Environment and Development Economics 21: 812–838 © Cambridge University Press 2016
doi:10.1017/S1355770X16000097

Adaptation to climate change: how does heterogeneity in adaptation costs affect climate coalitions?

ITZIAR LAZKANO
Department of Economics, University of Wisconsin-Milwaukee. P.O. Box 413, Bolton Hall, Room 840, Milwaukee, WI 53201, USA; Department of Economics, Norwegian School of Economics, Helleveien 40, 5045 Bergen, Norway.
Email: lazkano@uwm.edu

WALID MARROUCH
Department of Economics, Lebanese American University, Lebanon; CIRANO, Canada.
Email: walid.marrouch@lau.edu.lb

BRUNO NKUIYA
Campus Saint-Jean, University of Alberta, Canada.
Email: nkuiyamb@ualberta.ca

Submitted 5 May 2015; revised 23 November 2015, 9 February 2016, 22 March 2016; accepted 19 March 2016; first published online 31 May 2016

ABSTRACT. Adaptation costs to climate change vary widely across countries, especially between developed and developing countries. Adaptation costs also influence a country's decision to abate and join international environmental agreements (IEAs). In this paper, the authors study how these cost differences affect participation incentives. Their model identifies two channels through which adaptation affects free-riding incentives: carbon leakage and cost asymmetry in adaptation. In contrast with the common view, the authors find that the presence of adaptation is not necessarily an impediment to cooperation on abatement. They also present conditions under which adaptation can strengthen or weaken free-riding incentives. The results serve as a cautionary tale to policy makers and suggest that policies directed at reducing carbon leakage and/or cost differences between developed and developing countries may also affect the success and failure of IEAs.

The authors thank Scott Barrett, Hassan Benchekroun, Amrita Ray Chaudhuri, Michael Finus, Matthew McGinty, Sebastian Ille, Linda Nøstbakken, Yutaro Sakai, the journal editor, two anonymous referees, and participants at AERE 2013, CREE 2013, Calgary Inaugural Alumni Conference 2014, Montreal Natural Resource and Environmental Economics Workshop 2014, Université de Sherbrooke and The 4th World Congress of Environmental and Resource Economists 2014 for their invaluable comments on previous versions of this paper.

1. Introduction

The United Nations Conference on Climate Change in Cancún in 2010 (COP16) and in Durban in 2011 (COP17) adopted a new approach to designing international environmental agreements (IEAs) compared to the previous Kyoto framework. This new emerging post-Kyoto framework combines the efforts of emissions abatement with adaptation. While most climate experts agree that abatement and adaptation are the two main options available 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 incentives to join a coalition. In particular, we study how cross-country differences in adaptation costs affect the incentives to join an IEA.

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). The World Bank (2011) estimates that an approximate 2°C increase in world temperatures by 2050 may require between US $70 and US $100 bn a year in adaptation costs from 2010 to 2050.[2] These adaptation costs differ widely across countries. For instance, studies find evidence of cost differences between developed and developing countries (World Bank, 2010). In addition, adaptation efforts also affect country-level mitigation.[3] For example, in many developing countries, agroforestry helps farmers adapt to climate change while also helping country-level mitigation through carbon sequestration (Verchot *et al.*, 2007; Kristjanson *et al.*, 2012; Mbow *et al.*, 2014).[4] Thus, these cross-country differences in adaptation costs and the relationships between emissions and adaptation yield new challenges in understanding countries' incentives to join climate coalitions.

Our main goal is to study how the possibility to adapt to climate change affects countries' incentives to emit and to join an IEA. To do so, we first study how a country's emissions respond to their own higher adaptation effort and how a country's emissions respond to lower emissions by other countries. Next, we analyze how cross-country differences in adaptation costs can affect these strategic relationships and the incentives to join a coalition. We address these issues within the framework of IEA membership games first introduced by Carraro and Siniscalco (1993) and

[1] The two exceptions are Benchekroun *et al.* (2011) and Marrouch and Ray Chaudhuri (2011).

[2] These findings are from 'The Economics of Adaptation to Climate Change (EACC)' study (World Bank, 2010). They also find that this amount is comparable to the current annual foreign aid from developed to developing countries.

[3] The strategic relationship between adaptation and mitigation is complex. While some argue in favor of and against the substitutability between adaptation and mitigation, others focus on the synergies between them (Tol, 2005; Ravindranath, 2007). In reality, it seems likely that the empirical relationship between adaptation and mitigation varies with time, sector and geography.

[4] Agroforestry integrates trees into crop and animal farming to enhance environmental and economic benefits.

https://doi.org/10.1017/S1355770X16000097 Published online by Cambridge University Press

Barrett (1994). In contrast to the previous literature, we explicitly model the possibility of adaptation, in addition to emissions abatement, to reduce environmental damages.

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 damages have the nature of a global public bad. However, this is distinct from adaptation. While adaptation also generates a private benefit, its costs only affect the individual country. Therefore, in our setting, a key feature is that emissions abatement has an international public good nature, while adaptation has a national private good nature.

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

The third modeling feature that distinguishes our work from others is that we consider a general damage function that can be both linear and non-linear. By doing so, we are able to show that the existence of carbon leakage, a country's response to lower emissions by other countries, is determined by adaptation costs.[5]

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 that 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 that maximize their own payoff given others' strategies.

Within this context we derive several results. First, we find that reducing the adaptation cost disparity between countries leads to higher global emissions. Secondly, the strategic relationship between emissions and adaptation effort depends on adaptation costs. Moreover, an exogenous reduction in adaptation costs can switch a substitutable relationship between emissions and adaptation to a complementary relationship. We also find that the existence of carbon leakage is determined by adaptation costs and that only some countries have carbon leakage when cost heterogeneity is large.

[5] Carbon leakage is also referred to as emissions being strategic substitutes. In this paper we refer to this relationship as carbon leakage to avoid confusion with the strategic relationship between emission and adaptation levels.

https://doi.org/10.1017/S1355770X16000097 Published online by Cambridge University Press

Furthermore, an exogenous reduction in cost disparity between countries can eliminate carbon leakage.

In the membership game, we find that the presence of adaptation is not necessarily a destabilizing factor in coalition formation. This is in contrast to the view that putting efforts towards adaptation will discourage participation in IEAs. Finally, we find that a country's incentives to join a coalition depend on how a country responds to its own adaptation and how a country responds to others' higher emissions. Since these two effects depend on adaptation costs, an exogenous reduction in adaptation costs can change the incentives to emit and join a coalition. These findings imply that policies directed at reducing the gap in adaptation costs, such as the Cancún adaptation fund, or policies directed at reducing carbon leakage, such as the Clean Development Mechanism, can help reduce the adaptation burden for less developed countries, but they might also strengthen or weaken the incentives for large environmental agreements.

Our paper closely relates to two main strands of the literature: the literature studying the strategic relationship between emissions abatement and adaptation to climate change, and the literature studying the incentives to form IEAs. A main goal of the first strand of the literature is to understand how a country's incentives to emit respond to a higher adaptation effort by the same country. Kane and Shogren (2000) examine the optimal mix of the two measures in a one-country model, while Onuma and 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. Some studies analyze the *n*-country case. Buob and Stephan (2008, 2011) develop a multi-region model where countries choose abatement and adaptation non-cooperatively.[6] Zehaie (2009) studies the importance of the timing between adaptation and emissions, and Ebert and Welsch (2012) study the interactions between emissions and adaptation in a two-country model. Our work differs from these papers because we study the incentives to join IEAs and the role of cost heterogeneity in addition to the strategic relationship between emissions abatement and adaptation effort.

The second strand of the literature is extensive and studies the incentives to join IEAs and the stability of those agreements. Finus (2003) provides a detailed review of this literature.[7] However, a common feature of these studies is that they ignore the possibility to adapt to climate change. Our paper contributes to this broader literature as it is among the first to study adaptation possibilities within the context of IEAs. By doing so, we identify

[6] Buob and 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 and 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.

[7] See also Hoel and Schneider (1997), Eyckmans and Tulkens (2003), and Petrosjan and Zaccour (2003) and, more recently, McGinty (2007) or de Zeeuw (2008).

https://doi.org/10.1017/S1355770X16000097 Published online by Cambridge University Press

that the incentives to join IEAs directly depend on adaptation costs which present new challenges to the success and failure of IEAs. We are only aware of a few studies directly analyzing adaptation possibilities in the context of IEAs. Benchekroun *et al.* (2011) study the effect of an improvement in adaptation technologies on free-riding incentives, while Marrouch and Ray Chaudhuri (2011) focus on the impact of adaptation possibilities on the stable size of IEAs. Our paper differs from these two papers in that we analyse cross-country differences in adaptation costs. This enables us to identify how these differences in adaptation costs can encourage or discourage incentives to emit and join 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 non-cooperative and cooperative cases, while section 4 analyzes the strategic relationships between emission and adaptation levels and the existence of carbon leakage. In section 5 we examine coalition formation and the stability of IEAs. Finally, section 6 concludes.

2. Model: emissions game with adaptation

We consider an n-country model where each country emits a global pollutant as a result of its consumption and production activities. We let e_i denote the emission level of country i where $i \in N = \{1, 2, \ldots, n\}$, and $E = \sum_{i=1}^{n} e_i$ are total emissions. While total emissions damage all countries, each country can offset the negative effects of pollution by abating and/or investing in adaptation. Let a_i denote the adaptation level of country i, which we think of as the flow of effective adaptation that 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 international nature of pollution and the national nature of adaptation.[8] While each country's emissions are a private decision, pollution is a global public bad that creates free-riding incentives on emissions abatement. Instead, adaptation is a private decision with country-specific benefits and costs. This distinction between the public and the private nature of emissions and adaptation is key to understanding each country's incentives to choose emissions abatement.

Each country's welfare (i.e., payoff) consists of benefits from polluting activities, emission damages and adaptation costs. Global pollution damages all countries equally, while each has the option to reduce damages through adaptation. In our model, the only source of heterogeneity between countries is the difference in adaptation costs.[9]

[8] One might argue that adaptation could also have a public nature. We abstract from this possibility because our goal is to analyse how country incentives change when private adaptation is available. 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 underprovided.

[9] We consider that countries exhibit either high or low adaptation cost and thus we abstract from full heterogeneity in adaptation costs.

https://doi.org/10.1017/S1355770X16000097 Published online by Cambridge University Press

We first consider a benefit function that is identical across countries. Country i's benefit from polluting is:

$$B(e_i) \equiv e_i \left(\alpha - \beta \frac{e_i}{2}\right), \tag{1}$$

where α and β are positive parameters.[10] The concave functional form of this benefit function is convenient to restrict the maximum level of benefits from emissions. All countries benefit equally from emissions, which implies the same production technology across countries.[11]

Next, the damage function for country i is:

$$D(a_i, E) \equiv (\omega - a_i) \frac{E^\eta}{\eta}, \tag{2}$$

where $\omega > 0$ is a damage parameter from total pollution.[12] We do not allow for over-adaptation by assuming that ω is larger than effective adaptation, i.e., $\omega > a_i$.[13] Parameter $\eta \geq 1$ captures the curvature of the damage function including the commonly used linear and quadratic damage functions. We highlight three characteristics of equation (2). 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. Secondly, a country's damage decreases in its level of adaptation, $\frac{\partial D(E,a_i)}{\partial a_i} = \frac{-E^\eta}{\eta} \leq 0$. Thirdly, the marginal benefit from adaptation is increasing in total emissions, $\frac{\partial^2 D(E,a_i)}{\partial a_i \partial E} = -E^{\eta-1} \leq 0$.

The final component of a country's payoff is the adaptation cost:

$$C^j(a_i) \equiv \frac{c^j}{2} a_i^2, \quad j = H, L, \tag{3}$$

where c^j is the cost parameter for high (H) and low (L) adaptation cost countries. A novel feature of our model is that we consider cross-country differences in adaptation costs by allowing countries to be identical within each group but to differ across groups. Let n^H and n^L denote the number of each type such that they add up to the total number of countries, $n = n^L + n^H$. Equation (3) features diminishing returns to scale in the level of adaptation.

[10] Given our payoff function, the optimal emissions level satisfies $e_i \in \left(0, \frac{\alpha}{\beta}\right)$ which implies $E \in \left(0, n\frac{\alpha}{\beta}\right)$.

[11] One might argue that countries benefit differently from emissions. Our model can be extended to incorporate differences across countries in the benefit function.

[12] 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. Note also that the assumptions of symmetry in benefits and damages are important to make our results comparable with the existing literature.

[13] This condition implies that damages from total emissions cannot be negative in equilibrium.

https://doi.org/10.1017/S1355770X16000097 Published online by Cambridge University Press

We combine these three elements in (1)–(3) to define country i's payoff as:

$$W(a_i, e_i, E) \equiv e_i\left(\alpha - \beta\frac{e_i}{2}\right) - (\omega - a_i)\frac{E^\eta}{\eta} - \frac{c^j}{2}a_i^2. \tag{4}$$

Having defined the payoff function, we analyse the polar cases in the next section.

3. Non-cooperation and full cooperation

In this section we analyse the non-cooperative and cooperative emission strategies where each country chooses emission and adaptation levels simultaneously.[14] These polar cases are used as a benchmark and to identify the strategic relationships between variables in section 4. They also clarify the stability analysis in section 5 because non-signatory and signatory countries behave like non-cooperative and cooperative countries, respectively. In the following, we derive the non-cooperative outcome.

3.1. Non-cooperation

Country i simultaneously chooses emission and adaptation levels that maximize its own payoff, taking as given all other countries' choices.[15] Formally, country i solves:

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

where $W(a_i, e_i, E)$ is given by (4). In the subsequent sections, nc and c represent the non-cooperative and cooperative cases. The first-order conditions for emissions (e_i) and adaptation effort (a_i) are:

$$\alpha - \beta e_{nc}^j = (\omega - a_{nc}^j)E_{nc}^{\eta-1}, \quad j = L, H \tag{6}$$

$$\frac{E_{nc}^\eta}{\eta} = c^j a_{nc}^j, \quad j = L, H. \tag{7}$$

Equation (6) indicates that the marginal benefits of emissions must equal the adaptation-adjusted marginal damage from polluting in equilibrium. It

[14] Zehaie (2009) and Ebert and Welsch (2012) find that the sequential (*expost* adaptation) and simultaneous games are equivalent when a country chooses emissions and adaptation.

[15] The question of timing is inapplicable in our setting since the sequential (*expost* 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.

https://doi.org/10.1017/S1355770X16000097 Published online by Cambridge University Press

also shows how a country's adaptation reduces the marginal damage from global emissions. Meanwhile, condition (7) states the equality between the marginal benefit and the marginal cost of adaptation. As shown in (7), a country's choice of adaptation depends on global emissions and its own costs.[16] In addition, condition (7) suggests that countries with a low cost of adaptation choose to adapt more than countries with a high cost of adaptation. The possibility to adapt to climate change differentiates these conditions from the well-known optimality conditions in a pure IEA membership game. Finally, condition $\beta c^j + (\eta - 1)(\omega - a^j)c^j E^{\eta-2} - E^{2(\eta-1)} < 0$ satisfies the second-order condition which helps identify the direction of the strategic relationships between variables in section 4.

From (6) and (7), we derive the implicit best-response functions that depend on global emissions. Then, substituting the implicit adaptation function into the implicit best-response function yields individual emissions as a function of global emissions:

$$e_{nc}^j = \frac{1}{\beta}\left(\alpha + \frac{E_{nc}^{2\eta-1}}{\eta c^j} - \omega E_{nc}^{\eta-1}\right), \quad j = L, H. \tag{8}$$

Finally, using (8), and the fact that $E_{nc} = n^L e_{nc}^L + n^H e_{nc}^H$ when group symmetry is applied, yields:

$$\eta(\beta E_{nc} - n\alpha) = E_{nc}^{\eta-1}\left[-n\eta\omega + \left(\frac{n^L}{c^L} + \frac{n^H}{c^H}\right)E_{nc}^{\eta}\right]. \tag{9}$$

From this equation we can solve for the non-cooperative level of total emissions E_{nc} and therefore, given (6) and (7), we can also solve for the emission and adaptation levels of the non-cooperative equilibrium.

3.2. *Full cooperation*

All countries choose emission and adaptation levels that maximize the joint payoff. Formally:

$$\max_{\{a_i, e_i\}_{i\in N}} \sum_{i=1}^{n} W\left(a_i, e_i, E\right), \tag{10}$$

where $W(a_i, e_i, E)$ is given by (4). The first-order conditions for emissions and adaptation effort are:

$$\alpha - \beta e_c^j = \left(n\omega - n^H a_c^H - n^L a_c^L\right) E_c^{\eta-1}, \quad j = L, H, \tag{11}$$

$$\frac{E_c^{\eta}}{\eta} = c^j a_c^j, \quad j = L, H. \tag{12}$$

[16] Note that adaptation is a private decision in our setup. However, if adaptation were to exhibit public good characteristics, its aggregate level would then impact the marginal benefits from adaptation in equation (7). In this paper, we abstract from such a possibility.

https://doi.org/10.1017/S1355770X16000097 Published online by Cambridge University Press

Equation (11) indicates that the marginal benefit from individual emissions equals the sum of all marginal damages from pollution minus the adaptation level.[17] Since adaptation is a private decision, equation (12) states that the private marginal benefit and the private marginal cost from adaptation must be equal, as is the case in the non-cooperative case. The second-order conditions for a maximum are given by $c^L(n^H)^2 + c^H(n^L)^2 < c^H c^L \beta$. From equations (11) and (12) we derive the implicit best-response function. Then, by substituting adaptation into this equation, we obtain:

$$e_c^j = \frac{1}{\beta}\left[\alpha - \left(n\omega - \frac{E_c^\eta}{\eta}\left(\frac{n^H}{c^H} + \frac{n^L}{c^L}\right)\right) E_c^{\eta-1}\right], \quad j = L, H. \tag{13}$$

Note that equation (13) is identical for low and high adaptation cost countries. This shows that all countries emit the same amount in equilibrium even though they differ in adaptation costs. This is so because countries jointly maximize their payoffs and they fully internalize the negative global externality. Thus, in the full cooperative case, the only difference between low and high adaptation cost countries is given by their adaptation level in (12). As expected, low-cost countries always adapt more than high-cost countries.

Using equation (13) and $E_c = n^L e_c^L + n^H e_c^H$, we derive:

$$\eta\,(\beta E_c - n\alpha) = n E_c^{\eta-1}\left[-n\eta\omega + \left(\frac{n^L}{c^L} + \frac{n^H}{c^H}\right) {E_c}^{\eta}\right]. \tag{14}$$

At the aggregate level, total emissions are the positive root of (14). These calculations allow us to fully characterize the emission and adaptation levels of the cooperative case.

In appendix A, we present the formal comparison between total emissions under non- and full cooperation.[18] Recall that, in the absence of adaptation, full cooperation always leads to lower total emissions than no agreement because countries internalize the negative externality of polluting. As shown in appendix A, this result also holds when we account for adaptation. Specifically, this result is driven by our non over-adaptation assumption. Since each country is unable to over-adapt to climate change, their adaptation-adjusted marginal damage from polluting is higher under full cooperation than non-cooperation (see equations (6) and (11)). This is so because countries under cooperation do not only take into account the marginal damage from pollution in their countries, but also in other countries. Therefore, full cooperative countries internalize the pollution externality, which leads to lower total emissions in equilibrium, even when they are able to adapt to climate change.

Before we turn to analysing the strategic relationships between variables, we look at how the disparity in adaptation costs affects global emissions.

[17] It is also the Samuelson (1954) condition for the provision of public goods, which in this case is global environmental quality.

[18] As the number of countries n increases, the level of emissions in the non-cooperative outcome increases.

https://doi.org/10.1017/S1355770X16000097 Published online by Cambridge University Press

We summarize our finding for the linear case in result 1. In the non-linear case, this relationship is more complicated and depends on the magnitudes of variables.

Result 1. *An exogenous reduction in the adaptation cost gap between countries leads to higher global emissions when damages are linear.*

To see this, from equations (9) and (14), we obtain total emissions for non and full cooperation in the linear damage case:

$$E_{nc} = \frac{n(\alpha - \omega)}{\beta - \left(\frac{n^H}{c^H} + \frac{n^L}{c^L}\right)}, \tag{15}$$

$$E_c = \frac{n(\alpha - n\omega)}{\beta - n\left(\frac{n^H}{c^H} + \frac{n^L}{c^L}\right)}, \tag{16}$$

which depend on adaptation costs. Moreover, the optimality conditions (7) and (12) show that a country's adaptation effort increases as adaptation costs get smaller. Higher adaptation efforts in turn lead to higher individual and global emissions in the linear case.[19] With this in mind, we consider an exogenous change in the cost of adaptation (c). The first example considers a reduction in adaptation costs for high-cost countries, say as a response to a global policy to reduce the cost gap between countries. In the second example, we consider a reduction in adaptation costs for low-cost countries, say as a response to exogenous technological improvements in adaptation. We derive the effect of these two examples in global emissions from equations (15) and (16). In both examples, as adaptation costs get cheaper for some countries, they respond by increasing their adaptation effort. This in turn leads to higher individual emissions and also to higher global pollution. These effects imply that a policy directed at reducing the cost gap between countries or technological advancements in adaptation technologies lead to higher global emissions under non and full cooperation in the linear damage case.

Having established the benchmark cases, next we turn to the strategic relationships between emissions and adaptation.

4. Strategic relationships between emissions and adaptation

From our optimality conditions above, we characterize two strategic relationships: how a country's emissions respond to its own higher adaptation effort, and how a country's emissions respond to lower emissions by other countries.[20] This section is devoted to the study of these relationships which are key to understanding the incentives for emissions abatement

[19] This result is in line with Ebert and Welsch (2012) who find that any increase in adaptation by one country has a global negative effect under non-cooperation.

[20] There is no strategic relationship between adaptation between countries because adaptation is a country-specific decision.

https://doi.org/10.1017/S1355770X16000097 Published online by Cambridge University Press

analyzed in section 5. Our results generalize the two-country case by Ebert and Welsch (2011, 2012) to the n-country case with two-group heterogeneity. Our results differ from theirs because we also study the effect of cost heterogeneity on these strategic relationships. In particular, we analyse how reducing the adaptation cost gap between high- and low-cost countries affects a country's incentives to emit, in addition to analysing the existence of carbon leakage.[21] We start with the strategic relationship between a country's emissions and its adaptation effort.

We obtain the response of a country's emissions to its own higher adaptation effort by totally differentiating the first-order conditions and solving for this relationship. We show in proposition 1 that this strategic relationship depends on the curvature of the damage function and on the cost of adaptation.

Proposition 1. *Emissions and adaptation are strategic complements when damages are linear while they can be either complements or substitutes when damages are non-linear.*

Proof : The response of emissions to higher adaptation effort has the same sign for both the non-cooperative and the full cooperative outcome. Let us consider the non-cooperative case first. We substitute $E_{nc} = (e_i + e_{-i})$ into the first-order conditions (6) and (7) before we totally differentiate these two equations with respect to adaptation. We then solve for:

$$\frac{\mathrm{d}e^j_{nc}}{\mathrm{d}a^j_{nc}} = \frac{c^j(\eta-1)}{\beta E_{nc}}(a^j-\omega) + \frac{E_{nc}^{\eta-1}}{\beta}. \tag{17}$$

Emissions and adaptation effort are complements when $\frac{\mathrm{d}e^j_{nc}}{\mathrm{d}a^j_{nc}} > 0$ and substitutes when $\frac{\mathrm{d}e^j_{nc}}{\mathrm{d}a^j_{nc}} < 0$. When damages are linear ($\eta = 1$), equation (17) reduces to $\frac{1}{\beta} > 0$ for all cost types, which describes a complementarity between emissions and adaptation effort. However, when damages are non-linear ($\eta > 1$), the sign of (17) in equilibrium depends on adaptation costs; i.e., emissions and adaptation efforts are strategic complements when $c^j < \bar{c}$, where

$$\bar{c} \equiv \frac{(2\eta-1)(E^*_{nc})^{\eta}}{(\eta-1)\eta\omega} \tag{18}$$

where E^*_{nc} is the equilibrium level of total emissions.[22] Alternatively, they are strategic substitutes when $c^j > \bar{c}$. Using equations (12) and (13), we

[21] As noted before, we focus on high (developing) and low (developed) adaptation cost countries instead of considering full heterogeneity.

[22] Since total emissions depend on the cost of adaptation, we write these conditions by defining $\bar{c}$ given the equilibrium level of total emissions (E^*_{nc}). We show in appendix C that an exogenous reduction in adaptation costs increases $\bar{c}$ when damages are quadratic.

https://doi.org/10.1017/S1355770X16000097 Published online by Cambridge University Press

find that this strategic relationship also has the same sign in the cooperative case. In this latter case, when damages are linear, the relationship reduces to $\frac{\mathrm{d}e_c^j}{\mathrm{d}a_c^j} = \frac{n^j}{\beta} > 0$, which describes a strategic complementarity between one's private adaptation effort and the emissions of the cooperative group. When damages are non-linear, the coalition's emissions and a country's private adaptation can be complements or substitutes. □

We start our discussion with the linear damage case. Emission and adaptation levels are always strategic complements. This means that a country's private emissions increase as a response to higher adaptation effort in the non-cooperation case. In the cooperative case, this means that, as a country increases its adaptation effort, the emissions a coalition agrees upon also increase. Note also that a perfect complementarity between emissions and adaptation effort implies perfect substitutability between mitigation and adaptation effort.[23]

However, when the damages are non-linear, the response of emissions to higher adaptation effort depends on the parameter values.[24] We proceed with the well-known quadratic case ($\eta = 2$). Using (7) and (17), we obtain the equation that describes the strategic relationship between emissions and adaptation: $\frac{de_i^j}{da_i^j} = \frac{(2ca_i^j)^{1/2} - c(\omega - a_i^j)(2ca_i^j)^{-1/2}}{\beta}$. From this equation, emissions and adaptation effort are strategic substitutes $\left(\frac{de_i^j}{da_i^j} < 0\right)$ when $\omega > 3a_i^j$ and complements $\left(\frac{de_i^j}{da_i^j} > 0\right)$ when $\omega < 3a_i^j$. We rewrite these conditions in terms of adaptation cost since this strategic relationship is instrumental to understanding the incentives to emit and join a coalition in section 5, as well as to understanding the role of cost heterogeneity in a country's incentives to emit.

Thus, emissions and adaptation effort are strategic substitutes when the cost of adaptation satisfies $c^j > \bar{c} = \frac{3(E_{nc}^*)^2}{2\omega}$. For example, this is the case when the cost of adaptation and/or the impact of global emissions (ω) are large. On the contrary, when adaptation cost and/or the impact of global emissions are low, $c^j < \bar{c}$, emissions and adaptation effort are complements. In this case, and as seen in equation (7), countries adapt more with low adaptation costs which makes the overall cost of polluting cheaper.[25]

[23] Using a different model, Buob and Stephan (2011) demonstrate that, in such a case, countries will choose a corner solution, i.e., only mitigation or adaptation depending on their level of economic development and initial environmental damage.

[24] This result is in line with the two-country case proposed by Ebert and Welsch (2012), who find that the relationship between emissions and adaptation depends on the shape of the damage function.

[25] Our results are in line with Ebert and Welsch (2012) who find that improvements in the ability to adapt are equivalent to a lower impact of pollution.

https://doi.org/10.1017/S1355770X16000097 Published online by Cambridge University Press

Note also that these relationships hold for all countries, independent of their cost type.

Now that we have established the relationship between emissions and adaptation effort, we analyze how a change in the cost disparity between countries affects this relationship. We summarize our results in the following.

Result 2. *An exogenous reduction in adaptation costs can change the strategic relationship between emissions and adaptation from substitutability to complementarity.*

To see this, we consider three possible scenarios: all countries have effective adaptation technology ($c^L < c^H < \bar{c}$), all countries have ineffective adaptation technology ($\bar{c} < c^L < c^H$), and only some countries have effective adaptation technology ($c^L < \bar{c} < c^H$). We concentrate on the last scenario which describes a large cost heterogeneity. We analyse again an exogenous change in adaptation costs as we did in section 3. In appendix C, we show that an exogenous reduction in adaptation costs increases $\bar{c}$. Using this, we can see that, as adaptation costs decrease for high-cost countries (c^H), they can switch from exhibiting strategic substitutability between emission and adaptation levels to having a complementarity relationship. This in turn increases the incentives to adapt and emit more. Finally, note the effect of an exogenous increase in the pure effect of global emissions (ω). As the impact of global emissions increases, $\bar{c}$ gets smaller and the likelihood of a complementary relationship between emissions and adaptation effort decreases.

The second strategic relationship we study in this section shows how a country's emissions respond to another country's emission reductions. This is referred to as carbon leakage or emissions being strategic substitutes. In the following, we refer to this relationship as carbon leakage to avoid confusion with the strategic relationship between emissions and adaptation effort discussed above.

Recall that when the possibility to adapt to climate change is ignored, the curvature of the damage function solely determines the existence of carbon leakage (Finus, 2003). However, when we account for the possibility to adapt, we show in proposition 2 that the existence of carbon leakage not only depends on the curvature of the damage function, but also on adaptation costs. Technically, adaptation possibilities change the nature of the game by changing the slopes of the best-response functions. This means that cheap adaptation provides a new channel to counter the damages incurred by higher emissions, while expensive adaptation creates barriers to pollution. We summarize the effect of adaptation cost in proposition 2 and the effect of cost heterogeneity in result 3.

Proposition 2. *When damages are linear, there is always carbon leakage in emissions, while when damages are non-linear, the existence of carbon leakage depends on adaptation costs; i.e., for an equilibrium level of total emissions there is no carbon leakage when adaptation costs satisfy $c^j \in [\underline{c}, \bar{c}]$, while there is carbon leakage otherwise.*

https://doi.org/10.1017/S1355770X16000097 Published online by Cambridge University Press

Proof : We derive the explicit best-response function from equations (6) and (7). We start by substituting (7) into (6), which yields:

$$e_i^j - \frac{1}{\beta}\left(\alpha - \omega(e_i^j + e_{-i})^{\eta-1} + \frac{(e_i^j + e_{-i})^{2\eta-1}}{c^j \eta}\right) = 0, \tag{19}$$

where e_{-i} denotes emissions from all other countries, independently of cost type. We first consider linear damages. We totally differentiate (19) to find $\frac{de_i^j}{de_{-i}} = \frac{1}{\beta c^j - 1}$. The sign determines the existence of leakage; there is carbon leakage when $\frac{de_i^j}{de_{-i}} < 0$ while no carbon leakage when $\frac{de_i^j}{de_{-i}} \geq 0$. From the second-order conditions in section 3, $\beta c^j < 1$ always holds and, therefore, carbon leakage always exists when damages are linear.

When damages are non-linear, the total differentiation of (19) yields:

$$\frac{de_i^j}{de_{-i}} = \frac{(2\eta - 1)\, E_{nc}^{2\eta-2} - (\eta - 1)\, \eta c^j \omega E_{nc}^{\eta-2}}{\beta c^j \eta - (2\eta - 1)\, E_{nc}^{2\eta-2} + (\eta - 1)\, \eta c^j \omega E_{nc}^{\eta-2}}. \tag{20}$$

We present the existence of carbon leakage for an equilibrium level of total emissions in terms of adaptation costs. Equation (20) is positive (no carbon leakage) when adaptation costs satisfy $c^j \in [\underline{c}, \bar{c}]$ where:

$$\underline{c} \equiv \frac{(2\eta - 1)\, (E_{nc}^*)^{2\eta-2}}{(\eta - 1)\, \eta\omega (E_{nc}^*)^{\eta-2} + \beta\eta}, \tag{21}$$

$$\bar{c} \equiv \frac{(2\eta - 1)\, (E_{nc}^*)^{\eta}}{(\eta - 1)\, \eta\omega}, \tag{22}$$

where E_{nc}^* denotes the equilibrium level of total emissions. Note also that $\bar{c}$ in (22) equals $\bar{c}$ in (18). Thus, for the equilibrium level of total emissions (E_{nc}^*), carbon leakage exists when $c^j < \underline{c}$ or $c^j > \bar{c}$. □

In both the non-cooperative and cooperative cases with no adaptation possibilities, carbon leakage is never possible when damages are linear (Finus, 2003). However, when adaptation is possible, we find that there is always carbon leakage between countries. As other countries emit more, a country responds to higher total pollution by adapting more. As shown before, adaptation and emissions are always complements with linear damages and, therefore, a country responds to others' emissions by emitting more. This implies that the possibility to adapt leads to the existence of carbon leakage with linear damages.

In the non-linear case, however, carbon leakage depends on adaptation costs and we find that its existence is more complex than previously explained in the literature. In addition, cost heterogeneity plays a role in the incentives to emit. For example, if adaptation is highly effective ($c^j < \underline{c}$) or ineffective ($c^j > \underline{c}$), there is carbon leakage and a country increases emissions as a response to another country's emissions reduction. Let us first consider the case with cheap or effective adaptation. In this case, as others

https://doi.org/10.1017/S1355770X16000097 Published online by Cambridge University Press

increase their emissions, a country will respond to higher total emissions by adapting more. Since adaptation and emissions are complements with cheap adaptation, countries also respond by increasing their emissions. Next, think of the case with expensive or ineffective adaptation. In this case, this country responds to higher total emissions by reducing adaptation. Since adaptation and emissions are substitutes, a country responds to others by increasing emissions. Finally, when $c^j \in [\underline{c}, \bar{c}]$, there is no carbon leakage and a country reduces emissions as a response to emissions reduction by others.

Proposition 2 also implies that when the gap in adaptation cost is large between countries, some countries exhibit carbon leakage while others do not. We summarize in result 3 the effect of lowering the adaptation cost gap on the existence of carbon leakage.

Result 3. *An exogenous reduction in the adaptation cost gap between countries can change the existence of carbon leakage when damages are quadratic.*

In appendix C, we explicitly prove that an exogenous cost reduction leads to an increase in both $\underline{c}$ and $\bar{c}$. Not only that, but we show that the increase in $\bar{c}$ is higher than that of $\underline{c}$, which implies that the interval without carbon leakage gets larger. Given this, consider the case of a low adaptation cost country with $c^L < \underline{c}$ and a high adaptation cost country with $c^H \in [\underline{c}, \bar{c}]$. Then, there is carbon leakage in the low adaptation cost countries while there is no carbon leakage in the high adaptation cost countries. An exogenous reduction in adaptation costs leaves low-cost countries' incentives unchanged since $\underline{c}$ becomes higher. However, for some high adaptation cost countries, this reduction could imply a change in polluting strategy that leads to carbon leakage. Next, let us consider that low adaptation cost countries that satisfy $c^L \in [\underline{c}, \bar{c}]$ and high adaptation cost countries satisfy $c^H > \bar{c}$. This implies no carbon leakage for low-cost countries and carbon leakage for high-cost countries. In this scenario, a reduction in adaptation costs leads to higher $\underline{c}$ and $\bar{c}$, which can shift the existence of carbon leakage.

Overall, these results imply that heterogeneity in adaptation costs is a key factor that influences the incentives to emit and therefore to join international agreements. We turn to studying these incentives in the next section.

5. Coalition formation and stability

Now that we have established the incentives to emit, we turn to examining the incentives to voluntarily join a coalition and the stability of such self-enforcing agreements. To do so, we analyse a two-stage open membership game. We present the coalition formation game in section 5.1, while 5.2 and 5.3 analyse coalition formation. Section 5.2 presents analytical solutions for the linear damage case while in section 5.3, where we consider non-linear damages, we are unable to derive an analytical solution. In line with Pavlova and De Zeeuw (2013), numerical examples show that large stable coalitions could potentially exist. However, since such examples are sensitive to changes in parameter values, we discuss instead how the

https://doi.org/10.1017/S1355770X16000097 Published online by Cambridge University Press

strategic relationships between emissions and adaptation effort and carbon leakage affect the willingness to join a coalition.

5.1. Membership game

We consider a two-stage open-membership Cournot game where countries decide unilaterally whether to ratify the treaty in the first stage. The total number of low and high adaptation cost countries that join the IEA in the first stage is k^L and k^H respectively, while $n-k$ countries choose to stay out of the coalition, where $k = k^L + k^H$. In the following, the subscripts ns and s stand for non-signatory and signatory countries. In the second stage, non-signatory countries choose the individual emissions that maximize their own payoff, while signatory countries decide jointly the emission level that maximizes their aggregate payoff. Thus, non-signatory and signatory countries behave like countries in the non and full cooperation cases in section 3. In this second stage, countries also choose their own private adaptation levels. We solve this game by backward induction starting from the second stage.

In the second stage, non-signatory countries choose emissions and adaptation levels by solving:

$$\max_{\{a_i,e_i\}_{i\in N\setminus S}} W(a_i, e_i, E) = e_i\left(\alpha - \beta\frac{e_i}{2}\right) - (\omega - a_i)\frac{E^\eta}{\eta} - \frac{c^j}{2}a_i^2, \tag{23}$$

where $N\setminus S$ is the set of non-signatory countries. This problem is identical to the non-cooperative case in section 3 where the optimality conditions are given by equations (6) and (7). Next, we derive emission and adaptation strategies of signatory countries by solving:

$$\max_{\{a_i,e_i\}_{i\in S}} \sum_{i\in S} W(a_i, e_i, E) = \sum_{i\in S}\left(e_i\left(\alpha - \beta\frac{e_i}{2}\right) - (\omega - a_i)\frac{E^\eta}{\eta} - \frac{c^j}{2}a_i^2\right), \tag{24}$$

where S represents the set of signatory countries. The first-order conditions for emissions and adaptation are:

$$\alpha - \beta e_s^j = (k\omega - k^L a_s^L - k^H a_s^H)E^{\eta-1}, \quad j = L, H, \tag{25}$$

$$\frac{E^\eta}{\eta} = c^j a_s^j, \quad j = L, H. \tag{26}$$

Note that if all countries join the coalition ($k = n$), the first-order conditions coincide with equations (12) and (13) in the full cooperative case. From these equations, we calculate total emissions generated by non-signatories (E_{ns}) and signatories (E_s). Equation (6), combined with $E_{ns} = (n^L - k^L)e_{ns}^L + (n^H - k^H)e_{ns}^H$, yields:

$$E_{ns} = \frac{1}{\beta}\left[(n-k)\alpha - \left((n-k)\omega - \frac{n^L - k^L}{\eta c^L}E^\eta - \frac{n^H - k^H}{\eta c^H}E^\eta\right)E^{\eta-1}\right]. \tag{27}$$

https://doi.org/10.1017/S1355770X16000097 Published online by Cambridge University Press

Likewise, equation (25) and $E_s = k^L e_s^L + k^H e_s^H$ yield:

$$E_s = \frac{1}{\beta}\left[k\alpha - \left(k^2\omega - \frac{kk^L}{\eta c^L}E^\eta - \frac{kk^H}{\eta c^H}E^\eta\right)E^{\eta-1}\right]. \tag{28}$$

Thus, global emissions are the sum of emissions from non-signatories and signatories in (27) and (28), which is the positive root of the equation:

$$\eta(\beta E - n\alpha) = E^{\eta-1}\left[-\left(n - k + k^2\right)\eta\omega + \left(\frac{n^L + k^L(k-1)}{c^L} + \frac{n^H + k^H(k-1)}{c^H}\right)E^\eta\right]. \tag{29}$$

These partial cooperation relationships describe the incentives to emit for a given coalition size. Thus, all countries within the agreement emit equally as in the full cooperative case, while countries outside the coalition behave as singletons. This means that they act in their own self-interest and emit according to their adaptation cost as in the pure non-cooperative case. Furthermore, since global emissions affect all countries equally, these countries' adaptation levels in equilibrium are given by their cost types; every high- (or low-) cost country chooses the same adaptation level independent of whether it signed the agreement. Next, we analyse how the presence of adaptation affects behavior in equilibrium.

Result 4. *The presence of adaptation does not nullify the emissions-abating role of IEAs.*

We can see this result by using (6) and (25), along with $\omega \geq a_s^j$ and $\omega \geq a_{ns}^j$, which yield $e_{ns}^j - e_s^j \geq \omega(2k-1) + a_{ns}^j > 0$. Therefore, a non-signatory country always emits more than a signatory country for any coalition size k. Thus, we find adaptation possibilities are not a limiting factor in a climatic coalition. Some argue against putting efforts into adaptation, fearing diminished willingness to abate within environmental agreements (e.g., Faiola and Eilperin, 2009). Contrary to this belief, our result shows that the presence of adaptation does not obstruct the abilities of IEAs to reduce emissions within a coalition.

Now that we have established the equilibrium behavior of signatories and non-signatories in the second stage, we turn to the first stage and the stability of these coalitions. From the second stage, the equilibrium levels of a^j, e_i and E are the solution of (25)–(29) in terms of the stable size $k = k^L + k^H$. Using these equilibrium results, we write the payoff function in (4) in terms of the coalition size. 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 holds when no country inside the coalition has incentives to leave, $W_s^j\left(k^j, k^{-j}\right) \geq W_{ns}^j\left(k^j - 1, k^{-j}\right)$ for $j = L, H$, while external stability holds when no country outside the coalition has incentives to join, $W_{ns}^j\left(k^j, k^{-j}\right) \geq W_s^j\left(k^j + 1, k^{-j}\right)$ for $j = L, H$. The stability conditions are

https://doi.org/10.1017/S1355770X16000097 Published online by Cambridge University Press

computed using the equilibrium welfare levels in the second stage. Following Hoel and Schneider (1997) and Nkuiya *et al.* (2015), we summarize these conditions using a stability function: $\phi^j\left(k^j, k^{-j}\right) = W_s^j\left(k^j, k^{-j}\right) - W_{ns}^j\left(k^j - 1, k^{-j}\right)$, for $j = L, H$. The coalition $\left(k^L, k^H\right)$ is internally stable when $\phi^j\left(k^L, k^H\right) \geq 0$ for $j = L, H$ hold, and externally stable when $\phi^L\left(k^L + 1, k^H\right) \leq 0$ and $\phi^H\left(k^L, k^H + 1\right) \leq 0$ hold. The stable coalition size $k = k^L + k^H$ holds these two conditions simultaneously.

Having established the stability conditions, we analyze how adaptation and cost heterogeneity in adaptation change the incentives to join an IEA. We start with the linear damage case.

5.2. Linear damages, $\eta = 1$

In the baseline case where adaptation possibilities are ignored, a maximum of three countries join a stable agreement when signatories and non-signatories choose emissions simultaneously (Finus, 2003). We first examine the cost symmetry case before turning to cost asymmetry. In both cases, we find that a maximum of three countries form a stable coalition.

Result 5. *The possibilities to adapt do not reduce the incentives to join a coalition when damages are linear, even with heterogeneous adaptation costs.*

We prove result 5 analytically in appendix B, where we show that a maximum of three countries join a stable coalition. Since the maximum number of countries that join a coalition is also three in the IEA literature that ignores adaptation possibilities, result 5 implies that adaptation possibilities do not diminish the incentives to join a coalition. Note, however, that when damages are linear, there exists carbon leakage (proposition 1). While carbon leakage often reduces the incentives to join a coalition, in our setting we find that carbon leakage is not a destabilizing factor and that the maximum number of countries that join a coalition is unchanged.

Next, we explore the role of heterogeneity in adaptation costs. Propositions 1 and 2 show that the strategic relationship between emissions and adaptation and the existence of carbon leakage remain unchanged with cost heterogeneity and linear damages. Thus, since the incentives to emit are unchanged, by contradiction, the maximum stable coalition size must be equal to three. Thus, an exogenous reduction in the gap between adaptations costs between countries does not strengthen nor weaken the free-riding incentives. Remember, however, that as shown in section 3, a reduction in cost heterogeneity could increase global emissions. Thus, while we cannot observe changes in participation incentives, policies directed at reducing the adaptation cost gap should consider such an adverse effects on global emissions.

Our result sheds some light on the role of adaptation in changing country incentives to join IEAs. As mentioned before, some argue against putting efforts into adaptation, fearing diminished willingness to join international agreements to reduce emissions. (e.g., Faiola and Eilperin, 2009). Contrary to this belief, our results show that, when damages are linear, the incentives to join an agreement are unchanged. This is so because the complementarity between emissions and adaptation leads to carbon leakages between

https://doi.org/10.1017/S1355770X16000097 Published online by Cambridge University Press

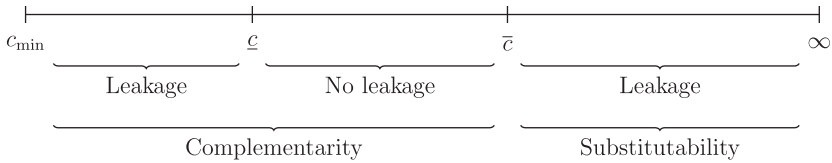

Figure 1. *Strategic relationships between variables in terms of adaptation cost when damages are quadratic*
Notes: Complementarity and substitutability refer to a country's emissions as a response to an increase in adaptation, while leakage (or the lack of) refers to a country's emissions as a response to other countries emission increases.

countries. Thus, the possibility to adapt to climate change creates a new channel to respond to changes in emissions instead of creating barriers for coalition formation.

5.3. Quadratic damages, $\eta = 2$

Next, we turn to non-linear damages where we focus on the widely used quadratic damage specification ($\eta = 2$). Recall that, when adaptation possibilities are ignored, a maximum of two countries choose to join a stable agreement when signatories and non-signatories choose emissions simultaneously (Finus, 2003). Accounting for adaptation possibilities, we identified in section 4 how the incentives to emit depend on each country's adaptation level (equation 17) and on other countries' emission strategies (equation 20). In the following, we discuss how these relationships affect the willingness to join a coalition. Figure 1 presents the incentives to emit for an equilibrium level of total emissions given different adaptation costs with $\underline{c}$ and $\bar{c}$ given by equations (21) and (22), respectively.

We start with the symmetric case where adaptation costs are identical for all countries. Our results are summarized in result 6.

Result 6. *When damages are quadratic and adaptation costs are homogenous, a large coalition is unlikely with cheap and effective adaptation cost. The willingness to join a coalition may increase adaptation costs.*

We first consider the case with effective adaptation ($c < \underline{c}$), where there is carbon leakage and emissions and adaptation are complements (figure 1). Carbon leakage enhances free-riding incentives as other countries abate their emissions. Furthermore, the strategic complementarity between emissions and adaptation effort provides a country with incentives to increase individual emissions in response to effective adaptation. As such, these two effects reinforce the incentives to emit and a large coalition size is unlikely to form. This scenario is perhaps the most pessimistic one from the perspective of a global agreement since each country takes care of its own pollution problem.

However, for higher adaptation cost ($c \in [\underline{c}, \bar{c}]$), there is no carbon leakage although emissions and adaptation are still complements. This complementarity indicates that, as a country adapts more, individual emissions also increase, which weakens the incentives to collaborate on abatement. However, the lack of carbon leakage enhances the incentives to join a

https://doi.org/10.1017/S1355770X16000097 Published online by Cambridge University Press

coalition. Thus, these two contradictory effects are at play when a country decides to join an agreement. This implies that, when the first effect is smaller than the second one, a country's willingness to join a coalition is enhanced. In reality, specific parameter values determine the magnitude of these effects.

Finally, we turn to the case with ineffective adaptation ($c > \bar{c}$); emissions and adaptation effort are strategic substitutes and carbon leakage exists. This implies that, on the one hand, the strategic substitutability between emissions and adaptation provides a country with incentives to lower individual emissions. On the other hand, carbon leakage leads to free-riding incentives. Again, these two contradictory effects are at play when a country chooses to join a coalition.

Next, we turn to cost asymmetry. When low and high adaptation cost countries are in the same cost range (figure 1), we find the same effects as those described in the symmetric case. Next, we turn to the case with large cost asymmetry where we find two relevant scenarios that we summarize in result 7.

Result 7. *When damages are quadratic and adaptation costs are heterogeneous, the willingness to join a coalition changes as the cost gap narrows. When cost heterogeneity is large, a cost reduction may strengthen participation incentives, while when cost heterogeneity is smaller, such reduction weakens participation incentives.*

First, we consider the case where high adaptation cost countries have an ineffective adaptation technology; $c^L < \underline{c}$ and $c^H > \bar{c}$. This, for example, could be the case of developed countries with effective adaptive capacity and the case of emerging economies with a costlier adaptation option. As described above, low-cost countries in this case are unlikely to join a coalition whereas high-cost countries may have incentives to join a coalition. Thus, it seems unlikely that a large stable agreement would arise when half the countries have cheap and effective adaptation costs ($c^L < \underline{c}$).[26]

In this scenario, the cost gap between the developed and developing countries increases further when, for example, low-cost countries develop even more efficient adaptation technologies (lowering c^L). We show in appendix C that such reduction shifts both $\underline{c}$ and $\bar{c}$ to the right in figure 1. While the incentives of high-cost countries may change, low-cost countries' incentives to emit are reinforced, which makes them less likely to participate in an agreement. On the other hand, if the cost asymmetry is reduced by, for example, a policy directed at increasing adaptation technology transfers from developed to developing countries, then high-cost countries are able to lower their adaptation costs. This cost reduction also shifts both $\underline{c}$ and $\bar{c}$ to the right in figure 1. However, a substantial cost reduction can make adaptation effective for developing countries, thus reversing the relationship between emissions and adaptation from being

[26] This, however, might not hold with group size asymmetry. Unfortunately, we are unable to analyze analytically how this result would change when a larger share of countries have high adaptation costs.

https://doi.org/10.1017/S1355770X16000097 Published online by Cambridge University Press

substitutes to complements. Note also that since such a policy has the potential of eliminating leakages for high-cost countries, it can be used as a device to promote their emissions abatement. This, however, comes at the cost of adaptation reinforcing individual emissions. Therefore, a policy aimed at reducing cost heterogeneity among countries might not improve participation incentives.

Secondly, we consider the case where both types of countries have an effective adaptation technology; $c^L < \underline{c}$ and $\underline{c} < c^H < \bar{c}$. High-cost countries may have incentives to form a coalition whereas low-cost countries are unlikely to form a coalition. In this case, a policy directed at reducing the cost gap may potentially eliminate any prospects for a successful agreement. This is so because a policy that reduces costs can shift $\underline{c}$ to the right such that it creates carbon leakage for high-cost countries. In these case, all countries end up in a scenario without incentives to form a coalition.

6. Conclusion and policy implications

In this paper we study the incentives to join IEAs when countries have the option to adapt to climate change, in addition to emissions abatement. We are particularly interested in the impact of cross-country differences in adaptation costs on the incentives to emit. We find that a country's incentives to join a coalition depends on two effects: the strategic relationship between emissions and adaptation, and carbon leakage. Our results suggest that the possibility to adapt to climate change does not necessarily reduce participation incentives. Furthermore, depending on the effectiveness of adaptation, a policy aimed at reducing the adaptation cost gap can either strengthen or weaken participation incentives.

Our results have implications for policies directed at reducing the gap in adaptation costs between developed and developing countries. For example, the Cancún Adaptation Fund,[27] established in 2010 to reduce the technological gap that exists between developed (low-cost) and developing (high-cost) countries. We find that a policy directed at reducing the cost gap in adaptation may increase global emissions without necessarily improving incentives to form a coalition. Nonetheless, such a policy must consider that the incentive to join a coalition might be altered when heterogeneity decreases or ceases to exist.

Our results also have implications for policies directed at regulating leakages. When adaptation costs are high, a policy aimed at reducing leakages may change the sign of the strategic relationship between emissions and adaptation. In our setting, such a policy could weaken the incentives to join a coalition. Policy makers then ought to be mindful of such a perverse outcome (see, for example, Kallbekken, 2007).

Our discussion draws attention to existing international climate policies, such as the Cancún Adaptation Fund or the Clean Development Mechanism, as we show that such policies change the incentives to form large

[27] More information regarding the Fund is available at https://www.adaptation-fund.org/.

https://doi.org/10.1017/S1355770X16000097 Published online by Cambridge University Press

coalitions. Our results indicate that heterogeneity among countries can change participation incentives and, hence, policies directed at reducing these heterogeneities could create barriers and opportunities for coalition formation.

Finally, we summarize some of the limitations of our study and we make suggestions for further research. First, in this study we have 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 possibilities. An extension could be to account for heterogeneity in both individual damages and adaptation possibilities. Another possible extension is to analyze transfer programs that reduce adaptation costs between developed and developing countries.[28] Despite these limitations, our paper provides a complementary explanation to better understand the incentives to abate and join IEAs.

References

Barrett, S. (1994), 'Self-enforcing international environmental agreements', *Oxford Economic Papers* **46**: 878–894.

Barrett, S. (2001), 'International cooperation for sale', *European Economic Review* **45**(10): 1835–1850.

Benchekroun, H., W. Marrouch, and A. Ray Chaudhuri (2011), 'Adaptation effectiveness and free-riding incentives in international environmental agreements', Discussion Paper No. 2011-120, Center for Economic Research, Tilburg University, Netherlands.

Buob, S. and G. Stephan (2008), 'Global climate change and the funding of adaptation', Discussion Paper No. 08-04, Universität Bern, Switzerland.

Buob, S. and G. Stephan (2011), 'To mitigate or to adapt: how to confront global climate change', *European Journal of Political Economy* **27**(1): 1–16.

Carraro, C. and D. Siniscalco (1993), 'Strategies for the international protection of the environment', *Journal of Public Economics* **52**(3): 309–328.

Carraro, C., J. Eyckmans, and M. Finus (2006), 'Optimal transfers and participation decisions in international environmental agreements', *Review of International Organizations* **1**(4): 379–396.

d'Aspremont, C., A. Jacquemin, J.J. Gabszewicz, and J.A. Weymark (1983), 'On the stability of collusive price leadership', *Canadian Journal of Economics* **16**(1): 17–25.

de Zeeuw, A. (2008), 'Dynamic effects on the stability of international environmental agreements', *Journal of Environmental Economics and Management* **55**(2): 163–174.

Ebert, U. and H. Welsch (2011), 'Optimal response functions in global pollution problems can be upward-sloping: accounting for adaptation', *Environmental Economics and Policy Studies* **13**(2): 129–138.

Ebert, U. and H. Welsch (2012), 'Adaptation and mitigation in global pollution problems: economic impacts of productivity, sensitivity, and adaptive capacity', *Environmental and Resource Economics* **52**(1): 49–64.

[28] For example, Barrett (2001), Carraro *et al.* (2006) and McGinty (2007) study transfer programs to increase the incentives to join IEAs.

https://doi.org/10.1017/S1355770X16000097 Published online by Cambridge University Press

Eyckmans, J. and H. Tulkens (2003), 'Simulating coalitionally stable burden sharing agreements for the climate change problem', *Resource and Energy Economics* **25**(4): 299–327.
Faiola, A. and J. Eilperin (2009), 'Dutch defense against climate disaster: adapt to the change', *The Washington Post*, 6 December.
Finus, M. (2003), 'Stability and design of international environmental agreements: the case of transboundary pollution', *International Yearbook of Environmental and Resource Economics* **4**: 82–158.
Hoel, M. and K. Schneider (1997), 'Incentives to participate in an international environmental agreement', *Environmental and Resource Economics* **9**(2): 153–170.
Kallbekken, S. (2007), 'Why the CDM will reduce carbon leakage', *Climate Policy* **7**(3): 197–211.
Kane, S. and J. Shogren (2000), 'Linking adaptation and mitigation in climate change policy', *Climatic Change* **45**(1): 75–102.
Kristjanson, P., H. Neufeldt, A. Gassner, *et al.* (2012), 'Are food insecure smallholder households making changes in their farming practices? Evidence from East Africa', *Food Security* **4**(3): 381–397.
Marrouch, W. and A. Ray Chaudhuri (2011), 'International environmental agreements in the presence of adaptation', Discussion Paper No. 2011.35, Fondazione Eni Enrico Mattei, Italy.
Mbow, C., P. Smith, D. Skole, L. Duguma, and M. Bustamante (2014), 'Achieving mitigation and adaptation to climate change through sustainable agroforestry practices in Africa', *Current Opinion in Environmental Sustainability* **6**: 8–14.
McGinty, M. (2007), 'International environmental agreements among asymmetric nations', *Oxford Economic Papers* **59**(1): 45–62.
Mendelsohn, R. (2000), 'Efficient adaptation to climate change', *Climatic Change* **45**(3): 583–600.
Nkuiya, B., W. Marrouch, and E. Bahel (2015), 'International environmental agreements under endogenous uncertainty', *Journal of Public Economic Theory* **17**(5): 752–772.
Onuma, A. and Y. Arino (2011), 'Greenhouse gas emission, mitigation and innovation of adaptation technology in a north–south economy', *Environment and Development Economics* **16**(6): 639–656.
Parry, M.L. (2007), *Climate Change 2007: Impacts, Adaptation and Vulnerability: Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Vol. 4*, Cambridge: Cambridge University Press.
Pavlova, Y. and A. de Zeeuw (2013), 'Asymmetries in international environmental agreements', *Environment and Development Economics* **18**(1): 51–68.
Petrosjan, L. and G. Zaccour (2003), 'Time-consistent Shapley value allocation of pollution cost reduction', *Journal of Economic Dynamics and Control* **27**(3): 381–398.
Ravindranath, N. (2007), 'Mitigation and adaptation synergy in forest sector', *Mitigation and Adaptation Strategies for Global Change* **12**(5): 843–853.
Samuelson, P.A. (1954), 'The pure theory of public expenditure', *Review of Economics and Statistics* **36**(4): 387–389.
Tol, R.S. (2005), 'Adaptation and mitigation: trade-offs in substance and methods', *Environmental Science & Policy* **8**(6): 572–578.
Verchot, L.V., M. Van Noordwijk, S. Kandji, *et al.* (2007), 'Climate change: linking adaptation and mitigation through agroforestry', *Mitigation and Adaptation Strategies for Global Change* **12**(5): 901–918.
World Bank (2010), *Economics of Adaptation to Climate Change*, Washington, DC: International Bank for Reconstruction and Development/World Bank.

Zehaie, F. (2009), 'The timing and strategic role of self-protection', *Environmental and Resource Economics* **44**(3): 337–350.

Appendix A: Comparison of total emissions in the two polar cases

Linear case, $\eta = 1$

From equations (9) and (14), we obtain total emissions for the no and full cooperation given by (15) and (16).

An interior solution where countries generate positive emission levels requires the following two conditions[29]:

$$\alpha > n\omega, \tag{A.1}$$

$$\beta > n\left(\frac{n^H}{c^H} + \frac{n^L}{c^L}\right). \tag{A.2}$$

From total emissions in the polar cases in equations (15) and (16), we derive:

$$E_{nc} - E_c = n\,(n-1)\,\frac{\beta\omega - \alpha\left(\frac{n^H}{c^H} + \frac{n^L}{c^L}\right)}{\left(\beta - \left(\frac{n^H}{c^H} + \frac{n^L}{c^L}\right)\right)\left(\beta - n\left(\frac{n^H}{c^H} + \frac{n^L}{c^L}\right)\right)}. \tag{A.3}$$

Assume by contradiction that $E_{nc} \leq E_c$. In this case, given the existence assumptions A.1 and A.2, equation (A.3) implies that:

$$\omega \leq \frac{\alpha}{\beta}\left(\frac{n^H}{c^H} + \frac{n^L}{c^L}\right). \tag{A.4}$$

Rearranging (A.4) leads us to

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

Combining this relation with the assumption that no over-adaptation is possible (i.e., $a_{nc}^L < \omega$), 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 $E_{nc} \leq E_c$ holds if and only if $c^L > c^H$. Since this condition is a contradiction with $c^H > c^L$, we necessarily have $E_{nc} > E_c$.

Non-linear case, $\eta > 1$

We define $l(E) \equiv \eta\,(\beta E - n\alpha)$ as a function given by the left-hand sides of both equations (9) and (14). We also denote $h(E) \equiv (E_{nc})^{\eta-1}\left[-n\eta\omega + \left(\frac{n^L}{c^L} + \frac{n^H}{c^H}\right)(E_{nc})^{\eta}\right]$ as the right-hand side of (9) and $g(E) \equiv$

[29] We derive these two existence conditions substituting equation (9) into equation (8) and equation (16) into equation (13) in the linear case ($\eta = 1$).

https://doi.org/10.1017/S1355770X16000097 Published online by Cambridge University Press

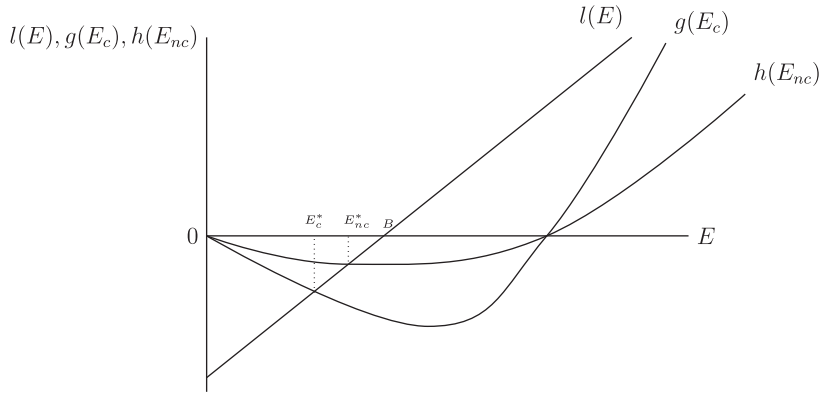

Figure 2. *The comparison between non-cooperative* (E_{nc}^*) *and cooperative* (E_c^*) *total emissions*

$n\,(E_c)^{\eta-1}\left[-n\eta\omega+\left(\frac{n^L}{c^L}+\frac{n^H}{c^H}\right)(E_c)^{\eta}\right]$ as the right-hand side of (14). We represent these functions in figure 2, with $\eta > 1$, where E_{nc} 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 (1), total emissions must be smaller than $B \equiv n\alpha/\beta$, which is true for both E_c^* and E_{nc}^* as illustrated in figure 2. Then, we necessarily have $E_c^* < E_{nc}^*$. For adaptation, since $E_{nc}^* > E_c^*$, by conditions (7) and (12), the result follows.

Appendix B: Proof of result 5

As defined in the membership game in section 5.1, the stability function depends on the stable size k. We rewrite the stability condition $\phi(k) = W_s(k) - W_{ns}(k-1)$ as:

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

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

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

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

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

https://doi.org/10.1017/S1355770X16000097 Published online by Cambridge University Press

$\Omega(k, n) \geq 0$. This inequality holds if and only if $c\beta \in [\beta_{2s}, \beta_{1s}]$. In addition, we find that $\beta_{2s} < \beta_{1s} < n^2$. These results combined with the existence assumption (A.2) suggest that any coalition of size $k \geq 4$ cannot be 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.

Appendix C: The effect of changes in adaptation cost on $\underline{c}$ and $\bar{c}$

In this section we show that an exogenous reduction of adaptation cost increases both $\underline{c}$ and $\bar{c}$ with quadratic damages ($\eta = 2$). We develop this proof in two steps. We first show how changes in adaptation cost affect total emissions and, next, we show how total emissions affect the range of adaptation cost $[\underline{c}, \bar{c}]$. We formulate this proof for the non-cooperative case but it is easy to see that it also applies to the cooperative case. In this proof, we denote E equal to E_{nc}.

To see how changes in adaptation cost affect emissions, we turn to figure 3 which shows the equilibrium level of total emissions for the quadratic case in equation (9). We define the left-hand side and the right-hand side of (9) as $l(E) \equiv \eta(\beta E - n\alpha)$ and $h(E) \equiv (E)^{\eta-1}\left[-n\eta\omega + \left(\frac{n^L}{c^L} + \frac{n^H}{c^H}\right)(E)^{\eta}\right]$, respectively. In figure 3, the intersection between the two curves illustrates total emissions in the quadratic case. Next, by taking the first-order derivatives of $l(E)$ and $h(E)$ with respect to adaptation cost, we can see that changes in adaptation costs leave $l(E)$ unchanged $\left(\frac{\partial l(E)}{\partial c} = 0\right)$ while $h(E)$ becomes smaller $\left(\frac{\partial h(E)}{\partial c} < 0\right)$. This implies that an exogenous cost reduction in adaptation costs will shift $h(E)$ upwards, which yields higher total emissions at the intersection between $l(E)$ and $h'(E)$. This new intersection in figure 3 illustrates that an exogenous reduction in adaption costs leads to an increase in total emissions $((E^*)')$.

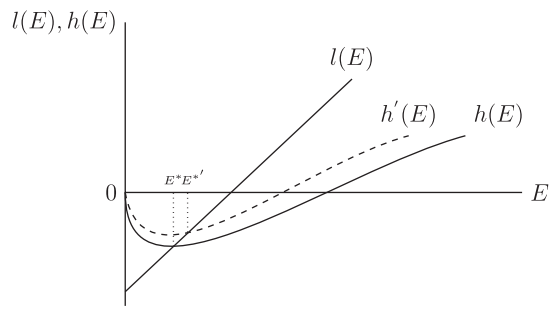

Figure 3. *The effect of changes in adaptation cost on total emissions in the quadratic case*

https://doi.org/10.1017/S1355770X16000097 Published online by Cambridge University Press

Next, we analyze the effect of higher total emissions in equilibrium on the range of adaptation cost $[\underline{c}, \bar{c}]$ in equations (21) and (22):

$$\frac{\partial \underline{c}}{\partial E^*} = \frac{1}{\eta}(E^*)^{2\eta-5} \frac{2\beta(E^*)^2 + \eta\omega(E^*)^{\eta}}{\left(\beta - \omega(E^*)^{\eta-2} + \eta\omega(E^*)^{\eta-2}\right)^2} (\eta(2\eta - 3) + 1) > 0, \tag{C.1}$$

$$\frac{\partial \bar{c}}{\partial E^*} = \frac{1}{\omega} \frac{(E^*)^{\eta-1}}{\eta - 1} (2\eta - 1) > 0. \tag{C.2}$$

Thus, higher equilibrium levels of total emissions leads to an increase in the interval $[\underline{c}, \bar{c}]$. Note that (C.2) is larger than (C.1), which implies that the $[\underline{c}, \bar{c}]$ interval becomes larger in response to an exogenous reduction in adaptation costs. While our main results hold, this finding is interesting on its own as it shows that, as we develop cheaper adaptation technologies, the interval with no leakage becomes larger.

Therefore, we can conclude that an exogenous reduction in adaptation costs leads to higher total emissions in equilibrium, which in turn increases both $\underline{c}$ and $\bar{c}$.

https://doi.org/10.1017/S1355770X16000097 Published online by Cambridge University Press