures in a one-country model while Onuma & Arino (2011) investigate how innovation in adaptation technology by a developed country may affect a developing country through changes in abatement efforts by both countries. There are also studies analyzing the n-country case. For example, Buob & Stephan (2008, 2011) develop a multi-region model where countries choose abatement and adaptation non-cooperatively.[5] Zehaie (2009) studies the importance of the timing between adaptation and emissions and Ebert & Welsch (2012) study the interactions between emissions and adaptation in a two country model. Our paper differs from prior work because we study the incentives to join IEAs in the presence of adaptation.

The second branch of the literature is extensive and studies the individual incentives to join IEAs and the stability of those agreements. Finus (2003) provides an excellent review of this literature.[6] These studies, however, ignore adaptation. Our paper contributes to this broader literature as it is among the first to study adaptation within the context of IEAs. By doing so, we can examine additional challenges to the success and failure of IEAs.

The remainder of the paper unfolds as follows. In Section 2, we present a model with heterogeneous adaptation costs. In Section 3, we present the polar cases of non-cooperative and cooperative behaviors. In Section 4, we examine coalition formation and the stability of IEAs. Finally, Section 5 concludes.

2 The Model

We consider a world economy with n countries. Countries emit a global pollutant as a result of their consumption and production activities. We denote e_i as the emission level of country i where $i \in N = \{1, 2, ..., n\}$, and $E = \sum_{i=1}^{n} e_i$ are total emissions. Countries can adapt

[5] Buob & Stephan (2011) study the strategic interaction between emissions and adaptation in a non-cooperative game between different regions, assuming that emissions and adaptation are perfect substitutes. In Buob & Stephan (2008) they use a non-cooperative Nash game to analyze whether funding adaptation is incentive compatible in the sense that it stimulates abatement of emissions.

[6] See also Hoel & Schneider (1997), Eyckmans & Tulkens (2003), and Petrosjan & Zaccour (2003), and more recently, Rubio & Ulph (2006, 2007), McGinty (2007), de Zeeuw (2008), Breton et al. (2010) and Nkuiya (2012).

to offset the effects of pollution and reduce their country-specific environmental damages. We denote a_i as the adaptation level of country i where $i = 1, 2, ...n$. We think of a_i as effective adaptation, which reflects both the level of the adaptation effort and the efficiency of the adaptation technology. The key difference between emissions and adaptation lies in the public nature of pollution and the private nature of adaptation. While global pollution is a global public bad, adaptation is a private decision with country-specific implications. Our paper focuses on this key difference since it changes each country's incentive to join coalitions.

Each country's welfare (i.e., payoff) consists of benefits, damages, and costs. Each country simultaneously chooses their emissions and adaptation levels to maximize their payoff.[7] Benefits depend on each country's individual emissions since it is a by-product of production and consumption. Global pollution damages all countries while each has the option to reduce damages through adaptation. Finally, adaptation is costly for each country. Formally, we define country i's payoff as:

$$W\left(e_i, a_i, E\right) \equiv B\left(e_i\right) - D(E, a_i) - C^j(a_i), \tag{1}$$

where $B\left(e_i\right)$ is benefits from emissions described in (2), $D(E, a_i)$ is damages from pollution in (3) and $C^j(a_i)$ is the cost of adaptation in (4).

First, we consider the benefit function, which is identical across countries. Country i's benefit from polluting is:

$$B\left(e_i\right) \equiv e_i\left(\alpha - \beta\frac{e_i}{2}\right), \tag{2}$$

where α and β are positive parameters. We necessarily have $0 < e_i < \alpha/\beta$ to guarantee non-negative marginal benefit and $0 < E < n\alpha/\beta$ since all countries are identical.

[7]Our approach draws from Zehaie (2009) and Ebert & Welsch (2012) who find that the sequential (ex-post adaptation) and simultaneous games are equivalent.

Second, the damage function for country i is:

$$D(E, a_i) \equiv (\omega - a_i)\, E^{\eta}/\eta, \tag{3}$$

where $\omega > 0$ is a damage parameter from total pollution.[8] Parameter $\eta \geq 1$ captures the curvature of the damage function which allows us to consider a continuum of cases, including linear and quadratic damage functions. This is in contrast to others who consider either the linear or the quadratic case. We account for the curvature of the damage function to study cases with no-leakages (linear) and leakages (non-linear) in emissions among countries. We highlight three characteristics from equation (3). First, the marginal damage from emissions, $\frac{\partial D(E,a_i)}{\partial e_i} = \frac{\partial D(E,a_i)}{\partial E} = (\omega - a_i)E^{\eta-1} \geq 0$, is decreasing in adaptation a_i. Second, a country's damage decreases in its level of adaptation, $\frac{\partial D(E,a_i)}{\partial a_i} = -E^{\eta}/\eta \leq 0$. Third, the marginal benefit from adaptation is increasing in total emissions, $\frac{\partial^2 D(E,a_i)}{\partial a_i \partial E} = -E^{\eta-1} \leq 0$.

Third, the adaptation cost function for county i, of type j, features diminishing returns to scale and is increasing in the level of adaptation:

$$C^j(a_i) \equiv \frac{c^j}{2}\,(a_i)^2\,, \quad j = H, L, \tag{4}$$

where c^H and c^L are two positive parameters satisfying $c^L < c^H$. While global emissions damage all countries equally, we include heterogeneous adaptation costs across countries. We allow countries to be identical within each group but differ across groups in their adaptation cost. We consider two types of countries: high (H) and low (L) adaptation cost where n^H and n^L denote the number of each type such that they add up to the total number of countries $n = n^L + n^H$.

In the next section we analyze and compare the polar cases where the decision to join an

[8] Some might argue that global pollution affects countries differently. We abstract from this effect without loss of generality to concentrate on the importance of heterogeneity in adaptation costs and its implications for the stability of IEAs.

IEA is exogenous. The partial equilibrium analysis follows in section 4 where the decision to join a coalition is endogenous.

3 Polar cases

This section presents the cooperative and non-cooperative emission strategies, and in section 3.3, we compare them to previous results in the IEA literature where adaptation is mainly ignored. In the subsequent sections, we denote subscripts n and c to represent the non-cooperative and cooperative equilibrium outcomes to simplify notation.

3.1 Non-cooperative outcome

Country i simultaneously chooses its emission and adaptation levels to maximize its own payoff taking as given the emission and adaptation choices of all other countries.[9] Formally, country i solves

$$\max_{\{e_i,a_i\}} W\left(e_i, a_i, E\right), \tag{5}$$

where $W\left(e_i, a_i, E\right)$ is given in (1).

The first-order conditions for emissions (e_i) and adaptation (a_i) are:

$$\alpha - \beta e_n^j = (\omega - a_n^j)(E_n)^{\eta-1}, \quad j = L, H \tag{6}$$

$$\frac{(E_n)^\eta}{\eta} = c^j a_n^j \quad j = L, H. \tag{7}$$

Condition (6) indicates that each country chooses its equilibrium emission level so as to

[9]The question of timing is inapplicable in our setting since the sequential (ex-post adaptation) and simultaneous games are equivalent. Note that the irrelevance of timing between emissions and adaptation only holds when adaptation happens after emissions in the sequential game. If a country chooses to adapt before polluting, the irrelevance of timing no longer holds. In our paper, we abstract from the possibility that countries would choose to adapt before polluting, and therefore, the irrelevance of timing shown by Zehaie (2009) holds. Therefore, the results of our simultaneous game are equivalent to those of a sequential game where countries choose adaptation after emissions.

equate its marginal benefit and its marginal damage from polluting. Condition (7) shows that in equilibrium, the marginal benefit and the marginal cost of adaptation are equal. Using conditions (6) and (7), we derive the best-response functions:

$$e_n^j = \frac{1}{\beta}\left(\alpha - (\omega - a_n^j)(E_n)^{\eta-1}\right), \quad j = L, H \tag{8}$$

$$a_n^j = \frac{(E_n)^\eta}{c^j \eta}, \quad j = L, H. \tag{9}$$

Substituting (9) into (8) yields emission levels as a function of total emissions for both types of countries:

$$e_n^L = \frac{1}{\beta}\left(\alpha + \frac{(E_n)^{2\eta-1}}{\eta c^L} - \omega(E_n)^{\eta-1}\right), \tag{10}$$

$$e_n^H = \frac{1}{\beta}\left(\alpha + \frac{(E_n)^{2\eta-1}}{\eta c^H} - \omega(E_n)^{\eta-1}\right). \tag{11}$$

Using (10) and (11) and the fact that $E_n = n^L e_n^L + n^H e_n^H$, the level, E_n, that solves the following equation is the non-cooperative level of total emissions:

$$\eta(\beta E_n - n\alpha) = (E_n)^{\eta-1}\left[-n\eta\omega + \left(\frac{n^L}{c^L} + \frac{n^H}{c^H}\right)(E_n)^\eta\right]. \tag{12}$$

This result allows us to fully characterize the emission and adaptation levels of the non-cooperative equilibrium. Indeed, the total emission level $E_n \in (0, n\alpha/\beta)$ is the unique positive solution of (12). Also, given E_n, country emission and adaptation levels are given in (8) and (9). As expected, condition (9) suggests that countries with a low cost of adaptation choose to adapt more than countries with a high cost of adaptation.

3.2 Full cooperative outcome

All countries choose their emission and adaptation levels under the full cooperation outcome to maximize joint payoff. Formally:

$$\max_{\{e_i,a_i\}_{i\in N}} \sum\nolimits_{i=1}^{n} W\left(e_i, a_i, E\right), \tag{13}$$

where $W(e_i, a_i, E)$ is given in (1).

The first-order conditions for emissions and adaptation are:

$$\alpha - \beta e_c^j = \left(n\omega - \sum_{j=L}^{H} n^j a_c^j\right)(E_c)^{\eta-1}, \quad j = L, H, \tag{14}$$

$$\frac{(E_c)^\eta}{\eta} = c^j a_c^j, \quad j = L, H. \tag{15}$$

Condition given by (14) indicates that when all countries cooperate, the marginal benefit from emissions equals the sum of the marginal damages from polluting. Equation (14) is the Samuelson (1954) condition for the provision of public goods, which in this case, is global environmental quality. Condition (15) states that the private marginal benefit and cost from adaptation should be equated. From conditions (14) and (15), we derive the best-response functions:

$$e_c^j = \frac{1}{\beta}\left[\alpha - \left(n\omega - \left(\sum_{j=L}^{H} n^j a_c^j\right)\right)(E_c)^{\eta-1}\right], \quad j = L, H, \tag{16}$$

$$a_c^j = \frac{(E_c)^\eta}{\eta c^j}, \quad j = L, H. \tag{17}$$

We substitute equation (17) into (16) and using $E_c = n^L e_c^L + n^H e_c^H$ we derive:

$$\eta\left(\beta E_c - n\alpha\right) = n\left(E_c\right)^{\eta-1}\left[-n\eta\omega + \left(\frac{n^L}{c^L} + \frac{n^H}{c^H}\right)(E_c)^\eta\right]. \tag{18}$$

These calculations allow us to fully characterize the emission and adaptation levels of the cooperative setting. Since countries have the same marginal benefit and marginal damage from pollution, they emit at the same level, even if they differ in adaptation costs. Furthermore, they fully internalize the negative global externality. Both a low and high cost country's emission levels are given in (16), while the differences among countries arise in their adaptation. For both country types, adaptation levels are given in (17). As expected, low cost countries always adapt more than high cost countries since the marginal cost to adapt is larger for a high cost country. At the aggregate level, total emissions, $E_c \in (0, n\alpha/\beta)$, are the unique positive root of (18).

In the next section, we investigate the role of carbon leakage in two polar cases.

3.3 Leakage vs no leakage

We first analyze the implications of carbon leakage. We consider two cases: linear and non-linear damages (equation (3)). Recall that in absence of adaptation ($a_i = 0$ in (3)-(4)), we know from the IEA literature that there are no leakages in emissions among countries when damages are linear ($\eta = 1$) because the best-response functions are orthogonal. With non-linear damages ($\eta > 1$), however, there exist leakages in emissions among countries since the best-response functions are downward slopping. From the best-response functions in equation (16), we confirm that the existence (and lack) of leakages remains as before even when we introduce adaptation into the IEA model (i.e. for linear case $\frac{\partial e_i}{\partial e_{-i}} > 0$, and for non-linear, $\frac{\partial e_i}{\partial e_{-i}} < 0$). With linear damages and adaptation, there are no leakages since the best-response functions become upward slopping while with non-linear damages, there are leakages in emissions because their best-response function remain downward sloping (eqs. (8)-(9)).

We compare the polar cases (cooperative and non-cooperative) in three propositions. First, we examine the strategic relationship between emissions and adaptation from the optimality conditions in (8) and (9).

Proposition 1. *The strategic relationship between emissions and adaptation depends on the existence of carbon leakage. In absence of leakage, emissions and adaptation are strategic complements in equilibrium while with leakages, they can be either complements or substitutes.*

Proof. We substitute E_n from (9) into (8) and we then differentiate individual emissions with respect to adaptation:

$$\frac{\partial e_n^j}{\partial a_n^j} = \frac{c^j\left(\omega - a_n^j\right)(1-\eta) + a_n^j \eta}{\beta\left(a_n^j c^j \eta\right)^{\frac{1}{\eta}}}. \tag{19}$$

When damages are linear ($\eta = 1$), equation (19) is always positive. However, with non-linear damages ($\eta > 1$), the sign depends on the magnitude of adaptation, costs and damages. This relationship also holds for the cooperative case using equations (16) and (17). ■

The strategic complementarity between emissions and adaptation describes how the incentives to emit relate to the possibilities to adapt. When there is no leakage, a country will increase its own emissions when others increase theirs since the best-response functions are upward sloping. As a result, the only available possibility to reduce damages is to adapt more. Conversely, when other countries emit less, a country will react by emitting less, which reduces the need to adapt. This mechanism establishes the strategic complementarity between emissions and adaptation under the no-leakage scenario. In the presence of leakage, however, a country reduces its own emissions when others increase theirs since the best-response functions are downward sloping. As a result, the need to adapt is reduced. Conversely, when other countries emit less, a country will react by emitting more, which leaves adaptation as the only option to reduce damages. In sum, the relationship between emissions and adaptation depends on the magnitude of adaptation and emissions, where these two variables could exhibit complementarity or substitutability.

Next, we compare total emissions in the two polar cases. We begin with the case of no leakage, ($\eta = 1$ in equation (3)), and calculate total emissions for the non-cooperative and cooperative cases. First, solving equation (12), we obtain total emissions for the non-cooperative case:

$$E_n = \frac{n(\alpha - \omega)}{\beta - \left(\frac{n^H}{c^H} + \frac{n^L}{c^L}\right)}. \tag{20}$$

Second, solving for (18), we obtain total emissions for the cooperative case:

$$E_c = \frac{n(\alpha - n\omega)}{\beta - n\left(\frac{n^H}{c^H} + \frac{n^L}{c^L}\right)}. \tag{21}$$

An interior solution where countries generate non-negative levels of emissions requires the following two existence conditions:[10]

$$\alpha > n\omega \quad , \tag{22}$$

$$\beta > n\left(\frac{n^H}{c^H} + \frac{n^L}{c^L}\right). \tag{23}$$

We compare total emissions in the two polar cases using equations (20) and (21). In the absence of adaptation, a global agreement to reduce pollution always leads to lower total emissions than the case with no agreement because countries internalize the negative externality of polluting. This result also holds when we introduce the possibility adapt and cost heterogeneity in adaptation costs. We summarize this result in proposition 2.

Proposition 2. *When there is a possibility to adapt and there is no leakage, total emissions are lower under full cooperation than under non-cooperation in emissions abatement. Furthermore, countries adapt more under non-cooperation.*

[10]We derive these two existence conditions substituting equation (12) into equation (10) and equation (21) into equation (16) in the linear case ($\eta = 1$)

Proof. See the Appendix. ■

Next, we analyze the effects of carbon leakage in total emissions ($\eta > 1$ in equation (3)).

Proposition 3. *When there is a possibility to adapt and there is leakage, total emissions are lower under full cooperation than under non-cooperation in emissions abatement. Furthermore, countries adapt more under non-cooperation.*

Proof. See the Appendix. ■

This result is consistent with the literature on transboundary pollution and holds because the marginal cost of emitting in the fully cooperative setting is larger than in the non-cooperative equilibrium. This is the case because the presence of adaptation does not change the negative sign of the slope of the best-response emissions function. As such, the disincentive to emit is larger under full cooperation. Following the same reasoning, with full cooperation, countries adapt less.

4 Coalition formation and stability

In this section, we examine the incentives to voluntarily join a coalition and the stability of such self-enforcing agreement. This IEA is a two-stage game. In the first stage (the membership game), countries decide unilaterally whether to ratify the treaty. In the second stage, signatory countries decide jointly the emission level that maximize their aggregate payoff, while non-signatory countries choose the individual emissions to maximize their own payoff. In the second stage, every country also decides their adaptation level. Our game follows the Cournot approach when choosing emissions and adaptation. We solve this game by backward induction starting from the second stage.

We denote k^L and k^H as the number of low and high cost signatory countries. Then, the total number of countries that join the IEA is $k = k^L + k^H$ while $n - k$ countries choose to stay out of the coalition. We first analyze the incentives to emit and adapt of non-signatory countries (denoted ns). A non-signatory country i solves:

$$\max_{\{e_i,a_i\}_{i\in N\setminus S}} W\left(e_i, a_i, E\right), \tag{24}$$

where $N\backslash S$ is the set of non-signatory countries. We derive the best-response functions for emissions and adaptation from the fist-order condition:

$$e^j_{ns} = \frac{1}{\beta}\left(\alpha - (\omega - a^j_{ns})(E)^{\eta-1}\right), \quad j = L, H \tag{25}$$

$$a^j_{ns} = \frac{(E)^\eta}{\eta c^j}. \quad j = L, H \tag{26}$$

Second, we derive the emission and adaptation strategies of signatory countries (denoted s). Signatory countries solves:

$$\max_{\{e_i,a_i\}_{i\in S}} \sum\nolimits_{i\in S} W\left(E, a_i\right), \tag{27}$$

where S represents the set of signatory countries. The best-response functions of emissions and adaptation are:

$$e^j_s = \frac{1}{\beta}\left(\alpha - (k\omega - k^L a^L_s - k^H a^H_s)(E)^{\eta-1}\right), \quad j = L, H, \tag{28}$$

$$a^j_s = \frac{(E)^\eta}{\eta c^j}, \quad j = L, H. \tag{29}$$

Next, we calculate total emissions for non-signatory and signatory countries. Total emissions from non-signatories are E_{ns}. Using equation (25), combined with the fact that $E_{ns} = (n^L - k^L)e^L_{ns} + (n^H - k^H)e^H_{ns}$, we get:

$$E_{ns} = \frac{1}{\beta}\left[(n-k)\alpha - \left((n-k)\omega - \frac{n^L - k^L}{\eta c^L}(E)^\eta - \frac{n^H - k^H}{\eta c^H}(E)^\eta\right)(E)^{\eta-1}\right]. \tag{30}$$

Likewise, using equation (28) along with the fact that total emissions by signatories satisfy $E_s = k^L e^L_s + k^H e^H_s$, we obtain:

$$E_s = \frac{1}{\beta}\left[k\alpha - \left(k^2\omega - \frac{kk^L}{\eta c^L}(E)^\eta - \frac{kk^H}{\eta c^H}(E)^\eta\right)(E)^{\eta-1}\right]. \tag{31}$$

Now, we calculate total emissions summing (30) and (31). After rearranging terms, we find that total emissions (E) are the positive root of the equation:

$$\eta(\beta E - n\alpha) = (E)^{\eta-1}\left[-\left(n-k+k^2\right)\eta\omega + \left(\frac{n^L + k^L(k-1)}{c^L} + \frac{n^H + k^H(k-1)}{c^H}\right)(E)^{\eta}\right]. \tag{32}$$

Notice that for $k^L = k^H = 0$ or $k^L + k^H = 1$, (32) yields exactly relation (12), characterizing total emissions obtained under the non-cooperative equilibrium. For $k^L = n^L$ and $k^H = n^H$, (32) becomes (18), characterizing total emissions for the cooperative setting. The equilibrium level of total emissions $E \in (0, n\alpha/\beta)$ is a root of (32). Given this result, the adaptation level of a non-signatory and a signatory are given in (26) and (29). Also, given adaptation, the emission level of a non-signatory and a signatory are given in (25) and (28). From these equations, we derive the following proposition.

Proposition 4. *All signatory countries choose the same emission level while non-signatory countries emit depending on their adaptation cost.*

Proof. For signatories, equilibrium emissions in equation (28) are independent of the cost type. For non-signatories, however, equilibrium emissions in equation (25) depend on the adaptation cost type. ■

Our results in proposition 4 describe country incentives to emit for a given coalition size. We find that all countries within the agreement emit equally while countries outside of the coalition behave as singletons. The non-signatory countries act in their own self interest and emit according to their adaptation cost as in the pure non-cooperative case. We explore adaptation next.

Proposition 5. *Adaptation in equilibrium is a dominant action and independent of a country's IEA membership decision.*

Proof. From equilibrium outcomes in equations (26) and (29) for non-signatories and signatories, a country's adaptation level is determined by total emissions while not by its individual emissions. ■

Proposition 5 suggests that countries choose the same level of adaptation independently of their IEA membership decision. This results is driven by the private good nature of adaptation.

Proposition 6. *The presence of adaptation does not nullify the abatement of emissions function of the IEA.*

Proof. Using (25) and (28) along with the facts that $\omega \geq a_s^j$, and $\omega \geq a_{ns}^j$, we get

$$e_{ns}^j - e_s^j \geq \omega(k-1) + a_{ns}^j + k\omega > 0.$$

Therefore, a non-signatory country always emits more than a signatory country. ■

This result, which is in line with the established IEA literature, describes that the presence of adaptation is not a limiting factor in the role of a climatic coalition. Some argue against placing efforts into adaptation, fearing diminished willingness to abate within environmental agreements.[11] Contrary to this belief, our results suggest that the presence of adaptation does not obstruct the success of IEAs at reducing emissions within the coalition.

4.1 Stability conditions

Next, we study the incentives to ratify an IEA. We follow the stability concept first introduced by d'Aspremont et al. (1983). A coalition is stable when both the internal and external stability conditions hold. Internal stability indicates that no country inside of the coalition has incentives to leave the coalition while external stability means that no country outside of the coalition has incentives to join the coalition. The internal stability conditions for low

[11] See for example the article *"Dutch defense against climate change: Adapt"* published in The Washington Post in 2009.

and high cost countries are:

$$W_s^L\left(k^L, k^H\right) \geq W_{ns}^L\left(k^L - 1, k^H\right), \tag{33}$$

$$W_s^H\left(k^L, k^H\right) \geq W_{ns}^H\left(k^L, k^H - 1\right), \tag{34}$$

and, the external stability conditions for low and high cost countries are:

$$W_{ns}^L\left(k^L, k^H\right) \geq W_s^L\left(k^L + 1, k^H\right), \tag{35}$$

$$W_{ns}^H\left(k^L, k^H\right) \geq W_s^H\left(k^L, k^H + 1\right). \tag{36}$$

We calculate the incentives to deviate by looking at the payoff of each country. For a given coalition size, $k = k^L + k^H$, the net payoff of a signatory and a non-signatory of type j are:

$$W_s^j(k^L, k^H) = e_s^j(\alpha - \frac{\beta}{2}e_s^j) - (\omega - a_s^j)\frac{E^\eta}{\eta} - \frac{1}{2}(a_s^j)^2, \tag{37}$$

$$W_{ns}^j(k^L, k^H) = e_{ns}^j(\alpha - \frac{\beta}{2}e_{ns}^j) - (\omega - a_{ns}^j)\frac{E^\eta}{\eta} - \frac{1}{2}(a_{ns}^j)^2, \tag{38}$$

where $e_s^j, e_{ns}^j, a_s^j, a_{ns}^j$, and E are defined in Equations (25), (26), (28), (29), and (32). Using this result along with $e_{ns}^j > e_s^j$ and $a_{ns}^j = a_s^j$, we compare the net payoff of countries with the same cost of adaptation inside and outside of the the agreement. Comparing equations (37) and (38), we find that low (high) adaptation cost countries who agree to join the coalition always gains less (more) than the countries of the same type who chooses to stay out of the coalition. This result provides a complementary reason why many countries have incentives not to ratify IEAs.

We summarize these stability conditions using a stability function for low and high cost countries following the approach by Hoel & Schneider (1997) and Nkuiya et al. (2014):[12]

$$\phi^L\left(k^L, k^H\right) = W_s^L(k^L, k^H) - W_{ns}^L(k^L - 1, k^H), \tag{39}$$

$$\phi^H\left(k^L, k^H\right) = W_s^H(k^L, k^H) - W_{ns}^H(k^L, k^H - 1). \tag{40}$$

When the conditions $\phi^j\left(k^L, k^H\right) \geq 0,\ j = L, H$ hold, the coalition $\left(k^L, k^H\right)$ is internally stable. When the conditions $\phi^L\left(k^L + 1, k^H\right) \leq 0$, and $\phi^L\left(k^L, k^H + 1\right) \leq 0$ hold, the coalition $\left(k^L, k^H\right)$ is externally stable.

4.2 Stability analysis

We consider four cases in the analysis of stability conditions. First we consider both identical and different adaptation costs when there is no carbon leakage. The last two cases concern leakages with identical and different adaptation costs.

4.2.1 Lack of carbon leakage

Identical adaptation costs

We start out with the case where all countries have identical adaptation costs *i.e.*, $c^L = c^H = c$. We do so to better understand how cost heterogeneity in adaptation affects the stability of the IEA in the next section. In the following proposition we present the result of the identical cost case.

Proposition 7. *A stable coalition of a maximum of three countries can arise when all countries have identical adaptation costs and there are no leakages among them.*

Proof. See the Appendix. ■

In proposition 7, we show that in the presence of the adaptation, the puzzle of small coalition persists. This is consistent with the IEA literature where adaptation is ignored.

[12] Following the norm in this literature, we restrict our attention to the largest stable coalition size that arises.

Indeed, in a Cournot IEA game with linear damages, the maximum number of countries in a stable coalitions is three (see, for example, Finus, 2003). Hence, the presence of adaptation does not change the incentives to participate in a coalition.

Differences in adaptation costs

Next, we explore the effect of cross-country differences in adaptation costs. This is consistent with the evidence showing cross-country heterogeneity in adaptation costs. For example, World-Bank (2011) presents extensive evidence of such heterogeneity between developed and developing countries.

We calculate the stability of an agreement using numerical simulations. We do so because analytical solutions cannot be derived since the equilibrium solutions are implicit. Our simulations constrain the set of parameter values such that both the non-negativity of emissions ($e_i > 0$) and no over-adaptation ($\omega > a_i$) hold. We first select a set of parameter values, and second, we study how sensitive our results are to changes in those values. We consider $n = 100$ countries where half are low cost countries. For the benefit function in equation (2), we choose a combination of α and β parameters such that the slope is larger than the intercept of the marginal benefit from emissions, i.e. $\alpha < \beta$. For example, $\alpha = 2.9$ and $\beta = 223$. In the damage function in equation (3), global pollution affects every country at the same amount and equals $\omega = 0.029$. For adaptation cost, we choose initial parameter values such that low and high costs are $c^L = 44.5$ and $c^H = 45$, i.e., $c^L < c^H$.[13] The following proposition summarizes our stability result.

Proposition 8. *The puzzle of small coalitions holds with heterogeneity in adaptation costs and no leakage.*

The maximum stable coalition size is equal to three in line with the case with symmetry

[13]These parameter values are robust. We carry out sensitivity analyses to study the robustness of our main results using simulations. First, we examine the implication of group size asymmetry on coalition stability. To do so, we fix the total number of countries at $n = 100$ while we study the effect of variation in group sizes. Our results suggest that the incentive to ratify the treaties are also unaffected by the group size asymmetry. Our variations consider cases with $n^L, n^H \in [2, 98]$.

in adaptation cost in proposition 7. These two propositions, (7) and (8), contribute to a better understanding of the role of adaptation and the lack of leakage in the success and failure of IEAs. The possibility to adapt does not change the incentives to join an IEA. This result is in contrast to Marrouch & Chaudhuri (2011) who find that the grand coalition can be an equilibrium outcome in a Stackelberg game. Unfortunately, the chances to increase the size of the coalition are unchanged when there are cross-country differences in adaptation costs (proposition 8).

Our propositions 7 and 8 have some policy implications. We find that the key to change the participation incentives relates to leakages instead of adaptation costs since the presence of adaptation does not change participation incentives. This result implies that, in the absence of leakages, policies directed at reducing the cross-country gap in adaptation costs are unconducive to the success of IEAs. In the next section, we study the relevance of leakages for the incentives to participate in IEAs.

4.2.2 Existence of carbon leakage

We now turn to the case with leakages, which is particularly interesting since leakages among countries may enhance participation. Following the existing literature, we consider the widely used quadratic damage function ($\eta = 2$) as an example of the non-linear case.

Identical adaptation costs

For completeness of the analysis, we analyze the stability conditions when countries have identical adaptation costs before we turn to cost heterogeneity in the next section. We derive our results using a numerical exercise as before. Our choice of values is: $n = 100$ countries, $\alpha = 2.9$ and $\beta = 223$, $\omega = 0.029$ and $c = 45$. As before, we conduct a sensitivity analysis for all these values and confirm the robustness of our results. We summarize our results in the following proposition.

Proposition 9. *The predominance of the puzzle of small coalitions breaks in the presence of adaptation and leakages in emissions.*

Our result in proposition 9 departs from previous work. With quadratic damages and in a Cournot game, the maximum number of countries that join a stable coalition is two (see, for example, Finus, 2003). In contrast, we find stable equilibria where there are at least three countries who join an IEA. This result implies that the existence of adaptation enhances the incentives to join an IEA. The intuition behind this result is as follows. With leakages in emissions, a country's response to more emissions by others is to reduce its own emissions since the best response functions are downward slopping (eqs. (25) and (28)). Moreover, the possibility to adapt makes these best response functions flatter (Benchekroun et al., 2011). This implies a lower willingness to reduce emissions when other countries increase theirs. This willingness yields a higher number of countries interested in joining an IEA relative to the case without adaptation.

Differences in adaptation costs

Now that we understand the pure contribution of adaptation to the stability of IEAs, we explore how cost heterogeneity affects participation incentives. We do so using numerical simulations. Our numerical values are as before, except that we add cost heterogeneity. The parameter values are: $n = 100$ countries, $n_L = 50$, $n_H = 50$ $\alpha = 2.9$ and $\beta = 223$, $\omega = 0.029$, $c_L = 44.5$ and $c_H = 45$. We summarize our numerical result in the following proposition.

Proposition 10. *The predominance of the puzzle of small coalitions breaks with cost heterogeneity in adaptation and leakages in emissions.*

In contrast to others, we find that there exist incentives to break the puzzle of small coalitions, even when countries differ in adaptation costs. This implies that leakages, in the presence of adaptation, not only encourage IEA participation, but also that cost heterogeneity does not undermine IEA participation. In fact, there are even cases in which the grand coalition is stable. For example, we find that all countries could join an IEA when parameter values are: $n = 20$ countries, $n_L = 10$, $n_H = 10$ $\alpha = 0.1$ and $\beta = 1500$, $\omega = 0.0000001$, $c_L = 14$ and $c_L = 16$. The stability of this grand coalition, however, is sensitive to changes in the total number of countries and parameter values in the benefit function (α and β).

Some might worry that cross-country differences in adaptation costs might weaken the incentives to join an IEA on the basis that the provision of adaptation is a private good. However, our results suggest that cross-country differences might strengthen IEA participation. The possibility to encourage participation even with cross-country differences is an optimistic result. The intuition is as follows. Cross-country differences yield higher emissions relative to the identical countries case. Therefore, there are stronger incentives to participate since the gain from an agreement in emissions abatement is larger.

Table 1: Coalition formation with heterogeneity in adaptation costs

	Identical adaptation costs	Different adaptation costs
No leakages ($\eta = 1$)	Puzzle of small coalition	Puzzle of small coalition
Leakages ($\eta = 2$)	Break puzzle of small coalition	Break puzzle of small coalition

To sum up, we summarize all stability results in table 1. Our most striking result arises when we compare the cases without carbon leakage and with leakage. In the absence of leakages, adaptation is not enough to increase the incentives to participate since countries have the option to reduce their damages with adaptation. However, with leakages, adaptation is no longer enough to compensate for global damages, and hence, the incentives to participate in an agreement increase. Furthermore, the incentives to participate are stronger the more heterogeneity exists among countries. These results imply that the success and failure of policies directed at encouraging participation depend on the magnitude of leakages. For example, a policy directed at reducing the cost gap in adaptation, such as the Cancún Fund, could be unsuccessful at increasing participation.

5 Conclusion and policy implications

In this paper we examine how adaptation affects countries' incentives to ratify IEAs. In particular, we study the impact of cross-country differences in adaptation costs and the role of leakages on participation incentives. In this setting, our results suggest that adaptation is unsuccessful at encouraging participation without leakages while successful with leakages. Furthermore, we find that cost heterogeneity in adaptation costs could strengthen the incentives to join a coalition when there are leakages among countries.

In our paper, countries' choice of emissions and adaptation are complements without leakages. This means that a country has stronger incentives to emit when the cost of adapting is low. With leakages, however, the strategic relationship depends on the magnitude of adaptation, costs and damages. While this relates to some's fears regarding high pollution as a consequence of low adaptation costs, our results suggest that the possibility to adapt does not necessarily limit a country's incentives to voluntarily reduce emissions within a climate coalition. In fact, we find that the role of adaptation in coalition formation is highly dependent on the the existence of leakages. In fact, we find stronger incentives to join a coalition to reduce emissions when countries generate leakages and have the option to adapt.

Our results have relevant implications for policies directed at reducing the gap in adaptation costs among developed and developing countries. For example, the Cancún Adaptation Fund,[14] established in 2010 to reduce the technological gap that exists between developed (low cost) and developing (high cost) countries. We find that cost heterogeneity in adaptation is associated with higher participation in IEAs. Hence, a policy directed at reducing

[14]More information regarding the Funds is available at `https://www.adaptation-fund.org/`.

the cost gap in adaptation should also consider that the incentive to join a coalition might be altered when heterogeneity decreases.

Our results also have implications for policies directed at regulating leakages. Since our analysis suggests the existence of stronger incentives to join a coalition with leakages, policies directed at reducing the leakage among countries could reduce the incentives to form a coalition to reduce emissions. For example, some argue in favor of the Clean Development Mechanism to reduce carbon leakage (see, for example, Kallbekken, 2007). In our setting, such a policy could weaken the incentives to join a coalition.

Our discussion should not be interpreted as criticism *per se* against existing international climate policies, such as the Cancún Adaptation Fund or the Clean Development Mechanism. Instead, we draw attention to how such policies may change the incentives to form large coalitions. Our results suggest that heterogeneity among countries encourage coalition formations, and hence, policies directed at reducing these heterogeneities could create barriers for coalition formation.

Finally, we summarize some of the limitations of our study and we make suggestions for further research. First, we assumed that the effect of pollution, (ω) is identical for all countries. While it is likely that global emissions affect each country differently, we chose to abstract from this heterogeneity and concentrate on the role of cross-country differences in adaptation. An extension could be to make this effect heterogeneous. Another possible extension is to analyze transfer programs in relationship with the policies discussed above. Despite these limitations, our paper provides a complementary explanation to better understand the incentives to join IEAs.

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Appendix

Proof of proposition 2

From total emissions in the polar cases in equations (20) and (21), we derive:

$$E_n - E_c = n\,(n-1)\,\frac{\beta\omega - \alpha\left(\frac{n^H}{c^H} + \frac{n^L}{c^L}\right)}{\left(\beta - \left(\frac{n^H}{c^H} + \frac{n^L}{c^L}\right)\right)\left(\beta - n\left(\frac{n^H}{c^H} + \frac{n^L}{c^L}\right)\right)}. \tag{41}$$

Assume by contradiction that $E_n \leq E_c$. In this case, given the existence assumptions 22 and 23, equation (41) implies that:

$$\omega \leq \frac{\alpha}{\beta}\left(\frac{n^H}{c^H} + \frac{n^L}{c^L}\right). \tag{42}$$

Rearranging (42) leads us to

$$a_n^L > \frac{1}{c^L}\frac{n\omega}{\left(\frac{n^H}{c^H} + \frac{n^L}{c^L}\right)}.$$

Combining this relation with the assumption that no over adaptation is possible (*i.e.*, $a_n^L < \omega$), we get $\omega > \frac{1}{c^L}\frac{n\omega}{\left(\frac{n^H}{c^H} + \frac{n^L}{c^L}\right)}$. This implies that $E_n \leq E_c$ holds if and only if $c^L > c^H$. Since this condition is a contradiction with $c^H > c^L$, we necessarily have $E_n > E_c$.

Proof of proposition 3

We define $l(E) \equiv \eta\,(\beta E - n\alpha)$ as a function given by the left-hand sides of both equations (12) and (18). We also denote $h(E) \equiv (E_n)^{\eta-1}\left[-n\eta\omega + \left(\frac{n^L}{c^L} + \frac{n^H}{c^H}\right)(E_n)^\eta\right]$ as the right-hand side of (12) and $g(E) \equiv n\,(E_c)^{\eta-1}\left[-n\eta\omega + \left(\frac{n^L}{c^L} + \frac{n^H}{c^H}\right)(E_c)^\eta\right]$ as the right-hand side of (18). We represent these functions in Figure 1, with $\eta > 1$, where E_n is defined by the intersection between $l(E)$ and $h(E)$ while E_c is given by the intersection between $l(E)$ and $g(E)$. From the benefit function in (2), total emissions must be smaller than $B \equiv n\alpha/\beta$, which is true for both E_c and E_n as illustrated in Figure 1. Then, we necessary have $E_c < E_n$. For adaptation, since $E_n > E_c$, by conditions (9) and (17), the result follows.

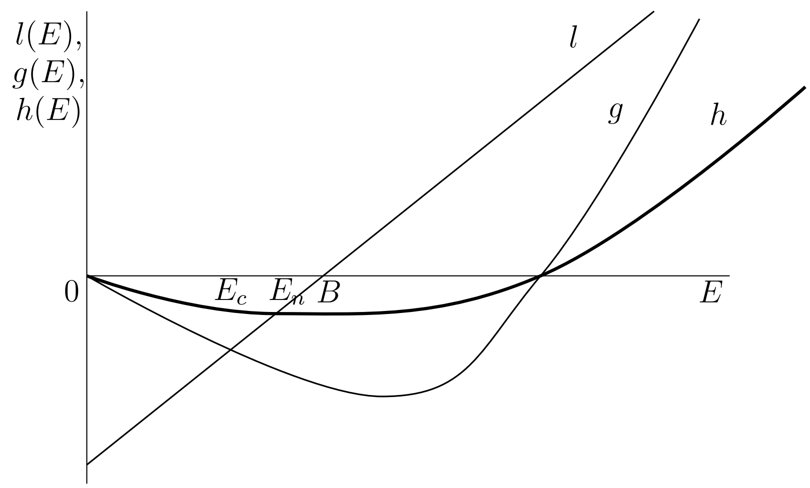

Figure 1: The comparison between E_n and E_c.

Proof of proposition 7

Consider countries with a linear damage function ($\eta = 1$) and identical adaptation costs. Then, the stability function is $\phi(k) = W_s(k) - W_{ns}(k-1)$. We re-write this stability condition as:

$$\phi(k) = \frac{(k-1)(n\alpha - c\beta\omega)^2}{2\beta\left((3k - k^2 - n + c\beta - 2)(k - k^2 - n + c\beta)\right)^2}\Omega(k,n), \tag{43}$$

where $\Omega(k,n) = (3-k)(c\beta)^2 + 2(k^3 - 4k^2 + (n+3)k - n - 2)(c\beta) - k^5 + 5k^4 - (2n+7)k^3 + (4n+3)k^2 + (2n - n^2)k - n^2$. $\Omega(k,n)$ is a second degree polynomial (in $c\beta$) with the following roots:

$$\beta_{1s} = \frac{1}{k-3}\left(3k - n + \sqrt{\Delta} + kn - 4k^2 + k^3 - 2\right), \tag{44}$$

$$\beta_{2s} = \frac{1}{k-3}\left(3k - n - \sqrt{\Delta} + kn - 4k^2 + k^3 - 2\right), \tag{45}$$

where $\Delta = -12k + 7n + kn^2 + 4k^2n - 17kn + 16k^2 - 4k^3 + n^2 + 4$.

Any coalition of size $k \geq 4$ is internally stable if and only if $\phi(k) \geq 0$. Since all terms multiplying $\Omega(k,n)$ are positive, this condition holds when $\Omega(k,n) \geq 0$. This inequality holds if and only if $c\beta \in [\beta_{1s}, \beta_{2s}]$. From assumption (23), stability requires $n^2 > c\beta$. However, this condition never holds and hence, by contradiction, any coalition of size $k \geq 4$ is not internally stable. It remains to show that a coalition of size $k = 3$ may be stable. By setting $k = 3$, we get $\Omega(3, n) = 4c\beta(n-1) - (3n^2 + 13n)$. Since $\Omega(3, n)$ is positive when $c\beta \geq (3n^2 + 13n)/4(n-1)$, we find that the maximum number of countries that can join a coalition is equal to three when this condition holds.