Climate Change Adaptation and International Agreements on Mitigation with Heterogeneous Countries

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Abstract

Global cooperation with respect to the mitigation of greenhouse gas (GHG) emissions appears increasingly contingent on finding common ground in addressing the problem of adaptation to climate change impacts. This paper uses a non-cooperative game theory model and coalition stability concepts to investigate the relationship between adaptation technology and the formation of emission-reducing International Environmental Agreements (IEAs) on climate change. We develop a framework where heterogeneity across countries is introduced with respect to the benefits and costs of both mitigation of emissions and adaptation to reduce the impacts of climate change. The paper shows that technological progress in adaptation in highly vulnerable countries can reduce gaps in vulnerability between countries and hence foster an IEA. Besides the traditional free-riding on climate change mitigation efforts, we find that free-riding on adaptation technology emerges among members of an IEA. Moreover, both types of free-riding can be reduced/eliminated by the diffusion of technological progress in adaptation among members of the IEA. A numerical example with parameters estimated from climate change data is provided to simulate stable coalitions and demonstrate how diffusion of adaptation technology reduces free-riding on an IEA.

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1. Introduction

According to rapidly accumulating evidence, increasing concentrations of greenhouse gases is a major driver of climate change, with severe economic and non-economic consequences expected (Stern, 2008; Kousky, 2012). Over the past several decades, jurisdictions across the world have been experimenting with ways to tackle climate change. Mitigation policies such as command and control, carbon tax and cap-and-trade systems aimed at reducing CO_2 emissions, and adaptation measures involving adjustments in ecological, social and economic systems meant to reduce climate change damage are two major approaches to address climate change. However, these efforts have to date been grossly inadequate. The recently released *Working Group II* contribution to the Fifth Assessment Report IPCC titled 'Climate Change 2014: Impacts, Adaptation and Vulnerability' paints a dire picture in terms of the timing and magnitude of the projected impacts around the world. One consequence of the sharper new focus on climate change impacts is that mitigation and adaptation are no longer considered alternative strategies. Increasingly, due to climate hysteresis and other factors, such as adaptation capability disparities among countries, they are seen as being required *simultaneously*. Indeed, one fact the recently concluded The United Nations Framework Convention on Climate Change (UNFCCC)'s Conference of the Parties (COP) 20 in Lima (December 2014) made exceedingly clear was that a global agreement that is agreed to by both developing and developed countries would have to include both adaptation and mitigation provisions.

This paper focuses on the interaction between adaptation and the incentives to participate in an International Environmental Agreement on emissions mitigation (referred to interchangeably as an IEA or IMA), in the presence of cross-country heterogeneity. We first analyze the two extreme no-cooperation and full-cooperation equilibria outcomes, and then study the more general case of partial coalitions. We focus on the incentives to free ride for each member, given their specific economic and environmental parameters, and we look at the way these incentives respond to exogenous changes in adaptation technology and net exposure to climate change impacts. The importance of accounting for country differences in both benefits and damages from GHG emissions cannot be overemphasized: different levels of development, technology and resource endowment translate into markedly different economic benefits per unit of carbon emitted, while differences in geography, local conditions and subjective evaluation practices also yield different

to substantially different economic damages around the world. Differences among countries are introduced here through four model parameters referring to the benefits and costs of both mitigation and adaptation. To our knowledge, this study is the first to systematically investigate the effect of heterogeneous benefits and costs of both mitigation and adaptation on a country's incentives with respect to optimal climate change policy and international cooperation.

GHGs are global pollutants, which implies that a country's emissions impose a negative externality on other countries by exacerbating climate change. When countries choose emission levels non-cooperatively, the global GHG emissions exceed the globally efficient level, defined as the full cooperative outcome where every country chooses its own emissions to maximize the joint welfare. Thus conceptually, international coordination is required in order to mitigate global GHG emissions effectively. International environmental initiatives, targeting at mitigation of GHGs through international cooperation, have been initiated for the past two decades. In 1997, the Kyoto Protocol was adopted by members of the UNFCCC, and it sets binding obligations on industrialized countries to reduce emissions of GHG. These so-called Annex I countries, including the EU and 37 other industrialized countries, agreed to reduce their GHG emissions by 5.2% on average during the first commitment period 2008-2012. The protocol was amended in 2012 with a second commitment period from 2012-2020. While the Kyoto Protocol has compelled some signatory countries to make some progress in reducing the global GHG emissions, there have been questions over its effectiveness, especially with respect to the large and increasing relative economic importance of non-participating countries. Several major emitters of GHG in the world including the U.S. (which signed the Protocol but failed to ratify it), India and China do not participate in the protocol. Canada withdrew from the Kyoto Protocol in 2011, and New Zealand, Russia and Japan refused to sign the extension of the Kyoto Protocol in 2012.

In general, any emissions mitigation agreement is undermined by the free-rider problem from nonparticipating countries, exacerbated potentially via the 'carbon leakage' effect.[1] Unilateral or plurilateral climate policies adopted by some developed countries will increase the production cost of domestic industries (especially for energy-intensive sectors), and reduce their international

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[1] Unilateral adoption of emission reduction policies in some countries can cause pollution-intensive good production to relocate to countries with unrestricted or less stringent environmental policy, and hence increase the emissions in those countries.

competitiveness. In addition, some have argued that the emission reduction target set by the Kyoto Protocol may be inadequate for slowing down climate change (UNEP, 2012). The ongoing concerns about the feasibility and effectiveness of global IEAs indicate that mitigation of GHG emissions cannot be the only policy response to climate change. Indeed in recent years, countries have increasingly considered undertaking adaptive measures to reduce the impact climate change.[2] Adaptation is mostly seen as a private good, which means both its costs and benefits are private to the respective country. This paper explores the relationship between mitigation and adaptation and specifically it focuses on effects of adaptation on the formation and stability of an IEA aimed at GHGs mitigation.

In addition to the different public/private good nature of mitigation and adaptation, asymmetric costs and benefits of both mitigation and adaptation across countries further complicate the relationship between mitigation and adaptation. In particular, a country with relatively low adaptation cost and/or low exposure to climate change but high mitigation cost may have little incentives to reduce GHG emissions. Thus the heterogeneity of costs and benefits of mitigation and adaptation should result in varying national optimal climate change policies. However, this heterogeneity in the context of mitigation and adaptation efforts is not sufficiently studied in the extant literature.

To preview the main results, technological progress in adaptation in a country has a public good feature within the IMA, compared to being a strictly private good outside an IMA. Besides the traditional free-riding in mitigation, free-riding with respect to adaptation technology emerges among members of an international mitigation agreement. Using two stability concepts, we find that large gaps in vulnerability to climate change prevent the formation of a large IEA. Thus, technological progress in adaptation in highly vulnerable countries can help form a larger international mitigation agreement. The paper also shows that free-riding with respect to mitigation of an international mitigation agreement can be reduced/eliminated with diffusion of technological progress in adaptation to members. If the R&D of technological progress is funded by members, free-riding with respect to adaptation technology within an IEA can be alleviated.

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[2] According to Parry (2007), adaptation refers to adjustments in ecological, social or economic systems to reduce the vulnerability of biological systems to climate change. Examples of adaptation include building dykes and levees to defend against rising sea levels, changing crop types, and even relocating population from especially vulnerable areas.

The interplay between GHG-emissions mitigation policies and adaptation activities has not received sufficient attention in the literature to date. The existing work on international cooperation on mitigation of GHG emissions mostly analyzes the stability of IEAs and incentives to join emission-reducing IEAs. A small body of work looking at adaptation and mitigation mostly exploits the trade-off between the two across identical countries. Only a handful of studies allow for heterogeneity across countries in either mitigation or adaptation, and few in a very comprehensive manner.

A substantial part of existing literature on IEAs analyzes the formation and stability of an IEA using mostly non-cooperative game theory tools. Since there does not exist a supranational institution that can enforce participation in an IEA, it must be *self-enforcing* as a result of the interplay of incentives and interactions among agents. The foundation of coalition stability theory in this context can be traced to D'Aspremont et al. (1983), which proves the existence of a stable dominant cartel in a cartel formation game. The most important contribution of that paper is that it defines the internal and external stability of a coalition, concepts which are extensively used in the literature on IEAs. Barrett (1994) studies the stability of an IEA adopting both a static and a repeated game modelling approach. The paper shows that a self-enforcing IEA may not sustain more than three signatories, or it may sustain a large number of countries, but only when the net gain between noncooperation and full cooperation is very small. Therefore, this literature suggests that IEAs that aim to coordinate GHG emissions mitigation may not achieve much.

Building on this work, more recent papers have explored the incentives for international cooperation from several different angles. Eichner and Pethig (2013) for instance introduce international trade of a composite consumer good and fossil fuel to the basic model of IEAs. Under the Stackelberg assumption, a stable IEA can be significantly larger compared to the basic model; however, gains and emission reduction of the coalition are still very small compared to the noncooperation equilibrium. Finus and Pintassilgo (2013) investigate the conditions under which uncertainty of benefits and costs of abatement has a positive/negative effect on a self-enforcing international climate agreement. A few studies highlight the importance of heterogeneity across countries, albeit in a limited way. Barrett (1997) explores the stability of an IEA when there are two types of countries, and finds that no more than three countries can sustain an IEA. The con-

clusion is similarly pessimistic to Barrett (1994): IEAs can achieve little in the effort to combat climate change. McGinty (2007) generalizes the benchmark model of IEAs by incorporating heterogeneity in mitigation across countries and allowing for transfer payments. Numerical exercises show that heterogeneity reduces the incentive of a member to leave an IEA by introducing gains from an emission permit trading system. With heterogeneous countries and transfers available, the size of a stable IEA varies and the gain from noncooperation to coalition can be large.

Only a small body of recent work looks explicitly at the interaction of adaptation and mitigation. The literature on adaptation to climate change in this context can be categorized into two streams. The first category highlights the trade-off between mitigation and adaptation across countries. The second stream incorporates adaptation in integrated assessment models (IAMs) and simulates the interaction between adaptation and mitigation. The present paper is in line with the first body of work, but explores the relationship between adaptation and coalition formation. Benchekroun et al. (2014) develop a model based on Barrett (1994) and with adaptation as a policy instrument additional to mitigation. With identical adaptation and mitigation across countries, more effective adaptation technologies may diminish a member's incentive to leave an emission-reducing IEA. Thus their conclusion is that adaptation and IEAs on mitigation are complements. While in reality costs and benefits of both mitigation and adaptation differ widely across countries, most studies in the sizeable literature on IEAs assume homogeneous agents (i.e. countries are symmetric). The body of work considering heterogeneous countries is comparatively much smaller. Close to our focus, Lazkano et al. (2014) assume two types of adaptation costs and analyze the incentives to join an IEA on mitigation with and without carbon leakage, which is shown to have a positive impact on the incentives to cooperate.

The main contribution of our paper is to be one of the first to allow for the full set of mitigation and adaptation parameters to be country-specific, as it studies the incentives of countries to join international GHG emission mitigation coalitions. Additionally, we show how shared technological advances in adaptation among the members of an IEA has the potential to increase cooperation. Another element that differentiates our paper from existing contributions is that we consider the choice of adaptation both prior to and simultaneous with (or, equivalently, sub-

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sequent to[3]) the choice of emission reductions. Finally, unlike the received literature, numerical simulations used to solve for the stable coalitions employ empirically accurate parameters, based on a dataset specifically assembled for this purpose.

The rest of the paper proceeds as follows. The model with heterogeneous agents is presented in section two. Section three characterizes the non-cooperative, fully cooperative, and coalition equilibria of the model. The incentive to participate in an IEA will be analyzed in section four. Section five tackles coalition stability, section six includes the numerical simulation, while section seven summarizes the main results and provides some directions for future work.

2. The Model

We model a non-cooperative IEA membership game, which is widely considered to be both more realistic and more general than cooperative games. According to a comprehensive literature survey by Finus (2008), 'the potential for explaining real world phenomena of IEAs is much higher for the non-cooperative than for the cooperative approach.'[4] The game structure is based on McGinty (2007) and Benchekroun et al. (2014), and it includes a standard coalition formation game theory setting with added heterogeneous costs and benefits of adaptation across countries. In this paper the full set of parameters characterizing both mitigation costs (i.e. benefits of emissions) and net damage costs (including natural vulnerability and adaptation effectiveness) are assumed to be country-specific.

Let $N = \{1, ..., n\}$ denote the set of all countries. The emissions of a global pollutant (like GHGs) is the by-product of the consumption and production activities of each country. Country i's emission level is denoted by e_i. While most of the literature is restricted to positive emission choices, we also allow for negative net country emissions, which would correspond to processes like carbon sequestration.[5] Global emissions are aggregated over all countries, $E \equiv \sum_{i=1}^{n} e_i$. For

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[3] See discussion in section 3 and Appendix.

[4] Among the reasons for this assessment are the lack of a clear supranational authority on which cooperative models are usually reliant on, the fact that non-cooperative models separate coalition formation from stability considerations and are able to replicate some cooperative assumptions and outcomes, and the fact that only the grand coalition can be stable according to the stability concept of the core, which is prevalent in cooperative models. See Finus (2008), p. 33-34 for a detailed discussion.

[5] An additional advantage of allowing $e_i < 0$ here is that we do not need to restrict how different countries are from each other. Otherwise, in order to keep e_i positive, one needs to assume country i cannot be 'too small' or 'too vulnerable' compared to the rest of the world.

country i, the emissions from the rest of the world are denoted by $E_{-i} \equiv \sum_{j \neq i \in N} e_j$.

Let $B(e_i)$ represent the benefit that country i derives from its own emissions:

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

with $\alpha_i, \beta_i > 0$. The first order derivative is given by $\frac{dB}{de_i} = \alpha_i - \beta_i e_i$. The benefit $B(e_i)$ is monotonically increasing over $(-\infty, \overline{e_i}]$, where $\overline{e_i} \equiv \frac{\alpha_i}{\beta_i}$.[6] Note that $\frac{d^2 B}{de_i^2} = -\beta_i < 0$, which indicates that the marginal benefit of emissions is diminishing.

While the benefits of emissions are private to a country, the effects of emissions are a global public bad: the damage is imposed to all countries, albeit differentially. Thus, the damage from emissions to country i is assumed to be a convex function of global emissions, and country-specific vulnerability and adaptation parameters:

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

with $v_i, \theta_i > 0$. The first term in (2) is the damage caused by global emissions, with v_i denoting the country's vulnerability to climate change. The second term in (2) represents the country-specific 'benefit' from adaptation. The adaptation level chosen by country i is denoted by a_i and is assumed to be private to that country: i.e. it reduces the climate-induced damage for country i only. θ_i denotes the effectiveness of adaptation. While expression (2) resembles the damage function adopted in Benchekroun et al. (2014) in the way in which adaptation enters the damage function, we differ in that both the vulnerability and the adaptation parameters are heterogeneous across countries.

The damage function in (2) has three main features. First, it is strictly increasing and convex in global emissions and decreasing in adaptation. Second, the marginal damage from emissions are decreasing in adaptation. Third, the marginal benefit of adaptation, given by $-\frac{\partial D(E, a_i)}{\partial a_i} = \theta_i E$, increases with global emissions. Therefore, a country that is less vulnerable and more adaptable to climate change suffers less from the impact of GHG emissions. Moreover, the higher the global emissions, the more valuable the adaptation activities. The marginal damage from emissions is given by $\frac{\partial D(E, a_i)}{\partial E} = v_i E - \theta_i a_i$. Thus, if adaptation is very effective and/or the adaptation level is very high, the marginal damage from emissions could turn negative, in what we term

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[6] The condition under which individual country emissions are in this range is provided in (3) below.

the 'productive over-adaptation' case. However, practically, adaptation cannot reduce natural vulnerability to climate change impacts to zero. To rule out this less interesting scenario, the following is assumed to hold:

$$v_i > \frac{\theta_i^2}{c_i}. \tag{3}$$

Technically, this assumption ensures two things. First, the marginal damage of global emissions for country i,[7] as derived in optimization problems under different cooperation scenarios in Section 3, is always positive. Second, this also guarantees a positive marginal benefit from emissions at the the optimal emission level. Therefore, the optimal emissions level of a country is always smaller than its maximum emission level: $e_i \leq \overline{e_i} \equiv \frac{\alpha_i}{\beta_i}$.

The cost of adaptation for country i is assumed to be convex in a_i:

$$C(a_i) \equiv \frac{c_i}{2} a_i^2, \tag{4}$$

with $c_i > 0$. The differences in adaptation costs across countries is captured by parameter c_i. If country i experiences technological progress in adaptation, either θ_i rises and/or c_i drops.

The social welfare of country i is determined by benefits of emissions, net of climate-induced damages given own adaptation efforts, and net of the cost of these efforts, as follows:

$$w(e_i, a_i, E) \equiv B(e_i) - D(E, a_i) - C(a_i). \tag{5}$$

3. Equilibrium

The model considered here is based on a two-stage, simultaneous-move, open membership game.[8] In the first stage, countries choose whether to participate or not in the international agreement on abatement, and in the second stage they concomitantly choose their level of emissions/abatement and adaptation. While some version of this is the most prevalent type of game in this literature, a brief discussion of these assumptions and some alternatives appears warranted at this point.

First, it should be noted that we assume that a single (global) agreement is under consideration, as opposed to several competing ones. Second, any country is eligible to join, i.e. there

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[7] i.e. $MD(E) \equiv \frac{dD(E)}{dE} = \left(v_i - \frac{\theta_i^2}{c_i}\right)E.$

[8] See Finus (2008), p. 35 for a detailed taxonomy of these models.

is no exclusivity clause. Third, countries decide on their participation in the agreement simultaneously, i.e. the Cournot-Nash assumption. In reality there is a sequential element to many agreements, whereby a small group of countries may initiate a regime that subsequently incorporates new members. However, as shown in Finus (2008), the results in the existing papers adopting a Stackelberg model for instance, are mixed and not sufficiently different to justify the loss in explanatory power. Moreover, these sequential games assume identical countries. In our heterogeneous countries setup, allowing for a sequential structure of the game would require endogenizing the order in which countries decide on their participation, substantially increasing the array of strategic options and further diluting the results.[9] In addition, players make the abatement and adaptation decisions simultaneously here, also an assumption which is widely used in the literature[10]. While there are several papers adopting a sequential model for the choice of emissions, they all assume symmetric countries and we leave this extension for future research.

Fourth, countries also choose adaptation and emissions at the same time in the second stage. This assumption is less restrictive than it may appear at first. According to Zehaie (2009), this scenario is equivalent to one in which the (private) adaptation decisions are made subsequent to (global) abatement choices, as also pointed out in Benchekroun et al. (2014).[11] However, there is another interesting possibility in the context of our setup. Given that many adaptation projects require substantial infrastructure investment, which may take a long time to complete, it is likely that some prospective IEA members to have already committed significant amounts of funds to such purposes *before* any mitigation agreement is reached. We look at this option in the Appendix, by assuming that countries choose their level of adaptation by taking the non-cooperative level of global emissions as given. The expected result is that countries have less incentive to join the coalition (more incentive to free ride) if they have already decreased their de facto vulnerability via adaptation investment. In other words, should an IEA be formed eventually, countries over-adapt compared to the efficient level.

Lastly, in order to keep the model comparable to our benchmarks, there are no transfers in the model. It is well known that side-payments, dispute settlement, and monitoring mechanisms

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[9] See Finus (2008), p. 49-51 for a discussion of existence of equilibrium and other issues in this context.
[10] See Carraro and Siniscalco (1993), Barrett (1994), Pavlova and de Zeeuw (2013)
[11] See Benchekroun et al. (2014), p. 4.

can extend cooperation;[12] however we aim here to focus on the main incentives in the absence of such schemes. Moreover, the logistics of such transfers, in a world in which the most vulnerable countries, having the most to benefit from an IEA, are also the ones who benefit the least from emissions and are the poorest, would conceivably have to compensate the richer, less vulnerable industrialized countries in order to induce them to join the IEA is problematic.[13] Transfers have rarely been used in existing IEAs due to moral hazard issues between donors and recipients, according to Finus (2000). Nevertheless, if allowing for country heterogeneity with respect to all dimensions related to abatement and adaptation increases the chances of cooperation, an optimally designed transfer scheme could further improve those odds.

3.1. The Non-cooperative Outcome

In the non-cooperative case, each country chooses emission (e_i) and adaptation (a_i) levels to maximize its own welfare, taking as given other countries' emissions:

$$\max_{e_i, a_i} w\left(e_i, a_i, E\right) = B(e_i) - D\left(E, a_i\right) - C\left(a_i\right). \tag{6}$$

The first order conditions are given by:

$$e_i : \alpha_i - \beta_i e_i - v_i E + \theta_i a_i = 0 \tag{7}$$

$$a_i : \theta_i E - c_i a_i = 0. \tag{8}$$

Solving for the best response functions of emissions and adaptation for country i yields:

$$e_i = \frac{\alpha_i - \Phi_i E_{-i}}{\beta_i + \Phi_i} \tag{9}$$

$$a_i = \frac{\theta_i}{c_i}\left(\frac{\alpha_i + \beta_i E_{-i}}{\beta_i + \Phi_i}\right), \tag{10}$$

where $\Phi_i \equiv v_i - \frac{\theta_i^2}{c_i}$. Substituting a_i from (8) into (2), we obtain the net marginal damage from emissions of adaptation: $\frac{dD(E)}{dE} = \Phi_i E$. Φ_i is the rate at which the net adaptation marginal damage increases, and hence it presents the net vulnerability in the presence of adaptation. From our assumption in (3), Φ_i is always positive. Note that θ_i rises and/or c_i drops as a result of

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[12] See for instance Carraro and Siniscalco (1993).

[13] Several such transfer schemes - including 'pragmatic' ones and some including ethical considerations - are discussed in Finus (2008), p. 42-44. It should be noted that full cooperation is still not achievable under most of these transfer mechanisms.

technological progress in adaptation in country i: e.g. country i's net vulnerability falls if it experiences technological progress in adaptation.

We add up (7) for all countries to derive global emissions and country i's emission and adaptation level. Country i's emission and adaptation level are given by,

$$e_i = \overline{e_i} - \frac{\Psi_i}{1 + \Psi}\overline{E} \tag{11}$$

$$a_i = \frac{\theta_i}{c_i}E, \tag{12}$$

where $\Psi_i \equiv \frac{\Phi_i}{\beta_i}$, $\Psi \equiv \sum_{k \in N} \Psi_k$. Note that Φ_i is the rate of change for (net of adaptation) marginal damage from emissions, while β_i is the rate of change for marginal benefit of emissions. Therefore, Ψ_i is the relative rate of change for marginal damage to marginal benefit. A country's emission level, as given by (11), is equal to its maximum emission level minus its abatement level. In the second term, Ψ_i is a country-specific 'abatement indicator': a country with a larger Ψ_i (i.e. larger Φ_i and/or smaller β_i) abates more. The underlying mechanism is related to net vulnerability Φ_i and the rate of change of marginal benefit β_i. A highly vulnerable country chooses a high abatement level to reduce the damage from climate change. Since β_i can be interpreted as the rate of change of the marginal cost of abatement, a country with a lower β_i has a marginal cost of abatement that increases more slowly with abatement, and hence abates more emissions.

From (11), one can see that abatement is undertaken even though no IEA is formed since natural vulnerability to climate change cannot be neutralized by adaptation ($\Phi_i > 0$). In the extreme case that the damage can be fully countered by adaptation (i.e. $\Phi_i = 0$), the country does not abate ($\Psi_i \equiv \frac{\Phi_i}{\beta_i} = 0$), and its emissions achieve the maximum level $\overline{e_i}$.

The global emission level is given by,

$$E = \frac{\sum_{k=1}^{n} \frac{\alpha_k}{\beta_k}}{1 + \sum_{k=1}^{n} \frac{\Phi_k}{\beta_k}} = \frac{1}{1 + \Psi}\overline{E}, \tag{13}$$

where $\overline{E} \equiv \sum_{k \in N} \overline{e_k} = \sum_{k \in N} \frac{\alpha_k}{\beta_k}$ is the maximum level of the world's emissions. The fraction multiplying $\overline{E}$ is decreasing in Ψ and thus - as expected - the actual aggregate emission are lower when countries (and the world as a whole) have higher 'abatement indicators'.[14]

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[14] Alternatively, note that $\frac{1}{1+\Psi} = 1 - \frac{\Psi}{1+\Psi}$ decreases with $\frac{\Psi}{1+\Psi}$ which is the fraction of total emissions mitigated by all countries.

A decrease in net vulnerability in country i (e.g. technological progress in adaptation) results in a smaller abatement indicator Ψ_i. From (11), (12) and (13), any change in an abatement indicator Ψ_i affects emission and adaptation levels in all countries.

Proposition 1. *When countries behave non-cooperatively, if country i's net vulnerability Φ_i decreases*[15]*, it will choose to emit more and adapt more. All other countries respond optimally by reducing emissions and adapting more, and yet the global emissions rise.*

Proof. See Appendix A.1 ▫

Country i's adaptation measures become more effective and/or less costly as a result of technological progress in adaptation. Its natural vulnerability to climate change drops, and its marginal damage of emissions falls. Hence, country i can afford a higher emission level. However, the marginal damage of emissions of the rest of the world rises as a result of the increase in country i's emissions, and all other countries need to reduce their emissions. Regarding adaptation, the marginal benefit increases for each country as the world's emissions rise, but the marginal cost remains the same. For country i, the increase in the marginal benefit of adaptation may also be obtained by changes in v_i or θ_i, and the marginal cost may fall as a result of a fall in exogenous c_i. As a result, all countries increase adaptation investments. In summary, only the country which experiences technological progress in adaptation benefits from the progress, while other countries reduce emissions and suffer more damage from climate change.

3.2. Fully-cooperative Outcome (The Grand Coalition)

Suppose all nations are signatories of the IEA. All countries choose simultaneously e_i and a_i to maximize the joint welfare,

$$\max_{e_i,a_i} \sum_{i \in N} w\left(e_i, a_i, E\right) = \sum_{i \in N} \left[B(e_i) - D\left(E, a_i\right) - C\left(a_i\right)\right] \tag{14}$$

The first order conditions are given by,

$$e_i : \alpha_i - \beta_i e_i - \sum_{i \in N} v_i E + \sum_{i \in N} \theta_i a_i = 0 \tag{15}$$

$$a_i : \theta_i E - c_i a_i = 0 \tag{16}$$

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[15] i.e. technological progress in adaptation: θ_i rises and/or c_i falls, and/or its natural vulnerability to climate impacts falls: v_i decreases.

The best response functions for a country i are given by,

$$e_i = \frac{\alpha_i - \sum_{k \in N} \Phi_k E_{-i}}{\beta_i + \sum_{k \in N} \Phi_k} \tag{17}$$

$$a_i = \frac{\theta_i}{c_i} \left(\frac{\alpha_i + \beta_i E_{-i}}{\beta_i + \sum_{k \in N} \Phi_k} \right)$$

The global emissions and the individual emission levels can be derived from (15) and (16). Country i's emission and adaptation level are given by:

$$e_i^G = \overline{e_i} - \frac{\Psi_i^G}{1 + \Psi^G} \overline{E} \tag{18}$$

$$a_i^G = \frac{\theta_i E^G}{c_i} \tag{19}$$

where $\Psi_i^G \equiv \frac{\Phi}{\beta_i}$.[16] Similar to (11), the second term in (18) is the abatement level. However, a country's abatement indicator Ψ_i^G in (18) is much larger than in the non-cooperation case Ψ_i In the grand coalition, every country takes the joint vulnerability Φ into account instead of its own vulnerability Φ_i.

The full-cooperation level of global emissions is given by the following,

$$E^G = \frac{1}{1 + \Psi^G} \overline{E}, \tag{20}$$

where $\Psi^G \equiv \sum_{k \in N} \Psi_k^G$ is the global abatement indicator under the grand coalition.

With a grand coalition, the impact of technological progress in adaptation is very different from the non-cooperation case.

Proposition 2. *When all countries behave cooperatively, if country i's net vulnerability Φ_i decreases (i.e. adaptation measures become more effective: θ_i rises and/or c_i falls, and/or its natural vulnerability to climate impacts falls: v_i decreases), it pollutes more and adapts more. All other countries respond by increasing emissions and adapting more; and global emissions rise.*

Proof. See Appendix A.2 □

It is worth noting that in Proposition 2, when a country's net vulnerability changes, the response by other countries under full-cooperation is the opposite to the non-cooperation case. With full cooperation, if one country's net vulnerability falls, not only does that country's equilibrium emission level rise, but so do other countries' emissions. However, if all countries cooperate,

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[16] Superscript 'G' denotes the 'grand coalition'.

the damage from climate change is internalized and shared by all countries. Hence the benefit from a decrease in net vulnerability in one country is shared: all countries afford higher emissions.

An interesting implication of Proposition 2 is that technological progress in adaptation now has a public good feature, compared to being a pure private good in the non-cooperation case. Suppose a member experiences technological progress in adaptation. Its emission level increases less compared to the non-cooperation case. However, unlike the non-cooperation case, where all other countries have to reduce emissions, these countries can afford higher emission levels under full cooperation. Therefore, with a grand coalition, all countries benefit from technological progress in adaptation in one country.

Proposition 3. *Under full cooperation, the world emission level is lower than that in the non-cooperative case, i.e. $E^G < E$. The adaptation levels fall for all countries, while individual emissions of country i fall (rise) iff $\frac{\Phi_i}{\Phi} \leq (\geq) \frac{1+\Psi}{1+\Psi^G}$.*

Proof. See Appendix A.3 ☐

In the non-cooperation case, a country with high vulnerability Φ_i emits at a low emission level due to high marginal damage from emissions. In the cooperative case, all countries choose emissions according to the aggregate damage. Less vulnerable countries reduce emissions, and the world emission level falls. Thus, highly vulnerable countries can emit more (or sequestrate less) after joining the grand coalition. To gain a better understanding of the result on emissions above, suppose n and Φ are sufficiently large, and β is identical for all countries. $\frac{1+\Psi}{1+\Psi^G} = \frac{1+\sum_{k \in N} \frac{\Phi_k}{\beta_k}}{1+\sum_{k \in N} \Phi_k \sum_{k \in N} \frac{1}{\beta_k}} \approx \frac{1}{n}$. $e_i^G > e_i$ if the following is satisfied:

$$\frac{\Phi_i}{\sum_{j \in N} \Phi_j} > \frac{1}{n} \Leftrightarrow \Phi_i > \Phi_m,$$

where $\Phi_m \equiv \frac{1}{n} \sum_{j \in N} \Phi_j$ is the average net vulnerability. Thus in the full cooperation case, a country's emissions are likely to rise if its net vulnerability is greater than the average level. A 'high-Φ_i' country benefits from joining the grand coalition since it can now afford a higher emission level, while a 'low-Φ_i' country may lose from joining the grand coalition since it has to keep a lower emissions level compared to its non-cooperative benchmark. Therefore, an IEA on climate change is beneficial to countries with high net vulnerability to climate change (e.g. highly vulnerable to climate change and less capable of adaptation).

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3.3. Coalition Formation

We now move to analyze the general case of an IEA formed by any number of countries. Let S denote the set of signatories to a coalition, or an IEA, and s denote the measure of S (the number of signatories). Let O denote the set of non-signatories, and $(n - s)$ the measure of O (the number of non-signatories). Let $E^O(S)$ denote the aggregate emissions by non-signatories, and $E^O_{-i}(S)$ the emissions by all other non-signatories. Let $E^S(S)$ denote the aggregate emissions by the set of signatories and $E^S_{-j}(S)$ the emissions by all other signatories. $E^N(S) \equiv E^O(S) + E^S(S)$ is the world emissions given a coalition S.

3.3.1. Non-signatories

A non-signatory i behaves like a singleton and maximizes its individual payoffs, given other countries' emissions.

$$\max_{e_i, a_i} w\left(e_i, a_i, E^N\right) = B(e_i) - D\left(E^N, a_i\right) - C\left(a_i\right) \tag{21}$$

First order conditions are given by,

$$e_i : \alpha_i - \beta_i e_i - v_i\left(E^O + E^S\right) + \theta_i a_i = 0, \tag{22}$$

$$a_i : \theta_i\left(E^O + E^S\right) - c_i a_i = 0. \tag{23}$$

The best response functions for a non-signatory i are given as follows,

$$e_i = \frac{\alpha_i - \Phi_i\left(E^S + E^O_{-i}\right)}{\beta_i + \Phi_i}, \tag{24}$$

$$a_i = \frac{\theta_i}{c_i} \frac{\alpha_i + \beta_i\left(E^S + E^O_{-i}\right)}{\beta_i + \Phi_i}. \tag{25}$$

From (24), the aggregate best response function of emissions of all non-signatories, given $E^S(S)$ is given by the following:

$$E^O(S) = \frac{\overline{E}^O - \Psi^O E^S(S)}{1 + \Psi^O}, \tag{26}$$

where $\overline{E}^O \equiv \sum_{i \in O} \bar{e}_i$, $\Psi^O \equiv \sum_{i \in O} \Psi_i$.

3.3.2. Signatories

Signatories recognize the behavior of non-signatories. Every signatory j maximizes the joint welfare of S, taking as given the emissions by all non-signatories E^O.

$$\max_{e_j, a_j} \sum_{j \in S} w\left(e_j, a_j, E^N\right) = \sum_{j \in S}\left[B(e_j) - D\left(E^N, a_j\right) - C\left(a_j\right)\right] \tag{27}$$

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First order conditions are given as follows,

$$e_j : \alpha_j - \beta_j e_j - \sum_{j \in S} v_j \left(E^S + E^O \right) + \sum_{j \in S} \theta_j a_j = 0, \tag{28}$$

$$a_j : \theta_j \left(E^S + E^O \right) - c_j a_j = 0. \tag{29}$$

The best response functions for a signatory j are given by,

$$e_j = \frac{\alpha_j - \Phi^S \left(E^S_{-j} + E^O \right)}{\beta_j + \Phi^S}, \tag{30}$$

$$a_j = \frac{\theta_j}{c_j} \frac{\alpha_j + \beta_j \left(E^S_{-j} + E^O \right)}{\beta_j + \Phi^S}, \tag{31}$$

where $\Phi^S = \sum_{j \in S} \Phi_j$.

Using (28), (29) and (26), the world emission level and individual emission level can be derived. The emission level of a non-signatory and a signatory are given as follows:

$$e_i^O = \overline{e_i} - \Psi_i E^N = \overline{e_i} - \frac{\Psi_i}{1 + \Psi^O + \Psi^S} \overline{E}, \tag{32}$$

$$e_j^S = \overline{e_j} - \Psi_j^S E^N = \overline{e_j} - \frac{\Psi_j^S}{1 + \Psi^O + \Psi^S} \overline{E}, \tag{33}$$

where $\Psi_j^S \equiv \frac{\Phi^S}{\beta_j}$. The emission levels differ across countries, depending on the net vulnerability and marginal abatement cost. In (32) and (33), the second term is the abatement amount. The abatement indicator for a non-member, Ψ_i, is based on its own net vulnerability Φ_i, while for a member its abatement indicator Ψ_j^S depends on the aggregate vulnerability of the coalition Φ^S. A member country abates more than a comparable non-member.

The world's total emissions is the sum of E^S and E^O:

$$E^N(S) = E^S(S) + E^O(S) = \frac{\overline{E}}{1 + \Psi^O + \Psi^S}. \tag{34}$$

From (34), for a non-signatory i leaving O and joining S, the denominator of the world emissions increases by $\left(\frac{\Phi^S}{\beta_i} + \Phi_i \sum_{j \in S} \frac{1}{\beta_j} \right)$. If the IEA contains a large number of members, the world emission level could fall by a substantial amount. Thus the size of the coalition is crucial to the impact of an IEA. As mentioned in the full-cooperative case, less vulnerable countries may not benefit from joining the IEA. However, in order to achieve large abatement, it is crucial to have those countries participate in the IEA.

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Finally, the adaptation level of any country i is given by,

$$a_i = \frac{\theta_i E^N}{c_i}, \forall i \in N. \tag{35}$$

Proposition 4. *Given an existing coalition S, the impact of a decrease in net vulnerability depends on whether it originates in a non-member or member country: if a non-member's vulnerability decreases, it will pollute more and adapt more. All other non-members and members respond by reducing emissions and adapting more. If a member's vulnerability decreases, all members including itself pollute more and adapt more. Every non-member responds by reducing emissions. The global emission level always rises, as does the adaptation level for every country.*

Proof. See Appendix A.4 □

An intriguing implication of Propositions 2 and 4 is that adaptation technology has a public good feature inside the coalition, compared to being strictly a private good outside the coalition. All members increase emissions in response to a member's decrease in net vulnerability, while non-signatories need to reduce emissions and suffer more damage from climate change. If a signatory invests in adaptation technology to innovate more effective adaptation measures, the benefit of this investment is shared by all members. In other words, free-riding with respect to adaptation technology emerges inside an IEA on mitigation.

One solution to this problem is to incorporate R&D spending on adaptation technology in the IEA, and to require all members to contribute. For example, a research hub on adaptation technology can be established and funded by all members of an IEA. Related to this, Proposition 7 below shows that if technological progresses from R&D on adaptation can be made excludable as a club good inside an IEA, the incentives to free-ride on an IEA can be significantly reduced. These insights form some of the most interesting implications derived from our model.

A country's marginal cost of abatement (or marginal benefit of emissions) may also increase exogenously, e.g. due to new CO_2 intensive mineral discoveries, or due to shifts in the production structure of the economy induced by international trade (e.g. carbon leakage). Without cooperation, its equilibrium emissions will increase - *ceteris paribus* - with implications for the rest of the world. The following intermediary result illustrates the effects of free-riding in the presence of a global externality:[17]

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[17] For the two polar cases, non-cooperation and full cooperation, the impact of exogenous changes in the benefit function parameters (α and β) are presented Appendix B.

Lemma 1. *The impact of a change in the benefit of emissions (the change in abatement cost) are similar regardless of whether it originates in a non-member or a member country. If country i's marginal benefit of emissions shifts up (i.e. α_i rises), its emissions level will increase. All other countries respond by reducing emissions and adapting more, and global emissions rise. If country i's marginal benefit of emissions becomes flatter (i.e. β_i falls), the absolute value of its emissions increases. All other countries will respond in the opposite way, yet the global emissions change in the same direction as country i's emission change.*

Proof. See Appendix B.3 □

Signatories in an IEA take into account the aggregate damage of the coalition, while the benefit of emissions is still private to a country regardless of the membership status. Thus the impact of exogenous changes in the benefit side is similar across countries regardless of the existing coalition and a country's membership status. Nevertheless the increase in emissions of signatories is less pronounced than for non-signatories, following an exogenous rise in the marginal benefit of emissions (as α rises and/or β falls).

Lemma 2. *If no country joins the coalition, i.e. $S = \varnothing$ and $O = N$, then $E^N = E$, the non-cooperative global emission level. If all countries are members of the coalition, $E^N = E^G$, which is the global emissions level in the presence of the grand coalition. The global emissions $E^G \leq E^N \leq E$, and the global emission level falls in the size of the coalition. Adaptation levels $a_i^G \leq a_i^N \leq a_i$ for $\forall i \in N$.*

Proof. See Appendix A.5 □

The non-cooperation and full cooperation are two polar cases of the general coalition outcome given in this section. The larger the IEA, the lower the global and individual emission levels.

Proposition 5. *A non-member free rides on the coalition and increases its emission level, compared to the non-cooperation equilibrium. However, a member's emissions level rises by forming the coalition if and only if $\frac{\Phi_j}{\Phi^S} \geq \frac{1+\Psi}{1+\Psi^O+\Psi^S}$, i.e. iff it is relatively more vulnerable among the signatories. The coalition as a whole generates less emissions.*

Proof. See Appendix A.6 □

If an IEA on mitigation is formed, the IEA as a whole ends up curbing emissions. Facing a lower global emission level, non-members free ride on the IEA: they receive less damage from climate change and respond by . increasing emissions. The world emission level still decreases, and every country pays less climate change cost than in the non-cooperation equilibrium. However, the achievement of the IEA is undermined by the free-riding of non-members. In a world with heterogeneous countries, a signatory may be able to pollute more than its non-cooperative

equilibrium level if it is relatively more vulnerable than other signatories. Combined with the fact that every country suffers less damages from climate change, a signatory that emits more than its non-cooperation level will certainly benefit from forming the coalition.

4. Stability

Since there does not exist a supranational institution that can enforce participation, an IEA must be *self-enforcing* as a result of the strategic behaviour of agents. A substantial part of existing literature on IEAs (Barrett (1994), Barrett (1997), McGinty (2007), Pavlova and de Zeeuw (2013), and Lazkano et al. (2014)) analyze the formation and stability of an IEA using the internal and external stability conditions defined in D'Aspremont et al. (1983): a coalition is stable internally if no member wants to leave and externally if no non-member wants to join. Most of the studies analyze stability of an IEA assuming limited types of agents and no role for adaptation. Lazkano et al. (2014) consider carbon leakage and incorporate adaptation in the model. If two types adaptation costs are assumed, the paper shows that such limited heterogeneity in adaptation cost may extend the coalition size, even to the grand coalition. Their result implies that policies aiming at reducing the gap in adaptation cost - for example by encouraging the diffusion of technology - may negatively affect an IEA on climate change.

However, we find that large gaps in vulnerability prevents the formation of a coalition. If gaps in vulnerability are large among countries, members that are less vulnerable to climate change are better off by leaving the coalition. The internal stability condition is violated, and a stable coalition cannot be formed with significant disparity of vulnerability among countries. This result implies technological progress in adaptation in highly vulnerable countries can help reduce the gaps, and hence fosters cooperation in climate change mitigation.

Three conditions need to be satisfied at a coalition equilibrium: profitability, internal stability and external stability (Hoel (1992), Finus (2001), and Carraro (2003)). Since internal stability implies profitability in our model (see (11)), we focus on internal and external stability conditions in this section. Nevertheless, the profitability condition is explored in Appendix E, and it can be applied to the pivotal-countries case where an IEA can only be formed when pivotal countries all participate. The result implies a large gap in adaptation among pivotal countries may prevent the emergence of an IEA.

4.1. Cooperative Incentives and Free-riding Incentives

Let $S\setminus\{j\}$ denote the remaining coalition when signatory j leaves the coalition S, and $S\cup\{i\}$ denote the coalition when non-signatory i accedes to the coalition S. The superscripts S and O denote whether the country behaves like a signatory or a non-signatory.

For a given coalition S, a signatory j's emission and the world emission levels are given by (33) and (34). From (32), a signatory's emissions if it leaves the IEA is given by (36). The world's total emissions can be derived from (34), and is given by (37).

$$e_j^O(S\setminus\{j\}) = \overline{e_j} - \frac{\Psi_j}{1+\Psi^O(S\setminus\{j\})+\Psi^S(S\setminus\{j\})}\overline{E} \tag{36}$$

$$E(S\setminus\{j\}) = \frac{\overline{E}}{1+\Psi^O(S\setminus\{j\})+\Psi^S(S\setminus\{j\})}, \tag{37}$$

where $1+\Psi^O(S\setminus\{j\})+\Psi^S(S\setminus\{j\}) = 1+\Psi^O+\Psi^S+2\Psi_j-\Psi_j^S-\Phi_j\sum_{k\in S}\frac{1}{\beta_k}, j\in S$.

Define the cooperative incentive for a signatory as the current welfare minus the welfare of being a non-signatory. From (33), (34), (36) and (37), the cooperative incentive for $j\in S$ is:

$$\Gamma_j^S(S) = w_j^S(S) - w_j^O(S\setminus\{j\}) \tag{38}$$

$$= [B_j^S(S)-B_j^O(S)] - \{[D_j^S(S)-D_j^O(S)]+[C_j^S(S)-C_j^O(S)]\} \tag{39}$$

$$= \frac{\overline{E}^2}{2}\left[\frac{\Phi_j\Psi_j+\Phi_j}{(1+\Psi^O(S\setminus\{j\})+\Psi^S(S\setminus\{j\}))^2} - \frac{\Phi^S\Psi_j^S+\Phi_j}{(1+\Psi^O+\Psi^S)^2}\right]. \tag{40}$$

For a given coalition S, a non-signatory i's emission and the world emission levels are given by (32) and (34). From (33), a non-signatory i's emissions if it joins the IEA is given by (41). The world's total emissions can be derived from (34), and is given by (42).

$$e_i^S(S\cup\{i\}) = \overline{e_i} - \frac{\Psi_i^S+\Psi_i}{1+\Psi^O(S\cup\{i\})+\Psi^S(S\cup\{i\})}\overline{E} \tag{41}$$

$$E(S\cup\{i\}) = \frac{\overline{E}}{1+\Psi^O(S\cup\{i\})+\Psi^S(S\cup\{i\})}, \tag{42}$$

where $1+\Psi^O(S\cup\{i\})+\Psi^S(S\cup\{i\}) = 1+\Psi^O+\Psi^S+\Psi_i^S+\Phi_i\sum_{k\in S}\frac{1}{\beta_k}, i\in O$. Note $1+\Psi^O(S\cup\{i\})+\Psi^S(S\cup\{i\}) > 1+\Psi^O+\Psi^S$. World emissions fall if the non-signatory joins the IEA.

The free-riding incentive for a non-member country is defined as its current welfare minus

welfare of being a signatory of a coalition. The free-riding incentive for a non-signatory $i \in O$ is:

$$\Gamma_i^O (S) = w_i^O (S) - w_i^S (S \cup \{i\}) \tag{43}$$

$$= [B_i^O(S) - B_i^S(S)] - \{[D_i^O(S) - D_i^S(S)] + [C_i^O(S) - C_i^S(S)]\} \tag{44}$$

$$= \frac{\overline{E}^2}{2} \left(\frac{(\Phi^S + \Phi_i)(\Psi^S + \Psi_i) + \Phi_i}{(1 + \Psi^O(S \cup \{i\}) + \Psi^S(S \cup \{i\}))^2} - \frac{\Phi_i \Psi_i + \Phi_i}{(1 + \Psi^O + \Psi^S)^2} \right). \tag{45}$$

It is easy to see that a non-member i's free-riding incentive given a coalition S is the negative of its cooperative incentive given a coalition $S \cup \{i\}$; a member j's cooperative incentive given a coalition S is the negative of its free-riding incentive given the coalition $S \backslash \{j\}$.

4.2. Stability

The internal and external stability conditions are given, respectively, by:

$$\Gamma_j^S (S) = w_j^S (S) - w_j^O (S \backslash \{j\}) \geq 0, \forall j \in S \tag{46}$$

$$\Gamma_i^O (S) = w_i^O (S) - w_i^S (S \cup \{i\}) > 0, \forall i \in O, \tag{47}$$

where (46) is the internal stability condition, which requires a signatory of the IEA to be no worse off than if it leaves the IEA. (47) is the external stable condition, which indicates any non-signatory should have higher welfare than if it joins the IEA. In summary, the coalition is stable if all members have non-negative cooperative incentives and all non-members have positive free-riding incentives.

Lemma 3. *(Sufficient condition to cooperative incentive) If a member j's emission level is no lower than if it leaves the coalition, its cooperative incentive for the given coalition is positive.*

Proof. see Appendix A.7.1 □

With heterogeneous countries, it is not necessary that every member reduces emissions. If a country could maintain at least the same emission level as when it is a non-member, its cooperative incentive is positive. Equation (39) helps interpret Lemma 3. The cooperative incentive of a member is composed of two parts: the change of the benefit of emissions (first terms) and the change of climate change costs (the last term). Since a country's benefit of emissions is increasing in its emissions, if a member's emission level is not lower than if it leaves the coalition, the change of the benefit of emissions is non-negative. Moreover, since the world emission level is always lower with a larger IEA, the member's climate change cost is lower if

it chooses to stay in the IEA. Thus such a signatory to an IEA has a higher welfare than if it leaves the IEA. However, if a signatory needs to reduce its emissions when joining, its cooperative incentive depends on whether its reduced climate change cost is enough to compensate to the foregone benefit of emissions.

Relationships between emission changes and cooperative incentives are illustrated in Table 1. There may exist three types of countries[18] inside any coalition S.

Types	Emission Change	Cooperative Incentives
Strongly-cooperative: e.g. high $\frac{\Phi_j}{\Phi^S}$, low β_j	$e_j^S(S) \geq e_j^O(S\backslash\{j\})$	$\Gamma_j^S(S) > 0$
Weakly-cooperative: e.g.medium $\frac{\Phi_j}{\Phi^S}$, low β_j	$e_j^S(S) < e_j^O(S\backslash\{j\})$	$\Gamma_j^S(S) \geq 0$
Non-cooperative: e.g. low $\frac{\Phi_j}{\Phi^S}$	$e_j^S(S) < e_j^O(S\backslash\{j\})$	$\Gamma_j^S(S) < 0$

Table 1: Emission Changes and Cooperative Incentives

For any given coalition, there may exist three types of members based on their net vulnerability and slope of marginal benefit of emissions. Strongly-cooperative members are described in Lemma 3. These countries can be relatively highly vulnerable to climate change compared to other members. Outside the coalition, a country with high vulnerability keeps a low emission level. After it joins the coalition, its vulnerability is considered by all other members and the global emission level falls. As a result the highly vulnerable country can afford higher emission level. It receives more benefit from emissions and less climate change damages. A weakly-cooperative member needs to reduce its emissions if it chooses to join in the coalition, but its total welfare rises: the reduced climate change cost by joining the coalition is enough to compensate for the foregone benefits of emissions. With homogeneous countries, a stable coalition consists only of weakly-cooperative members, while with heterogeneous countries, a stable coalition can include a mix of strongly-cooperative and weakly-cooperative members.

Non-cooperative countries can be less vulnerable relative to other members. They need to reduce a significant amount of emissions but benefit little from global emissions reduction. Thus their welfare is lower if they choose to join the coalition, according to the internal stability condition in (46). Such 'non-cooperative countries' cannot belong to a stable coalition since

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[18] Exact conditions on both Φ and β that define these types can be found in Appendix A.8

free-riding on the coalition is a better choice for them.

4.3. Disparity in Vulnerability and Cooperative Incentives

Vulnerability to climate change differs greatly across countries as a result of dissimilar natural sensitivity, disparate technology levels etc. In this section, we focus on disparity in vulnerability and the formation of an IEA. If the gap in net vulnerability is large enough, less vulnerable countries are not likely to cooperate with highly vulnerable countries. Thus if countries differ much in net vulnerability, a large stable coalition is not likely to be formed.

Proposition 6. *In a given coalition, less vulnerable countries have lower cooperative incentives. If there exists at least one member j with relatively low vulnerability, s.t.$\frac{\Phi_j^2 + \beta_j \Phi_j}{(\Phi^S)^2 + \beta_j \Phi_j} < \frac{(1 + \Psi^O(S \backslash \{j\}) + \Psi^S(S \backslash \{j\}))^2}{(1 + \Psi^O + \Psi^S)^2}$, its cooperation incentive is negative and the coalition is not stable.*

Proof. See Appendix A.9 □

To better understand the role of heterogeneous vulnerability in countries' cooperative incentives and the structure of stable coalitions, suppose countries are symmetric on benefit side (identical α and β for all countries). From (40), $\lim_{\Phi_j \to 0} \Gamma_j^S(S) < 0$, and $\lim_{\Phi_j \to \Phi^S} \Gamma_j^S(S) > 0$. Thus there exists a $\Phi^* \in (0, \Phi^S)$ such that $\Gamma_j^S(S) = 0$. For countries with vulnerability greater than Φ^*, their cooperative incentives are positive. However, if a signatory's vulnerability is below Φ^*, its welfare rises if it leaves the IEA. Thus the IEA is internally stable if and only if all signatories have vulnerability no less than Φ^*.

Let us look at a simple case with an IEA that consists only two countries. For a given agreement, all coalition-level parameters are fixed, and countries differ in their net vulnerability. Suppose the two countries' vulnerability does not differ much from each other (every country's vulnerability is close to the average level), as shown in Fig.(A.2); all countries may have positive cooperative incentives as their vulnerability is close to the average vulnerability Φ^m. However, if two countries substantially differ from each other in vulnerability, for example, as the Φ^L and Φ^H in Fig.(A.2), the one with low vulnerability becomes 'non-cooperative' and will choose to stay outside the coalition. Hence a stable coalition cannot be formed if members differ much in vulnerability.

The result implies policies which assist vulnerable countries with adaptation technology can help reduce the gaps and foster international cooperation on mitigation. Thus climate change

funds like the Green Climate Fund, which is meant to assist developing countries with adaptation may actually be instrumental in forming an IEA on climate change mitigation.

5. Diffusion of Adaptation Technology

Free-riding on mitigation is the main problem preventing a large IEA from being formed (Yi (1997), Finus (2008)). Since climate change mitigation is a public good, countries have an incentive to stay out and free ride on an international mitigation agreement. As a result, the size of a stable IEA is small, or - as mentioned already in the introduction - a high degree of cooperation can be achieved only when the gains of cooperation is small (Barrett (1994), Barrett (1997), Pavlova and de Zeeuw (2013)). The literature on IEA formation has suggested many ways to extend the cooperation, (Carraro and Siniscalco (1993), Hoel and Schneider (1997), McGinty (2007), Fuentes-Albero and Rubio (2010)), for example side-payments, dispute settlement and monitoring mechanisms. However, as mentioned above, the logistics of transfers and moral hazard issue are problematic. From Proposition 4, adaptation technology has a public good feature inside a coalition, compared to being strictly a private good outside the coalition. In other words, besides the free-riding with respect to mitigation, free-riding with respect to adaptation technology emerges inside an IEA on mitigation.

In this section, we show that technological progress in adaptation, provided as a excludable 'club good' to members of an IEA, can effectively reduce the free-riding with respect to mitigation. For example, the IEA can be accompanied by an R&D hub on adaptation technology. Any innovation from the R&D hub will be diffused and implemented by members only. Moreover, if all members are required to contribute to the R&D hub, the free-riding with respect to adaptation technology within an IEA can be mitigated.

Technological progress in adaptation increases the effectiveness and/or reduce the cost of adaptation activities (θ_i rises and/or c_i falls), and hence reduces a member's net vulnerability to climate change Φ_i. Also, new general adaptation technologies need to be adopted to country j's specific adaptation needs, and the cost and effectiveness of adopting new technology should be country-specific. Suppose the net vulnerability becomes $r_j \Phi_j$ for a member of the IEA, where $r_j \in [0, 1]$ is a country-specific index measuring adoption cost. The higher the r_j is, the more difficult for country j to adopt the new technology, and the less it can benefit from the

technological progress in adaptation. If a member j leaves the IEA, its access to the technology diffusion will be ceased, and its net vulnerability reverts to Φ_j. The technological progress is assumed to be restricted to the members of the IEA. Thus for a non-member $i \in O$, its vulnerability remains Φ_i.

Proposition 7. *Incentives to free-ride on an IEA can be reduced/eliminated by a coalition which diffuses technological progress on adaptation among its members. If in general $\beta_i >> \Phi_i$, $\forall i \in N$, incentives to free-ride on an IEA increases in adoption cost index, i.e. the more a country could benefit from the technology diffusion the less its incentive to free-ride on an IEA.*

Proof. See Appendix A.10 □

The numerical example illustrating Proposition (7) in Section 6. The opposite case to $\beta_i >> \Phi_i, \forall i \in N$ is trivial since this case implies that the damage from emissions is much greater than the benefit from emissions and the net welfare can be negative for all countries [19]. $\beta_i >> \Phi_i$ where countries benefit to emit GHGs is a more likely case. Free riding on an international mitigation agreement can be reduced or even eliminated with the diffusion of adaptation technology inside an IEA since the incentive to free ride is offset by the benefits stemming from the technology diffusion. Thus international cooperation on mitigation can be fostered by the formation of an R&D hub on adaptation technology which diffuses technological progress in adaptation. Moreover, if the R&D on adaptation technology is funded by all members of an IEA, free-riding with respect to adaptation inside an IEA can be mitigated.

6. Simulation

Previous literature on IEAs has shown that analytical solutions of stable coalitions are not available with non-linear functional forms (Barrett (1997), McGinty (2007), Finus (2008)). Thus, simulation has been heavily relied upon to analyze the stability of coalitions. However, most studies focusing on formation and stability of an IEA assume arbitrary parameters (Barrett (1997), McGinty (2007), Pavlova and de Zeeuw (2013), Lazkano et al. (2014)). Botteon and Carraro (1997) and Botteon and Carraro (2001) analyze stability of an IEA using calibrated costs and benefits for five countries/regions. Botteon and Carraro (1997) focus on partial commitment and transfers, and find that with heterogeneous countries a transfer system can induce very high

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[19] The exact condition which needs to be satisfied to have $\frac{\partial \Gamma_i^O}{\partial r_i} > 0$ can be found in the Appendix A.10

cooperation. Botteon and Carraro (2001) add carbon leakage (increasing marginal damages), and obtain an ambiguous impact of carbon leakage on the stability of an IEA. In this section, we focus on stability of a coalition and technology diffusion using parameter estimated from climate change data. As noted in Finus (2008), simulations based on scientifically estimated parameters should have some merits.

6.1. Data

The benefits of emissions function is estimated using GDP and GHG emissions for each country. GDP (current US dollars) is collected from the World Bank (2014). The GHG emission (kt of CO2 equivalent) is aggregated from CO_2, Methane emissions, Nitrous oxide emissions, and other greenhouse gas emissions (HFC, PFC and SF6), which are obtained from the World Bank (2014). Due to the adaptation data limitations,[20] parameters in the damage function and cost of adaptation are integrated into the net vulnerability, $\Phi_i \equiv v_i - \frac{\theta_i^2}{c_i}$. Φ_i can be estimated by the damage caused by GHG emissions and the world's total GHG emissions. We use the climate change cost from DARA International (2012) as a proxy for the damage[21]. The estimated net vulnerability is lower than the actual vulnerability for two reasons: first, adaptation cost is not included due to the limitation of data; second, indirect impacts of climate change, which are difficult to quantify are not included. Thus, our estimation provides a conservative insight into vulnerability and welfare gain of international cooperation on climate change. The summary statistics can be found in Appendix Appendix C.

Parameters in the model are estimated from GDP, GHG emissions, and climate change costs. First, α_i and β_i are estimated for each country using data from 1960-2010. A caveat is that the relation between GDP and GHG emissions is far more complicated than a benefit function. As such, the estimation does not aim to quantify the relationship between GDP and emissions; rather, the goal is only to obtain parameters for the numerical example. Hence, observations with negative α_i or positive βi are dropped, and 143 observations (countries) are left.

$$GDP_{it} = \alpha_i e_{it} - \frac{\beta_i}{2} e_{it}^2.$$

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[20] To our best knowledge, there has not been any data comprehensively measuring cross-country adaptation cost and effectiveness.

[21] For details, please visit http://daraint.org/climate-vulnerability-monitor/climate-vulnerability-monitor-2012/

Second, using climate change costs in 2010 from DARA International (2012), the net vulnerability Φ_i is estimated for each country. The world's total GHG emissions is obtained from the World Bank (2014).

$$climate\_ change\_ cost_i = \Phi_i E^2.$$

Third, countries are clustered into 10 groups by α_i, β_i, and Φ_i using the the *k-means* method. A representative country whose parameters are closest to the group mean will be chosen from each group. The net vulnerability Φ_i is estimated using the global emission level that is much higher than the emissions of the 10 representative countries, and, hence, the climate change damage for each representative country is substantially under-estimated. Thus, Φ_i is re-scaled using the climate change cost and the aggregate emission level of the 10 representative countries. Last, with all the parameters, α_i, β_i, and the rescaled Φ_i, stable coalitions and impacts of diffusion of adaptation technology are simulated.

6.2. Results

The parameter values are given in Table C.4. Note that β_i in general is $10 - 10^9$ times larger than Φ_i since, from the data, the benefits of emissions are greater than damages from climate change. As shown in Table C.5, the largest stable coalition consists of representative countries $\{2, 4, 5, 6\}$, which lead to 2.5% fall of global emissions. With a grand coalition, the world's emission level drops by 7.6% and the welfare rises by 0.8% compared to the non-cooperative equilibrium. Here, the results are very conservative as a result of the 10 representative countries and under-estimated net vulnerability. The outcome is affected by parameter choice. With heterogeneous benefits and damage and cost function, multiple equilibria may exist, and large coalitions are expected with certain set of parameters.

As stated in Proposition 7, incentives to free ride can be effectively reduced or even eliminated with a coalition that diffuses adaptation technology. Figure 1 illustrates that a non-member's free-riding incentive decrease as the adoption cost of new adaptation technology drops. When $r_i = 1$ (the right end of Figure 1), non-members do not benefit from the technology diffusion if they choose to join the IEA since the cost to adopt the new technology is too high. This case is equivalent to the original case in Section 2 where diffusion is not considered. Indeed, for non-members $\{1, 3, 7, 8, 9, 10\}$, their free-riding incentives are positive, which is consistent with the external stability condition in Section 4. However, if $r_i < 1, i \in \{1, 3, 7, 8, 9, 10\}$, which indicates
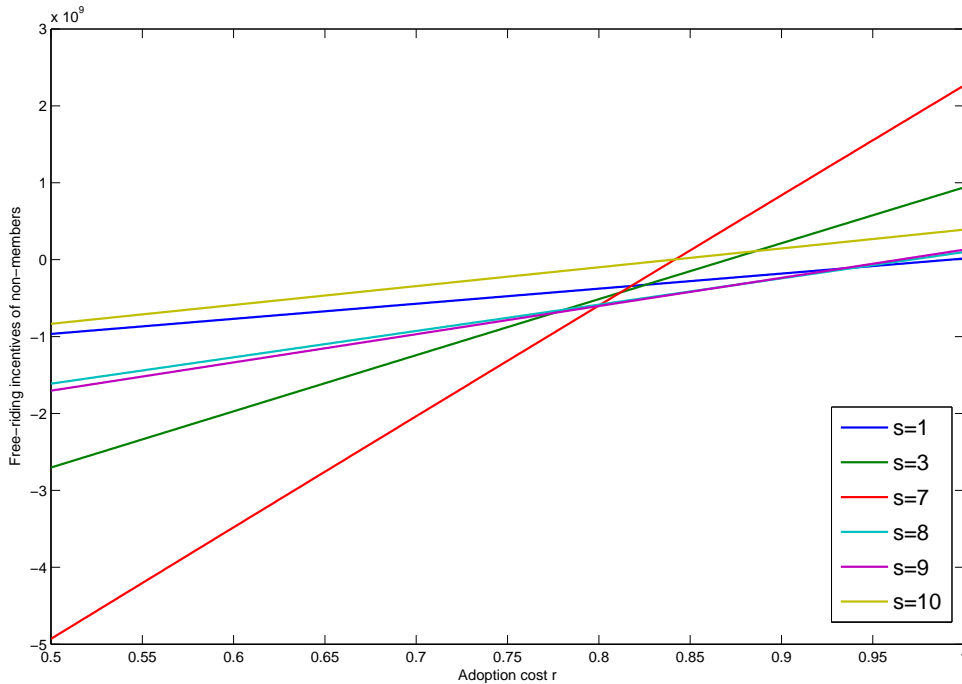
Figure 1: Free-riding Incentives and diffusion of technological progress: $\Gamma_i^O(r_i)$

a non-member i can benefit from the technology diffusion and reduce its vulnerability if it joins the IEA, country i's free-riding incentive decreases compared to the original case. Moreover, the lower the adoption cost, the more a non-member can benefit from the within-coalition diffusion, and the less free-riding incentive it has. Last, free-riding incentives of non-members can be negative, which implies that incentives to free ride on an IEA are eliminated with a low enough adoption cost of the new technology.

7. Conclusion

This paper investigates the impact of adaptation technology on a country's incentive to participate in emission-reducing International Environmental Agreements on climate change. We develop a framework where heterogeneity across countries is introduced with respect to the benefits and costs of both mitigation of emissions and adaptation to reduce the impact of climate change. Using two coalition stability concepts, the paper focuses on the relationship between adaptation technology and the formation of an IEA. More effective adaptation technology in highly vulnerable countries can foster an IEA on mitigation. If an IEA exists, adaptation tech-

nology has a public good feature among the members of the agreement and can be under-provided in member countries. Moreover, the role of knowledge diffusion is explored in this paper. Diffusion of adaptation technology among members can reduce/eliminate free-riding with respect to mitigation and enlarge an IEA. Lastly, we simulate stable coalitions with parameters estimated from climate change data, and demonstrate how diffusion of adaptation technology reduces free-riding in an IEA.

The global debates around the issue of cooperation on climate change are becoming increasingly polarized, often with developing and developed countries on opposite sides. While the former are stressing global participation in emission reduction pledges, the latter insist on adaptation funding for the poorer and more vulnerable countries. Between July to December in 2014, US\$ 10.14 billion from 24 countries had been pledged to the Green Climate Fund, which is a part of the UNFCCC assisting the developing countries in adaptation and mitigation practices. Moreover, the primary focus of the COP21 in Paris in 2015 is to reach a treaty on mitigation of GHGs, in which the responsibility of reducing GHG emissions is shared with both developed and developing economies. Our results shed some light on these practical international cooperation issues: first, we show how disparity in terms of vulnerability between countries prevents the formation of a large IEA. Thus, policies directed at helping the poorer and most vulnerable countries protect themselves against climate-induced impacts (e.g. the Cancun Adaptation Fund and the Green Climate Fund) can foster cooperation on mitigation between vulnerable and less vulnerable countries.

Secondly, mitigation and R&D in adaptation can work together. Mitigation of GHG emissions is a global public good, and hence countries want to be free riders rather than participate in an emission-reducing agreement. However, this type of free-riding incentives can be reduced by the diffusion of adaptation technology among the members of the agreement. Therefore, an international mitigation agreement can be negotiated jointly with an R&D hub on adaptation technology which diffuses new technology to only members. Moreover, the papers shows that progress in adaptation technology in a member country has a public good feature. Thus, if an R&D hub on adaptation is formed within an international mitigation agreement, the cooperation incentives are enhanced just as free riding on adaptation innovation is reduced.

References

Barrett, S., 1994. Self-enforcing international environmental agreements. Oxford Economic Papers 46, 878–894.

Barrett, S., 1997. Heterogeneous international environmental agreements. In: Carraro, C. (Ed.), International Environmental Negotiations: Strategic Policy Issues. Edward Elgar Publishing, Ch. 2, pp. 9–25.

Benchekroun, H., Marrouch, W., Chaudhuri, A. R., 2014. Adaptation technology and free riding incentives in international environmental agreements. American Economic Association Annual Meeting.

Botteon, M., Carraro, C., 1997. Burden-sharing and coalition stability in environmental negotiations with asymmetric countries. In: Carraro, C. (Ed.), International Environmental Negotiations: Strategic Policy Issues. Edward Elgar Publishing, Ch. 3, pp. 26–55.

Botteon, M., Carraro, C., 2001. Environmental coalitions with heterogeneous countries: Burden-sharing and carbon leakage. In: Ulph, A. (Ed.), Environmental Policy, International Agreements, and International Trade. Oxford University Press, Ch. 3, pp. 38–65.

Carraro, C., 2003. The endogenous formation of economic coalitions. Edward Elgar Publishing.

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

DARA International, 2012. Climate Vulnerability Monitor 2nd Edition: A Guide to the Cold Calculus of a Hot Planet. Accessed: 2014-12-24.
URL http://daraint.org/climate-vulnerability-monitor/climate-vulnerability-monitor-2012

D'Aspremont, C., Jacquemin, A., Gabszewicz, J. J., Weymark, J. A., 1983. On the stability of collusive price leadership. Canadian Journal of Economics 16, 17–25.

Eichner, T., Pethig, R., 2013. Self-enforcing environmental agreements and international trade. Journal of Public Economics 102, 37–50.

Finus, M., 2000. Game theory and international environmental co-operation: a survey with an application to the kyoto-protocol, nota di Lavoro Fondazione Eni Enrico Mattei: 86.2000.

Finus, M., 2001. Game Theory and International Environmental Cooperation. Edward Elgar Publishing.

Finus, M., 2008. Game theoretic research on the design of international environmental agreements: Insights, critical remarks, and future challenges. International Review of Environmental and Resource Economics 2 (1), 29–67.

Finus, M., Pintassilgo, P., 2013. The role of uncertainty and learning for the success of international climate agreements. Journal of Public Economics 103, 29–43.

Fuentes-Albero, C., Rubio, S. J., 2010. Can international environmental cooperation be bought? European Journal of Operational Research 202 (1), 255–264.

Hoel, M., 1992. International environment conventions: the case of uniform reductions of emissions. Environmental and Resource Economics 2 (2), 141–159.

Hoel, M., Schneider, K., 1997. Incentives to participate in an international environmental agreement. Environmental and Resource Economics 9 (2), 153–170.

Kousky, C., 2012. Informing climate adaptation: a review of the economic costs of natural disasters, their determinants, and risk reduction options. Resources For the Future Discussion Papers 12-28.

Lazkano, I., Marrouch, W., Nkuiya, B., 2014. Adaptation to climate change: How does heterogeneity in adaptation costs affect climate coalitions? CIRANO Scientific Publications 2014s-29.

McGinty, M., 2007. International environmental agreements among asymmetric nations. Oxford Economic Papers 59 (1), 45.

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. Cambridge University Press.

Pavlova, Y., de Zeeuw, A., 2013. Asymmetries in international environmental agreements. Environment and Development Economics 18 (1), 51–68.

Stern, N., 2008. The economics of climate change. American Economic Review 98 (2), 1–37.

UNEP, 2012. The Emissions Gap Report 2012. United Nations Environment Programme (UNEP), Nairobi.

World Bank, 2014. Climate change indicators. Accessed: 2014-12-24.
    URL http://data.worldbank.org/indicator

Yi, S.-s., 1997. Stable coalition structures with externalities. Games and Economic Behavior 20 (2), 201–237.

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

APPENDIX:

Appendix A. Proofs

Appendix A.1. Proof of Proposition 1

Proof. For country i, from (11) and (13),

$$\frac{\partial e_i}{\partial \Phi_i} = -\frac{1 + \Psi - \Psi_i}{\beta_i (1 + \Psi)^2} \overline{E} < 0, \tag{A.1}$$

$$\frac{\partial e_j}{\partial \Phi_i} = \frac{\Psi_j}{\beta_i (1 + \Psi)^2} \overline{E} > 0, j \neq i \in N,$$

$$\frac{\partial E}{\partial \Phi_i} = -\frac{1}{\beta_i (1 + \Psi)^2} \overline{E} < 0.$$

If country i's net vulnerability Φ_i decreases, it will choose to emit more. All other countries respond by reducing emissions, while the global emissions rise.

Substituting (13) into (12), the adaptation level of country i is given by,

$$a_i = \frac{\theta_i}{c_i} \frac{\overline{E}}{1 + \sum\limits_{k=1}^{n} \frac{\Phi_k}{\beta_k}}$$

The net vulnerability change may be caused by change(s) of any of θ_i, c_i, and v_i. Hence the change of adaptation level of country i is given by,

$$\frac{da_i}{d\theta_i} = \frac{\overline{E}}{c_i(1 + \Psi)} \left(1 + \frac{2\theta_i^2}{\beta_i c_i} \frac{1}{1 + \Psi}\right) > 0,$$

$$\frac{da_i}{dc_i} = -\frac{\theta_i \overline{E}}{c_i^2(1 + \Psi)} \left(1 + \frac{\theta_i^2}{\beta_i c_i} \frac{1}{1 + \Psi}\right) < 0,$$

$$\frac{da_i}{dv_i} = -\frac{\theta_i \overline{E}}{\beta_i c_i} \frac{1}{(1 + \Psi)^2} < 0.$$

Thus a decrease in net vulnerability of country i (which can be caused by an increase in θ_i, and/or a decrease in c_i, and/or a decrease in v_i) lead to higher adaptation level of country i.

For any other country j, the adaptation level will rise:

$$\frac{da_j}{d\Phi_i} = \frac{\partial a_j}{\partial E} \frac{\partial E}{\partial \Phi_i} = -\frac{\theta_j \overline{E}}{\beta_i c_j} \frac{1}{(1 + \Psi)^2} < 0 < 0, j \neq i \in N.$$

$\square$

Appendix A.2. Proof of Proposition 2

Proof. From (18) and (20),

$$\frac{\partial e_i^G}{\partial \Phi_i} = -\frac{1}{\beta_i (1 + \Psi^G)^2} \overline{E} < 0 \tag{A.2}$$

$$\frac{\partial e_j^G}{\partial \Phi_i} = -\frac{1}{\beta_j (1 + \Psi^G)^2} \overline{E} < 0 \tag{A.3}$$

$$\frac{\partial E^G}{\partial \Phi_i} = -\left(\sum_{k \in N} \frac{1}{\beta_k}\right) \frac{1}{(1 + \Psi^G)^2} \overline{E} < 0 \tag{A.4}$$

where $j \neq i \in N$, and $\Phi_i \equiv v_i - \frac{\theta_i^2}{c_i}$. If country i's net vulnerability Φ_i decreases, all countries choose to emit more, and the global emissions rise.

The adaptation level of country i is given by,

$$a_i^G = \frac{\theta_i}{c_i} \frac{\overline{E}}{1 + \sum\limits_{k=1}^{n} \frac{\Phi}{\beta_k}}$$

The net vulnerability change may be caused by change(s) of any of θ_i, c_i, and v_i. Hence the change of adaptation level of country i is given by,

$$\frac{da_i^G}{d\theta_i} = \frac{\overline{E}}{c_i(1 + \Psi^G)} \left(1 + \frac{2\theta_i^2}{c_i} \frac{1}{1 + \Psi} \sum_{k=1}^{n} \frac{1}{\beta_k}\right) > 0,$$

$$\frac{da_i^G}{dc_i} = -\frac{\theta_i \overline{E}}{c_i^2(1 + \Psi)} \left(1 + \frac{\theta_i^2}{c_i} \frac{1}{1 + \Psi} \sum_{k=1}^{n} \frac{1}{\beta_k}\right) < 0,$$

$$\frac{da_i^G}{dv_i} = -\frac{\theta_i \overline{E}}{c_i} \frac{1}{(1 + \Psi)^2} \sum_{k=1}^{n} \frac{1}{\beta_k} < 0.$$

Thus a decrease in net vulnerability of country i (which can be caused by an increase in θ_i, and/or a decrease in c_i, and/or a decrease in v_i) lead to higher adaptation level of country i.

For any other country j, the adaptation level will rise as well:

$$\frac{da_j^G}{d\Phi_i} = \frac{\partial a_j^G}{\partial E^G} \frac{\partial E^G}{\partial \Phi_i} = -\frac{\theta_j \overline{E}}{c_j} \frac{1}{(1 + \Psi)^2} \sum_{k=1}^{n} \frac{1}{\beta_k} < 0, j \neq i \in N.$$

$\square$

Appendix A.3. Proof of Proposition 3

Proof. For emission and adaptation levels,

$$\frac{E^G}{E} = \frac{1 + \Psi}{1 + \Psi^G} < 1,$$

$$a_i^G = \frac{\theta_i E^G}{c_i} < a_i = \frac{\theta_i E}{c_i}.$$

The difference in emission level is given by,

$$e_i^G - e_i = \frac{\Psi_i}{1+\Psi}\overline{E} - \frac{\Psi_i^G}{1+\Psi^G}\overline{E}.$$

Note $\frac{\Psi_i}{1+\Psi}\overline{E}$ and $\frac{\Psi_i^G}{1+\Psi^G}\overline{E}$ are abatement levels. A country can increase its emissions if it can abate less by joining the grand coalition, and this happens if its vulnerability is relatively large compared to the coalition:

$$e_i^G \leq e_i \Leftrightarrow \frac{\Psi_i}{1+\Psi} \leq \frac{\Psi_i^G}{1+\Psi^G} \Leftrightarrow \frac{\Phi_i}{\Phi} \leq \frac{1+\Psi}{1+\Psi^G}.$$

$\square$

Appendix A.4. Proof of Proposition 4

Proof. Suppose a non-member country i experiences a technological progress in adaptation (i.e. adaptation measures become more effective and costless: θ_i rises and/or c_i falls, and/or its natural vulnerability to climate impacts falls: v_i decreases).

$$\frac{\partial e_i^O}{\partial \Phi_i} = -\frac{1 + \Psi^O + \Psi^S - \Psi_i}{\beta_i \left(1 + \Psi^O + \Psi^S\right)^2}\overline{E} < 0.$$

All other countries respond oppositely:

$$\frac{\partial e_k^O}{\partial \Phi_i} = \frac{\Psi_i}{\beta_i \left(1 + \Psi^O + \Psi^S\right)^2}\overline{E} < 0, k \neq i \in O,$$

$$\frac{\partial e_j^S}{\partial \Phi_i} = \frac{\Psi_j^S}{\beta_i \left(1 + \Psi^O + \Psi^S\right)^2}\overline{E} > 0, j \in S,$$

$$\frac{\partial E^N}{\partial \Phi_i} = -\frac{1}{\beta_i \left(1 + \Psi^O + \Psi^S\right)^2}\overline{E} < 0.$$

Suppose a member country j experiences a vulnerability decrease. Country j and all other members increase emissions:

$$\frac{\partial e_j^S}{\partial \Phi_j} = -\frac{1 + \Psi^O}{\beta_j \left(1 + \Psi^O + \Psi^S\right)^2}\overline{E} < 0,$$

$$\frac{\partial e_k^S}{\partial \Phi_j} = -\frac{1 + \Psi^O}{\beta_k \left(1 + \Psi^O + \Psi^S\right)^2}\overline{E} < 0, k \neq j \in S.$$

Non-member countries respond oppositely to members:

$$\frac{\partial e_i^O}{\partial \Phi_j} = \frac{\Psi_i \sum_{j \in S}\frac{1}{\beta_j}}{\left(1 + \Psi^O + \Psi^S\right)^2}\overline{E} > 0, i \in O.$$

The world emission level changes in the same direction as the member country j:

$$\frac{\partial E^N}{\partial \Phi_j} = -\frac{\sum_{j \in S}\frac{1}{\beta_j}}{\left(1 + \Psi^O + \Psi^S\right)^2}\overline{E} < 0.$$

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The adaptation level is given by (35). The change of adaptation level of the country with vulnerability change is given by,

$$da_i = \frac{\partial a_i}{\partial \theta_i} d\theta_i + \frac{\partial a_i}{\partial c_i} dc_i + \frac{\partial a_i}{\partial E^N} \frac{\partial E^N}{\partial \Phi_i} d\Phi_i > 0$$

since $d\theta_i \geq 0, dc_i \leq 0, d\Phi_i \leq 0, \frac{\partial a_i}{\partial \theta_i} > 0$, and $\frac{\partial a_i}{\partial c_i} < 0$.

For any other country j, the adaptation level will rise as well:

$$\frac{da_j}{d\Phi_i} = \frac{\partial a_j}{\partial E^N} \frac{\partial E^N}{\partial \Phi_i} < 0, j \neq i \in N.$$

$\square$

Appendix A.5. Proof of Lemma 2

Proof. Suppose $S = \varnothing$ [22] and $O = N$. $\Psi^O = \sum_{i \in N} \frac{\Phi_i}{\beta_i} = \Psi$, and $\Psi^S = 0$. From (13),

$$E^N = \frac{\overline{E}}{1 + \Psi^O + 0} = \frac{\overline{E}}{1 + \Psi} = E.$$

Suppose $S = N$ and $O = \varnothing$. $\Phi^O = 0$ and $\Phi^S = \sum_{j \in S} \frac{\Phi_j}{\beta_j} = \Psi^G$. From (20),

$$E^N = \frac{\overline{E}}{1 + 0 + \Psi^S} = \frac{\overline{E}}{1 + \Psi^G} = E^G.$$

To compare E, E^G and E^N,

$$\frac{E^G}{E^N} = \frac{1 + \Psi^G}{1 + \Psi^O + \Psi^S} \leq 1,$$
$$\frac{E^N}{E} = \frac{1 + \Psi^O + \Psi^S}{1 + \Psi} \leq 1,$$
$$\Rightarrow E^G \leq E^N \leq E.$$

From (34), the world's total emissions is given by,

$$E^N(S) = \frac{\overline{E}}{1 + \Psi^O + \Psi^S}. \tag{A.5}$$

If any country $i \in O$ joins the coalition S, the global emissions becomes,

$$E^N(S \cup \{i\}) = \frac{\overline{E}}{1 + \Psi^O + \Psi^S + \Psi_i^S + \Phi_i \sum_{k \in S} \frac{1}{\beta_k}}, \tag{A.6}$$

where $1 + \Psi^O + \Psi^S + \Psi_i^S + \Phi_i \sum_{k \in S} \frac{1}{\beta_k} > 1 + \Psi^O + \Psi^S$. Thus $E^N(S \cup \{i\}) < E^N(S)$. Since S can be any coalition, the global emission level decreases as the coalition has more members.

From (35), $a_i^G \leq a_i^N \leq a_i, \forall i \in N.$

$\square$

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[22] If S has only one element, $E^N = E$ as well. A country as the only signatory to an IEA behaves like a singleton. In this paper a valid coalition is defined as a treaty among two or more individuals.

Appendix A.6. Proof of Proposition Appendix A.6

Proof. Suppose a coalition exists, $S \neq \varnothing$. From (11) and (32),

$$e_i^O(S) - e_i = \left(\frac{1}{1+\Psi} - \frac{1}{1+\Psi^O+\Psi^S} \right) \Psi_i \overline{E}, i \in O,$$

$$1 + \Psi^O + \Psi^S = 1 + \Psi + \sum_{j \in S} \left(\Psi_j^S - \Psi_j \right) > 1 + \Psi,$$

$$\Rightarrow e_i^O(S) > e_i.$$

From (11) and (33),

$$e_j^S(S) - e_j = \left(\frac{\Psi_j}{1+\Psi} - \frac{\Psi_j^S}{1+\Psi^O+\Psi^S} \right) \overline{E}, j \in S,$$

$$e_j^S(S) \geq e_j \Leftrightarrow \frac{\Psi_j}{\Psi_j^S} \geq \frac{1+\Psi}{1+\Psi^O+\Psi^S}.$$

From Lemma 2, $E^N < E$ if $S \neq \varnothing$.

$$E^N(S) = E^O(S) + E^S(S) = \sum_{i \in O} e_i^O(S) + \sum_{j \in S} e_j^S(S),$$

$$E = \sum_{i \in O} e_i + \sum_{j \in S} e_j.$$

We have already proven that $e_i^O(S) > e_i, \forall i \in O$, and hence $\sum_{i \in O} e_i^O(S) > \sum_{i \in O} e_i$. Thus $E^S(S) < \sum_{j \in S} e_j$. □

Appendix A.7. Sufficient condition to cooperative incentive

Lemma 4. *For a given coalition S,*

i) a member j's emissions fall ($e_j^S(S) > e_j^O(S \backslash \{j\})$) when it leaves the coalition iff $\frac{\Phi_j}{\Phi^S} > 1 - \frac{\Psi_j^S - 2\Psi_j + \Phi_j \sum_{k \in S} \frac{1}{\beta_k}}{1+\Psi^O+\Psi^S}$;

ii) a non-member i's emissions fall ($e_i^S(S \cup \{i\}) < e_i^O(S)$) when it joins the coalition iff $\frac{\Phi_i}{\Phi^S} < \frac{1+\Psi^O+\Psi^S}{\Psi_i^S + \Phi_i \sum_{k \in S} \frac{1}{\beta_k}}$.

Proof. For a member j in S, from (33) and (36), the change in emissions is given by,

$$e_j^S(S) - e_j^O(S \backslash \{j\}) = \left(\frac{\Psi_j}{1+\Psi^O(S \backslash \{j\})+\Psi^S(S \backslash \{j\})} - \frac{\Psi_j^S}{1+\Psi^O+\Psi^S} \right) \overline{E},$$

where $1 + \Psi^O(S \backslash \{j\}) + \Psi^S(S \backslash \{j\}) = 1 + \Psi^O + \Psi^S + 2\Psi_j - \Psi_j^S - \Phi_j \sum_{k \in S} \frac{1}{\beta_k}$.

$$e_j^S(S) > e_j^O(S \backslash \{j\}) \Leftrightarrow \frac{\Psi_j}{\Psi_j^S} > \frac{1+\Psi^O(S \backslash \{j\})+\Psi^S(S \backslash \{j\})}{1+\Psi^O+\Psi^S}$$

$$\Leftrightarrow \frac{\Phi_j}{\Phi^S} > 1 - \frac{\Psi_j^S - 2\Psi_j + \Phi_j \sum_{k \in S} \frac{1}{\beta_k}}{1+\Psi^O+\Psi^S}.$$

For a non-member i in O, from (32) and (41), the change in emissions is as following,

$$e_i^O(S) - e_i^S(S \cup \{i\}) = \left(\frac{\Psi_i + \Psi_i^S}{1 + \Psi^O(S \cup \{i\}) + \Psi^S(S \cup \{i\})} - \frac{\Psi_i}{1 + \Psi^O + \Psi^S} \right) \overline{E},$$

where $1 + \Psi^O(S \cup \{i\}) + \Psi^S(S \cup \{i\}) = 1 + \Psi^O + \Psi^S + \Psi_i^S + \Phi_i \sum_{k \in S} \frac{1}{\beta_k}$.

$$e_i^S(S \cup \{i\}) > e_i^O(S) \iff \frac{\Psi_i + \Psi_i^S}{\Psi_i} > \frac{1 + \Psi^O(S \cup \{i\}) + \Psi^S(S \cup \{i\})}{1 + \Psi^O + \Psi^S}$$

$$\iff \frac{\Phi_i}{\Phi^S} < \frac{1 + \Psi^O + \Psi^S}{\Psi_i^S + \Phi_i \sum_{k \in S} \frac{1}{\beta_k}}.$$

□

Lemma 5. *For a given coalition S, a member's cooperative incentive is non-negative iff* $\frac{\Phi_j^2 + \beta_j \Phi_j}{(\Phi^S)^2 + \beta_j \Phi_j} \geq$
$\left(1 - \frac{\Psi_j^S - 2\Psi_j + \Phi_j \sum_{k \in S} \frac{1}{\beta_k}}{1 + \Psi^O + \Psi^S} \right)^2$, $j \in S$. *A non-member's free-riding incentive is positive iff* $\frac{\Phi_i^2 + \beta_i \Phi_i}{(\Phi^{S \cup \{i\}})^2 + \beta_i \Phi_i} <$
$\left(\frac{1 + \Psi^O + \Psi^S}{1 + \Psi^O + \Psi^S + \Psi_i^S + \Phi_i \sum_{k \in S} \frac{1}{\beta_k}} \right)^2$, $i \in O$.

Proof. From (40), $\Gamma_j^S(S) \geq 0$ is equivalent to the following,

$$\frac{\Phi_j \Psi_j + \Phi_j}{\Phi^S \Psi_j^S + \Phi_j} \geq \frac{(1 + \Psi^O(S \setminus \{j\}) + \Psi^S(S \setminus \{j\}))^2}{(1 + \Psi^O + \Psi^S)^2},$$

$$\frac{\Phi_j^2 + \beta_j \Phi_j}{(\Phi^S)^2 + \beta_j \Phi_j} \geq \left(1 - \frac{\Psi_j^S - 2\Psi_j + \Phi_j \sum_{k \in S} \frac{1}{\beta_k}}{1 + \Psi^O + \Psi^S} \right)^2,$$

where $1 + \Psi^O(S \setminus \{j\}) + \Psi^S(S \setminus \{j\}) = 1 + \Psi^O + \Psi^S + 2\Psi_j - \Psi_j^S - \Phi_j \sum_{k \in S} \frac{1}{\beta_k}$.

From (45), $\Gamma_i^O(S) > 0$ is equivalent to the following,

$$\frac{(\Phi^S + \Phi_i)(\Psi^S + \Psi_i) + \Phi_i}{\Phi_i \Psi_i + \Phi_i} > \frac{\left(1 + \Psi^O(S \cup \{i\}) + \Psi^S(S \cup \{i\}) \right)^2}{(1 + \Psi^O + \Psi^S)^2},$$

$$\frac{\Phi_i^2 + \beta_i \Phi_i}{(\Phi^{S \cup \{i\}})^2 + \beta_i \Phi_i} < \left(\frac{1 + \Psi^O + \Psi^S}{1 + \Psi^O + \Psi^S + \Psi_i^S + \Phi_i \sum_{k \in S} \frac{1}{\beta_k}} \right)^2,$$

where $1 + \Psi^O(S \cup \{i\}) + \Psi^S(S \cup \{i\}) = 1 + \Psi^O + \Psi^S + \Psi_i^S + \Phi_i \sum_{k \in S} \frac{1}{\beta_k}$. □

Appendix A.7.1. Proof of Lemma 3
Proof. $e_j^S(S) \geq e_j^O(S \setminus \{j\})$ iff

$$\frac{\Phi_j}{\Phi^S} \geq 1 - \frac{\Psi_j^S - 2\Psi_j + \Phi_j \sum_{k \in S} \frac{1}{\beta_k}}{1 + \Psi^O + \Psi^S}.$$

$\frac{\Phi_j}{\Phi^S} < 1 \Rightarrow \frac{\Phi_j^2}{(\Phi^S)^2} < \frac{\Phi_j^2 + \beta_j \Phi_j}{(\Phi^S)^2 + \beta_j \Phi_j}.$

$$\frac{\Phi_j^2 + \beta_j \Phi_j}{(\Phi^S)^2 + \beta_j \Phi_j} > \frac{\Phi_j^2}{(\Phi^S)^2} \geq \left(1 - \frac{\Psi_j^S - 2\Psi_j + \Phi_j \sum_{k \in S} \frac{1}{\beta_k}}{1 + \Psi^O + \Psi^S} \right)^2$$

From Lemma 5, $\Gamma_j^S(S) > 0$. □

Appendix A.8. Emissions and cooperative incentives

Conditions defining the three types of countries in a coalition can be derived from Lemma 4, Lemma 5, and Lemma 3.

Type	Relation	Emission Change	Cooperative Incentives
Strong-cooperative	$\left(1 - \frac{\Psi_j^S - 2\Psi_j + \Phi_j \sum_{k \in S} \frac{1}{\beta_k}}{1 + \Psi^O + \Psi^S}\right)^2 \leq \frac{\Phi_j^2}{(\Phi^S)^2} < \frac{\Phi_j^2 + \beta_j \Phi_j}{(\Phi^S)^2 + \beta_j \Phi_j}$	$e_j^S(S) \geq e_j^O(S \backslash \{j\})$	$\Gamma_j^S(S) > 0$
Weak-cooperative	$\frac{\Phi_j^2}{(\Phi^S)^2} < \left(1 - \frac{\Psi_j^S - 2\Psi_j + \Phi_j \sum_{k \in S} \frac{1}{\beta_k}}{1 + \Psi^O + \Psi^S}\right)^2 \leq \frac{\Phi_j^2 + \beta_j \Phi_j}{(\Phi^S)^2 + \beta_j \Phi_j}$	$e_j^S(S) < e_j^O(S \backslash \{j\})$	$\Gamma_j^S(S) \geq 0$
Non-cooperative	$\frac{\Phi_j^2}{(\Phi^S)^2} < \frac{\Phi_j^2 + \beta_j \Phi_j}{(\Phi^S)^2 + \beta_j \Phi_j} < \left(1 - \frac{\Psi_j^S - 2\Psi_j + \Phi_j \sum_{k \in S} \frac{1}{\beta_k}}{1 + \Psi^O + \Psi^S}\right)^2$	$e_j^S(S) < e_j^O(S \backslash \{j\})$	$\Gamma_j^S(S) < 0$

Table A.2: Emission Changes and Cooperative Incentives

Appendix A.9. Disparity in Vulnerability

Proof. For a given coalition, all coalition-level parameters, i.e. Φ^O, Φ^S, Ψ^O and Ψ^S, are fixed. Thus the cooperative incentive of any member in the coalition is a function of that member's parameters. Specifically, let j be any arbitrary member in the coalition, and its cooperative incentive depends β_j and ϕ_j.

$$\frac{\partial \Gamma_j^S(\Phi_j, \beta_j; S)}{\partial \Phi_j} = \frac{\overline{E}^2}{2} \left[2\Psi_j \frac{1 + \Psi^O + \Psi^S - (1 + \Psi_j)(2 - \sum_{k \in S} \frac{\beta_j}{\beta_k})}{(1 + \Psi^O(S \cup \{i\}) + \Psi^S(S \cup \{i\}))^3} \right.$$
$$\left. + \frac{1}{(1 + \Psi^O(S \cup \{i\}) + \Psi^S(S \cup \{i\}))^2} - \frac{1}{(1 + \Psi^O + \Psi^S)^2} \right]$$

$$(1 + \Psi_j)(2 - \sum_{k \in S} \frac{\beta_j}{\beta_k}) < (1 + \Psi_j) < 1 + \Psi^O + \Psi^S,$$
$$1 + \Psi^O + \Psi^S > 1 + \Psi^O(S \backslash \{j\}) + \Psi^S(S \backslash \{j\})$$
$$\Rightarrow \frac{\partial \Gamma_j^S(\Phi_j, \beta_j; S)}{\partial \Phi_j} > 0$$

If two signatories have the same β, whoever is more vulnerable has more incentives to cooperate.

$$\frac{\partial \Gamma_j^S(\Phi_j, \beta_j; S)}{\partial \beta_j} = \frac{\overline{E}^2}{2} \left[\frac{\Psi_j^{S2}}{(1 + \Psi^O + \Psi^S)^2} - \frac{\Psi_j^2}{(1 + \Psi^O(S \cup \{i\}) + \Psi^S(S \cup \{i\}))^2} \right.$$
$$\left. - \frac{2\Psi_j(1 + \Psi_j)\left(\Psi_j^S - \Psi_j\right)}{(1 + \Psi^O(S \cup \{i\}) + \Psi^S(S \cup \{i\}))^3} \right]$$

The sign of $\frac{\partial \Gamma_j^S(\Phi_j, \beta_j; S)}{\partial \beta_j}$ is ambiguous without parameter values. However, from Lemma 4, if $e_j^S(S) \geq e_j^O(S \backslash \{j\})$, the first two terms in $\frac{\partial \Gamma_j^S(\Phi_j, \beta_j; S)}{\partial \beta_j}$ is non-positive:

$$e_j^S(S) \geq e_j^O(S\backslash\{j\}) \Leftrightarrow \quad \frac{\Psi_j}{1 + \Psi^O + \Psi^S + 2\Psi_j - \Psi_j^S - \Phi_j \sum_{k \in S} \frac{1}{\beta_k}} \geq \frac{\Psi_j^S}{1 + \Psi^O + \Psi^S}$$

$$\Leftrightarrow \quad \frac{\Psi_j^{S2}}{(1 + \Psi^O + \Psi^S)^2} - \frac{\Psi_j^2}{(1 + \Psi^O(S \cup \{i\}) + \Psi^S(S \cup \{i\}))^2} \leq 0$$

Since the last term is positive, $\frac{\partial \Gamma_j^S(\Phi_j, \beta_j; S)}{\partial \beta_j} < 0$ if $e_j^S(S) \geq e_j^O(S\backslash\{j\})$. This implies that if the value of vulnerability is high the cooperative incentive is negatively related with β. In this case for countries with identical Φ_j (vulnerability), the country with smaller β (flatter marginal abatement cost) has more cooperative incentive than the country with larger β. $\square$
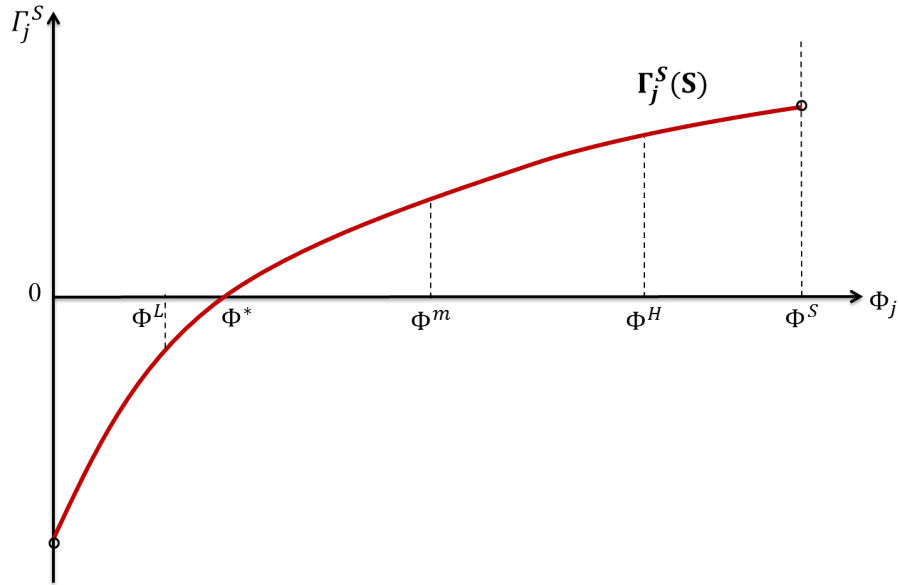

Figure A.2: Cooperative incentives for member countries

Appendix A.10. Proof of Proposition 7

Proof. The emission level of country i outside and inside of the existing coalition are given by,

$$e_i^O(S) = \overline{e_i} - \frac{\Psi_i}{1 + \Psi^O + \Psi^S}\overline{E}$$

$$e_i^S(S \cup \{i\}) = \overline{e_j} - \frac{\Psi_i^S + r_i\Psi_i}{1 + \Psi^O + \Psi^S + \Psi_i^S + r_i\Phi_i \sum_{j \in S} \frac{1}{\beta_j} + r_i\Psi_i - \Psi_i}\overline{E}$$

From (44), the free riding incentive is given as the following,

$$\Gamma_i^O(S) = \frac{\beta_i \overline{E}^2}{2}\left[\frac{(\Psi_i^S + r_i\Psi_i)^2 + r_i\Psi_i}{(1 + \Psi^O + \Psi^S + \Psi_i^S + r_i\Phi_i \sum_{j \in S} \frac{1}{\beta_j} + r_i\Psi_i - \Psi_i)^2} - \frac{\Psi_i^2 + \Psi_i}{(1 + \Psi^O + \Psi^S)^2}\right] \quad (A.7)$$

Take derivative of Γ_i^O with respect of r_i,

$$\frac{\partial \Gamma_i^O}{\partial r_i} = \frac{\beta_i \overline{E}^2}{2} \left\{ \frac{2\Psi_i(\Psi_i^S + r_i\Psi_i) + \Psi_i}{(1 + \Psi^O + \Psi^S + \Psi_i^S + r_i\Phi_i \sum_{j \in S} \frac{1}{\beta_j} + r_i\Psi_i - \Psi_i)^2} \right.$$
$$\left. - \frac{2[(\Psi_i^S + r_i\Psi_i)^2 + r_i\Psi_i](\Phi_i \sum_{j \in S} \frac{1}{\beta_j} + \Psi_i)}{(1 + \Psi^O + \Psi^S + \Psi_i^S + r_i\Phi_i \sum_{j \in S} \frac{1}{\beta_j} + r_i\Psi_i - \Psi_i)^3} \right\}$$

Hence the condition on which $\frac{\partial \Gamma_i^O}{\partial r_i} > 0$ holds is given by,

$$\frac{2\Psi_i(\Psi_i^S + r_i\Psi_i) + \Psi_i}{2[(\Psi_i^S + r_i\Psi_i)^2 + r_i\Psi_i]} > \frac{\Phi_i \sum_{j \in S} \frac{1}{\beta_j} + \Psi_i}{(1 + \Psi^O + \Psi^S + \Psi_i^S + r_i\Phi_i \sum_{j \in S} \frac{1}{\beta_j} + r_i\Psi_i - \Psi_i)}.$$

$$\lim_{\beta_i \to \infty} LHS = \frac{1}{2r_i},$$
$$\lim_{\beta_i \to \infty} RHS = 0.$$

If in general $\beta >> \phi$, LHS $= \frac{1}{2r_i} > $ RHS $= 0$, and $\frac{\partial \Gamma_i^O}{\partial r_i} > 0$.

Since the coalition S is arbitrary, the free-riding incentive of any country is negatively related with its adoption cost of the new technology if $\beta >> \phi$. $\qquad \square$

From (11), (12), and (13), the welfare for a country i is given by:

$$\begin{aligned}
w(e_i, a_i, E) &= B(e_i) - D(E, a_i) - C(a_i) \\
&= \alpha_i e_i - \frac{\beta_i}{2}e_i^2 - \frac{\Phi_i}{2}E^2 \\
&= \frac{\alpha_i}{2}\bar{e}_i - \frac{\Phi_i}{2}\frac{1 + \Phi_i}{(1 + \Phi)^2}\bar{E}^2
\end{aligned}$$

If Φ_i is very large, the net welfare generated from emissions is negative. However, the damage from climate change is considered to be much smaller than the GDP generated from emissions. Thus, the opposite case of $\beta_i >> \Phi_i$ is a trivial one. Note that even if the benefit and damage are of the similar amount, β is expected to be much larger than Φ since benefit is generated by private emissions, while damage is based on aggregate emissions of all countries. Indeed, β_i is much larger than Φ_i for all countries as shown in our numerical example.

Appendix B. Changes of the benefit of emissions

A country's marginal cost of abatement (or marginal benefit of emissions) may also increase exogenously, e.g. due to new CO_2 intensive mineral discoveries, or due to shifts in the production structure of the economy induced by international trade (e.g. carbon leakage). Without cooperation, its equilibrium emissions will increase - *ceteris paribus* - with implications for the rest of the world. The following intermediary result illustrates the effects of free-riding, which is characteristic of the non-cooperation scenario in the presence of a global externality:

Appendix B.1. Non-cooperative Outcome

Lemma 6. *When countries behave non-cooperatively, if country i's marginal benefit of emissions shifts up (i.e. α_i rises), its emissions level increases. All other countries respond by reducing emissions and adapting more, and global emissions rise. If country i's marginal benefit of emissions becomes flatter (steeper), that is β_i falls (increases), the absolute value of its emissions increases (decreases). All other countries will respond in the opposite way, yet the global emissions change in the same direction as country i's emission change.*

Proof. First, suppose α_i changes. Country i's emissions rise in α_i:

$$\frac{\partial e_i}{\partial \alpha_i} = \frac{1}{\beta_i}\left(1 - \frac{\Psi_i}{1+\Psi}\right) > 0.$$

Any other country $j \neq i \in N$ will choose a lower emission level,

$$\frac{\partial e_j}{\partial \alpha_i} = -\frac{1}{\beta_i}\frac{\Psi_j}{1+\Psi} < 0,$$

while the global emission level still increases:

$$\frac{\partial E}{\partial \alpha_i} = \frac{1}{\beta_i(1+\Psi)} > 0.$$

Second, suppose β_i changes.

$$
\begin{aligned}
\frac{\partial e_i}{\partial \beta_i} &= -\frac{\overline{e_i}}{\beta_i} + \Psi_i\frac{(\overline{E}+\overline{e_i})(1+\Psi) - \Psi_i\overline{E}}{\beta_i(1+\Psi)^2} \\
&= -\frac{1}{\beta_i}\left[\left(1 - \frac{\Psi_i}{1+\Psi}\right)\left(\overline{e_i} - \frac{\Psi_i}{1+\Psi}\overline{E}\right)\right] \\
&= -\frac{1}{\beta_i}\left(1 - \frac{\Psi_i}{1+\Psi}\right)e_i.
\end{aligned}
$$

$\frac{\partial e_i}{\partial \beta_i}$ is of the same sign of e_i: if the country emits (rather than sequestrating GHGs) in the non-cooperation equilibrium, a rise in β_i will cause the country to emit more. If the country sequestrates GHGs, flatter marginal benefit will cause the country to sequestrate more.

For any other country $j \neq i \in N$,

$$\frac{\partial e_j}{\partial \beta_i} = \frac{1}{\beta_i}\frac{\Psi_j}{1+\Psi}e_i.$$

$\frac{\partial e_j}{\partial \beta_i}$ is of the opposite sign of $\frac{\partial e_i}{\partial \beta_i}$. Thus all other countries respond oppositely to country i.
The change of global emission level is given by,

$$\frac{\partial E}{\partial \beta_i} = -\frac{1}{\beta_i(1+\Psi)}e_i.$$

$\frac{\partial E}{\partial \beta_i}$ is of the same sign of $\frac{\partial e_i}{\partial \beta_i}$. Thus the global emission level goes in the same direction as country i's emission changes.
The responses of the adaptation level to changes in the benefit of emissions are:

$$\frac{\partial a_i}{\partial \alpha_i} = \qquad\qquad \frac{da}{dE}\frac{\partial E}{\partial \alpha_i} = \frac{\theta i}{c_i}\frac{\partial E}{\partial \alpha_i} > 0,$$

$$\frac{\partial a_i}{\partial \beta_i} = \qquad\qquad \frac{da}{dE}\frac{\partial E}{\partial \beta_i}, \forall i \in N,$$

thus a_i goes in the same direction as the global emissions, in response to changes in parameters α_i and β_i. □

Appendix B.2. Full-cooperative Outcome

Lemma 7. *When all countries behave cooperatively, if country i's marginal benefit of emissions shift up (i.e. α_i rises), its emission level will increase. All other countries respond by reducing emissions and adapting more, and global emissions rise. If country i's marginal benefit of emissions becomes flatter (i.e. β_i falls), the absolute value of its emissions increases. All other countries will respond oppositely, and yet the global emissions change in the same direction as country i's emission change.*

Proof. If α_i changes,

$$\frac{\partial e_i^G}{\partial \alpha_i} = \frac{1}{\beta_i}\left(1 - \frac{\Psi_i^G}{1+\Psi^G}\right) > 0.$$

For any other countries $j \neq i \in N$,

$$\frac{\partial e_j^G}{\partial \alpha_i} = -\frac{1}{\beta_i}\frac{\Psi_j^G}{1+\Psi^G} < 0.$$

For the global emission level,

$$\frac{\partial E^G}{\partial \alpha_i} = \frac{1}{\beta_i(1+\Psi^G)} > 0.$$

If β_i changes,

$$\frac{\partial e_i^G}{\partial \beta_i} = -\frac{1}{\beta_i}\left(1 - \frac{\Psi_i^G}{1+\Psi^G}\right)e_i^G,$$

thus $\frac{\partial e_i^G}{\partial \beta_i}$ is of the same sign as e_i.
For any other countries $j \neq i \in N$,

$$\frac{\partial e_j^G}{\partial \beta_i} = \frac{1}{\beta_i}\frac{\Psi_j^G}{1+\Psi^G}e_i^G,$$

$\frac{\partial e_j^G}{\partial \beta_i}$ is of the opposite sign of $\frac{\partial e_i^G}{\partial \beta_i}$. Thus all other countries respond oppositely to country i.
For the global emission level,

$$\frac{\partial E^G}{\partial \beta_i} = -\frac{1}{\beta_i(1+\Psi^G)}e_i^G.$$

$\frac{\partial E^G}{\partial \beta_i}$ is of the same sign of $\frac{\partial e_i^G}{\partial \beta_i}$, and global emissions change in the same direction as country i's emission changes.
For adaptation level, $\forall i \in N$,

$$\frac{\partial a_i^G}{\partial \alpha_i} = \frac{da}{dE^G}\frac{\partial E^G}{\partial \alpha_i} > 0, \frac{\partial a_i^G}{\partial \beta_i} = \frac{da}{dE^G}\frac{\partial E^G}{\partial \beta_i}$$

Thus a_i changes in the same direction as the global emissions. □

Appendix B.3. Proof of Lemma 1

Proof. First, suppose a country i's α_i changes. A non-member i's emissions rise if its α_i increases:

$$\frac{\partial e_i^O}{\partial \alpha_i} = \frac{1}{\beta_i}\left(1 - \frac{\Psi_i}{1 + \Psi^O + \Psi^S}\right) > 0, i \in O.$$

For any other countries $k \neq i \in O$ and $j \in S$, the emissions reduces as a result of an increase in α_i:

$$\frac{\partial e_k^O}{\partial \alpha_i} = -\frac{1}{\beta_i}\frac{\Psi_k}{1 + \Psi^O + \Psi^S} < 0, k \neq i \in O$$

$$\frac{\partial e_j^S}{\partial \alpha_i} = -\frac{1}{\beta_i}\frac{\Psi_j^S}{1 + \Psi^O + \Psi^S} < 0, j \in S.$$

Then suppose a member j's α_j changes. Member j's emission level rises in response to an increase in α_j:

$$\frac{\partial e_j^S}{\partial \alpha_j} = \frac{1}{\beta_j}\left(1 - \frac{\Psi_j^S}{1 + \Psi^O + \Psi^S}\right) > 0, j \in S.$$

For any other countries, the emissions reduces as a result of an increase in α_j.

$$\frac{\partial e_k^S}{\partial \alpha_j} = -\frac{1}{\beta_j}\frac{\Psi_k^S}{1 + \Psi^O + \Psi^S} < 0, k \neq j \in S,$$

$$\frac{\partial e_i^O}{\partial \alpha_j} = -\frac{1}{\beta_j}\frac{\Psi_i}{1 + \Psi^O + \Psi^S} < 0, i \in O.$$

The global emission level always rises no matter which country experiences reduced α:

$$\frac{\partial E^N}{\partial \alpha_i} = \frac{1}{\beta_i\left(1 + \Psi^O + \Psi^S\right)} > 0, i \in N.$$

Second, suppose β changes in a country. If a non-member i's β_i drops, its emission level rises:

$$\frac{\partial e_i^O}{\partial \beta_i} = -\frac{1}{\beta_i}\left(1 - \frac{\Psi_i}{1 + \Psi^O + \Psi^S}\right)e_i^O.$$

$\frac{\partial e_i^O}{\partial \beta_i}$ is of the opposite sign of e_i. If the country emits in the non-cooperation equilibrium, improvement in marginal benefit will cause the country to emit more. If the country sequestrates emissions, a flatter marginal benefit will cause the country to sequestrate more.

For any other countries $k \neq i \in O$ and $j \in S$, the change in emissions can be derived as the following,

$$\frac{\partial e_k^O}{\partial \beta_i} = \frac{1}{\beta_i}\frac{\Psi_k}{1 + \Psi^O + \Psi^S}e_i^O,$$

$$\frac{\partial e_j^S}{\partial \beta_i} = \frac{1}{\beta_i}\frac{\Psi_j^S}{1 + \Psi^O + \Psi^S}e_i^O.$$

Since $\frac{\partial e_i^O}{\partial \beta_i}\frac{\partial e_k^O}{\partial \beta_i} \leq 0$, and $\frac{\partial e_i^O}{\partial \beta_i}\frac{\partial e_j^S}{\partial \beta_i} \leq 0$, emissions of other countries respond oppositely to country i.

The changes of global emission level is given by,

$$\frac{\partial E^N}{\partial \beta_i} = -\frac{1}{\beta_i\left(1 + \Psi^O + \Psi^S\right)}e_i^O.$$

$\frac{\partial E^N}{\partial \beta_i}$ is of the same sign with $\frac{\partial e_i^O}{\partial \beta_i}$. Thus the global emission level goes the same direction as country i's emission changes.

Now suppose a member j's β_j drops. The member j increases its emission level:

$$\frac{\partial e_j^S}{\partial \beta_j} = -\frac{1}{\beta_j}\left(1 - \frac{\Psi_j^S}{1 + \Psi^O + \Psi^S}\right)e_j^S.$$

For any other countries, emissions respond oppositely to country j. The global emissions level goes to the same direction as country j's emission. These results are given by,

$$\frac{\partial e_k^S}{\partial \beta_j} = \frac{1}{\beta_j}\frac{\Psi_k^S}{1 + \Psi^O + \Psi^S}e_j^S, k \neq j \in S,$$

$$\frac{\partial e_i^O}{\partial \beta_j} = \frac{1}{\beta_j}\frac{\Psi_i}{1 + \Psi^O + \Psi^S}e_j^S, i \in O,$$

$$\frac{\partial E^N}{\partial \beta_j} = -\frac{1}{\beta_j(1 + \Psi^O + \Psi^S)}e_j^S.$$

Additionally, from (35) adaptation level always goes to the same direction as the global emission level does. □

Appendix C. Simulation Statistics

Variable	Obs	Mean	Std. Dev.	Min	Max
GDP (Million US $)	7062	120000.00	695000.00	9.12	15000000.00
totalGHG (kt of CO2 equivalent)	8772	97168.53	486456.30	-80.67	10800000.00
Climate_change_cost (Million US $)	172	3510.00	10600.00	5.00	90000.00

Table C.3: Summary Statistics

	α_i	β_i	Φ_i
1	2726563.75	-254.92	0.000535
2*	832838.63	-0.45	0.026759
3	1210438.38	-4.83	0.002007
4*	1530063.75	-6.58	0.009366
5*	232675760.00	-6619563.00	0.000040
6*	6543675.50	-4941.58	0.000401
7	955863.94	-1.88	0.004014
8	1054546.00	-43.55	0.000937
9	1908327.88	-33.74	0.001003
10	444350.00	-12.30	0.000669

*: countries in the largest stable coalition

Table C.4: Estimated Parameters

	World's emissions (kt of CO2 equivalent)	Welfare (Million US$)
Non-cooperative equilibrium	2777422.04	1250495.90
Full-cooperative equilibrium	2572505.81	1259387.99
With stable coalition {2,4,5,6}	2711780.17	1253297.08

*: compared to the non-cooperative equilibrium

Table C.5: World's emissions and welfare

Appendix D. Timing of Adaptation

In this paper we modify the standard two-stage model by adding a third stage in order to highlight *adaptation* as a private good to fight climate change. The first stage is the "open membership game" in which countries decide whether to participate in an IEA. The second stage is the "emission game" in which the IEA and non-signatories choose their emission and adaptation levels simultaneously. This Nash-Cournot assumption is more widely used in the literature (Carraro and Siniscalco (1993), Barrett (1994), Pavlova and de Zeeuw (2013)) as the Stackelberg leadership between the IEA and non-signatories is more difficult to justify. The two existing studies on IEA and adaptation relies on the assumption of simultaneous adaptation and emissions (Benchekroun et al. (2014) and Lazkano et al. (2014)).

A caveat is that adaptation activities usually include investment in infrastructure which may take decades to complete. Once a country is aware of the damage from climate change, adaptation may take place soon after and has a much longer time frame than the formation of an IEA. An example is the Netherlands which for decades has been investing in upgrading its flood defenses and reducing the damage of climate change. If adaptation decisions are undertaken prior to mitigation, Benchekroun et al. (2014) explains that countries can use adaptation strategically to reduce their own mitigation effort at the expense of others', and hence a more pessimistic relationship between adaptation and mitigation is expected. To address the timing of adaptation decision, here we model the decision to adapt to climate change as it is made before an IEA is formed. In the first stage countries realize the climate change and hence choose adaptation level. The second stage is the "open membership game" where countries decide simultaneously whether to participate in an IEA. The third stage is the "emission game" in which the IEA and non-signatories choose their emission levels simultaneously. We first solve the first stage, and then use backward induction to solve the third and second stage.

Appendix D.1. The First Stage

The first stage is equivalent to the non-cooperative outcome (11), (12) and (13):

$$
\begin{aligned}
e_i &= \overline{e_i} - \frac{\Psi_i}{1+\Psi}\overline{E}, \\
a_i &= \frac{\theta_i}{c_i}E, \\
E &= \frac{1}{1+\Psi}\overline{E}.
\end{aligned}
$$

The adaptation level is chosen prior to an IEA, and is not adjustable hereafter. The second and third stage need to be solved by backward induction.

Appendix D.2. The Third Stage

In the third stage, each country maximizes the objective with respect to its own emissions, given the adaptation level already chosen in the first stage.

Appendix D.2.1. Non-signatories

Similar to the original case with adjustable adaptation level, a non-signatory i behaves like a singleton and maximizes its individual payoffs. However, the payoff is maximized with respect to individual emission level only.

$$\max_{e_i} w\left(e_i, E^N; a_i\right) = B(e_i) - D\left(E^N; a_i\right) - C\left(a_i\right)$$

The first order condition is given by,

$$e_i : \alpha_i - \beta_i e_i - v_i\left(E^O + E^S\right) + \theta_i a_i = 0 \tag{D.1}$$

The best response function for a non-signatory i is given by,

$$e_i = \overline{e}_i - \frac{v_i}{\beta_i}\left(E^O + E^S\right) + \frac{\theta_i}{\beta_i} a_i \tag{D.2}$$

$$\tag{D.3}$$

The aggregate emissions of all non-signatories can be obtained from the sum of (D.2) over all non-signatories.

$$E^O\left(S, a\right) = \frac{\overline{E}^O - \sum_{i \in O} \frac{v_i}{\beta_i} E^S + \sum_{i \in O} \frac{\theta_i}{\beta_i} a_i}{1 + \sum_{i \in O} \frac{v_i}{\beta_i}}. \tag{D.4}$$

E^O is a function of the coalition and adaptation level of all countries (which is represented by a).

Appendix D.2.2. Signatories

Signatories recognize the behavior of non-signatories. Every signatory j maximizes the joint welfare of the coalition S with respect to its own emissions, taking as given the emissions by all non-signatories $E^O\left(S, a\right)$.

$$\max_{e_j} \sum_{j \in S} w\left(e_j, E^N; a_j\right) = \sum_{j \in S}\left[B(e_j) - D\left(E^N; a_j\right) - C\left(a_j\right)\right] \tag{D.5}$$

The first order condition is given by,

$$e_j : \alpha_j - \beta_j e_j - \sum_{j \in S} v_j\left(E^S + E^O\right) + \sum_{j \in S}\theta_j a_j = 0. \tag{D.6}$$

The best response function for a signatory j is given by,

$$e_j = \overline{e}_j - \frac{\sum_{k \in S} v_k}{\beta_j}\left(E^O + E^S\right) + \frac{\sum_{k \in S}\theta_k a_k}{\beta_j}.$$

The aggregate best response function, which is the sum of (D.6) over all signatories to, combined with (D.4) provide the world emission level and individual emission level.

$$E^N(S, a) = \frac{\overline{E} + \sum_{i \in O}\frac{\theta_i a_i}{\beta_i} + \sum_{j \in S}\frac{1}{\beta_j}\sum_{j \in S}\theta_j a_j}{1 + \sum_{i \in O}\frac{v_i}{\beta_i} + \sum_{j \in S}\frac{1}{\beta_j}\sum_{j \in S} v_j}. \tag{D.7}$$

$$e_i^O(S, a) = \overline{e}_i - \frac{v_i}{\beta_i} E^N(S, a) + \frac{\theta_i}{\beta_i} a_i. \tag{D.8}$$

$$e_j^S(S, a) = \overline{e}_j - \frac{\sum_{j \in S} v_j}{\beta_j} E^N(S, a) + \frac{\sum_{j \in S}\theta_j a_j}{\beta_j}. \tag{D.9}$$

Emission levels of all countries are affected by the adaptation levels chosen in the first stage. Specially, from (35), if $a_i = \frac{\theta_i}{c_i} E^N(S), \forall i \in N$, we have the coalition outcome in the original model. If $a_i = \frac{\theta_i}{c_i} E$, the world emission rises. This is given by,

$$\frac{\partial E^N(S,a)}{\partial a_i} = \frac{\theta_i}{\beta_i} \frac{1}{1 + \sum_{i \in O} \frac{v_i}{\beta_i} + \sum_{j \in S} \frac{1}{\beta_j} \sum_{j \in S} v_j} > 0, \forall i \in O,$$

$$\frac{\partial E^N(S,a)}{\partial a_j} = \left(\sum_{k \in S} \frac{\theta_j}{\beta_k} \right) \frac{1}{1 + \sum_{i \in O} \frac{v_i}{\beta_i} + \sum_{j \in S} \frac{1}{\beta_j} \sum_{j \in S} v_j} > 0, \forall j \in S.$$

Since $a_i = \frac{\theta_i}{c_i} E > \frac{\theta_i}{c_i} E^N(S), \forall i \in N$, the world emission rises. The adaptation level chosen in the first stage is higher than that is chosen after an IEA. Thus overall countries are less vulnerable to climate change and able to emit more. For a non-member, its emission level rises in its adaptation level chosen in Stage 1, and falls in any other country's adaptation level. The underlying reason is that adaptation activities reduce a country's vulnerability to climate change. As a country becomes more (less) vulnerable compared to other countries, it can afford less (more) emissions. In summary, investment in adaptation is strictly a private good outside an IEA.

$$\frac{\partial e_i^O(S,a)}{\partial a_i} = \frac{\theta_i}{\beta_i} \left(1 - \frac{\frac{v_i}{\beta_i}}{1 + \sum_{i \in O} \frac{v_i}{\beta_i} + \sum_{j \in S} \frac{1}{\beta_j} \sum_{j \in S} v_j} \right) > 0, i \in O,$$

$$\frac{\partial e_i^O(S,a)}{\partial a_k} = -\frac{v_i}{\beta_i} \frac{\theta_k}{\beta_k} \frac{1}{1 + \sum_{i \in O} \frac{v_i}{\beta_i} + \sum_{j \in S} \frac{1}{\beta_j} \sum_{j \in S} v_j} < 0, k \neq i \in O,$$

$$\frac{\partial e_i^O(S,a)}{\partial a_j} = -\frac{v_i}{\beta_i} \left(\theta_j \sum_{j \in S} \frac{1}{\beta_j} \right) \frac{1}{1 + \sum_{i \in O} \frac{v_i}{\beta_i} + \sum_{j \in S} \frac{1}{\beta_j} \sum_{j \in S} v_j} < 0, j \in S.$$

For a member, its emission level rises in its adaptation level chosen in Stage 1, and also rises in other member's adaptation level. All members increase emissions in response to a higher level of adaptation in member country, while non-members need to reduce emissions. The underlying reason is the same with Proposition 4: members take account of the aggregate vulnerability of the IEA.

$$\frac{\partial e_j^S(S,a)}{\partial a_j} = \frac{\theta_j}{\beta_j} \left(1 - \frac{\sum_{j \in S} \frac{v_j}{\beta_j}}{1 + \sum_{i \in O} \frac{v_i}{\beta_i} + \sum_{j \in S} \frac{1}{\beta_j} \sum_{j \in S} v_j} \right) > 0, j \in S,$$

$$\frac{\partial e_j^S(S,a)}{\partial a_k} = \frac{\theta_k}{\beta_j} \left(1 - \frac{\sum_{j \in S} \frac{v_j}{\beta_j}}{1 + \sum_{i \in O} \frac{v_i}{\beta_i} + \sum_{j \in S} \frac{1}{\beta_j} \sum_{j \in S} v_j} \right) > 0, k \neq j \in S,$$

$$\frac{\partial e_j^S(S,a)}{\partial a_i} = -\frac{\theta_i}{\beta_i} \frac{\sum_{j \in S} v_j}{\beta_j} \frac{1}{1 + \sum_{i \in O} \frac{v_i}{\beta_i} + \sum_{j \in S} \frac{1}{\beta_j} \sum_{j \in S} v_j} < 0, i \in O.$$

If countries are homogeneous, every country's emission level increases given a higher adaptation level. However, if countries are heterogeneous, some countries may decrease emissions even its adaptation level is higher. The reason is that emission is chosen based on relative terms of vulnerability , not absolute value ((32) and (33)). If all countries increase adaptation levels, each country will be less vulnerable

to climate change in absolute terms. However, a country may become more vulnerable compared to other countries, and have to cut more emissions. If in Stage 1 the decision of adaptation is completely exogenous, the more a country invest in adaptation, the more emission level it can afford.

The emission level changes with respect to θ can be derived from D.8 and D.9:

$$\frac{\partial e_j^S(S,a)}{\partial \theta_j} = \frac{a_j}{\beta_j}\left(1 - \frac{\sum_{j\in S}\frac{1}{\beta_j}\sum_{j\in S}v_j}{1 + \sum_{i\in O}\frac{v_i}{\beta_i} + \sum_{j\in S}\frac{1}{\beta_j}\sum_{j\in S}v_j}\right) > 0, j \in S,$$

$$\frac{\partial e_j^S(S,a)}{\partial \theta_k} = \frac{a_j}{\beta_j}\left(1 - \frac{\sum_{j\in S}\frac{1}{\beta_j}\sum_{j\in S}v_j}{1 + \sum_{i\in O}\frac{v_i}{\beta_i} + \sum_{j\in S}\frac{1}{\beta_j}\sum_{j\in S}v_j}\right) > 0, k \neq j \in S,$$

$$\frac{\partial e_i^O(S,a)}{\partial \theta_k} = -\frac{v_i}{\beta_i}\frac{\sum_{j\in S}\frac{1}{\beta_j}\sum_{j\in S}v_j}{1 + \sum_{i\in O}\frac{v_i}{\beta_i} + \sum_{j\in S}\frac{1}{\beta_j}\sum_{j\in S}v_j} < 0, i \in O.$$

Although the adaptation level is chosen in Stage 1, a country may still have the option to invest in adaptation technology to increase the effectiveness of adaptation activities. In such a case, similar with Proposition 4, adaptation technology has a public good feature inside an IEA. If θ_j increases, member j becomes less vulnerable to climate change and all members can afford more emissions. In contrast, non-members have to reduce their emissions to offset part of the damage from the emission increase by the IEA. Therefore, with adaptation level chosen before the formation of an IEA, there is free-riding on adaptation technology inside an IEA.

Appendix E. Profitability

A minimum requirement for a stable coalition is that the welfare of each country forming the coalition must be greater than the status quo where agents behave non-cooperatively. This condition is called profitability of a coalition. However, profitability is only a necessary condition to a stable coalition (Hoel (1992), Carraro and Siniscalco (1993)). Free-riding is the main problem preventing a large coalition being formed. In other words, internal and external stability conditions are sufficient but not necessary to profitability in most models used in the IEA literature. Therefore, only internal and external stability are extensively used as the definition of a stable coalition in literature of IEA and coalition theory. However, if there exists some pivotal countries such that an IEA on mitigation will either formed with the participation of these countries or not formed at all, a coalition should be formed based on profitability to pivotal countries. In this section, with the profitability condition we show that a coalition cannot be achieved if members differ much from each other with respect to their net vulnerability since such a coalition is not profitable for less vulnerable members. If pivotal countries are also less vulnerable to climate change compare to the rest of the world, an IEA cannot be achieved.

Definition 1. *A coalition S is profitable for country j if its welfare increases as a result of its membership: $\Delta w_j \geq 0$, $j \in S$, where*

$$\begin{aligned}\Delta w_j &= w\left(e_j^S\right) - w\left(e_j\right)\\ &= \left[B(e_j^S) - B(e_j)\right] - \left[\left(D(E^N, a_j^N) + C(a_j^N)\right) - \left(D(E, a_j) + C(a_j)\right)\right]\end{aligned} \quad (E.1)$$

The profitability of a coalition is defined as the gains from forming the coalition as compared to the non-cooperation equilibrium. (E.1) can be divided into two parts: the first part is the change in benefit of emissions resulted from the formation of the coalition; the second part is the change in the climate change cost (the damage from emissions plus the adaptation cost). The climate change cost

will be reduced for every country after a coalition is formed. However, from Proposition 5, a member with relatively low vulnerability needs to cut emissions, and the foregone benefit of emissions may far exceed the reduced climate change cost. Therefore with heterogeneous agents, satisfying the profitability condition is unsurprisingly difficult.

Lemma 8. *A coalition is profitable for a member country $j \in S$, i.e. $\Delta w_j = w\left(e_j^S\right) - w\left(e_j\right) \geq 0$, iff*
$$\frac{\Phi_j \Psi_j + \Phi_j}{\Phi^S \Psi_j^S + \Phi_j} \geq \left(\frac{1 + \Psi}{1 + \Psi^O + \Psi^S}\right)^2.$$

Proof. From (E.1), the welfare difference by forming the coalition for a member $j \in S$ is given by,

$$\Delta w_j = \left[\alpha_j \left(e_j^S - e_j\right) - \frac{\beta_j}{2}\left(e_j^{S2} - e_j^2\right)\right] - \frac{1}{2}\left(v_j - \frac{\theta_j^2}{c_j}\right)\left(E^{N2} - E^2\right)$$

$$= \frac{\beta_j}{2}\left[\left(\frac{\Psi_j}{1 + \Psi}\right)^2 - \left(\frac{\Psi_j^S}{1 + \Psi^O + \Psi^S}\right)^2\right]\overline{E}^2 - \frac{\Phi_j}{2}\left[\left(\frac{1}{1 + \Psi^O + \Psi^S}\right)^2 - \left(\frac{1}{1 + \Psi}\right)^2\right]\overline{E}^2$$

$$= \frac{\overline{E}^2}{2}\left[\frac{\Phi_j \Psi_j + \Phi_j}{(1 + \Psi)^2} - \frac{\Phi^S \Psi_j^S + \Phi_j}{(1 + \Psi^O + \Psi^S)^2}\right].$$

Thus the coalition is profitable for j iff,

$$\frac{\Phi_j \Psi_j + \Phi_j}{(1 + \Psi)^2} \geq \frac{\Phi^S \Psi_j^S + \Phi_j}{(1 + \Psi^O + \Psi^S)^2} \Leftrightarrow \frac{\Phi_j \Psi_j + \Phi_j}{\Phi^S \Psi_j^S + \Phi_j} \geq \left(\frac{1 + \Psi}{1 + \Psi^O + \Psi^S}\right)^2.$$

$\square$

Lemma 9. *(Sufficient condition for profitability) If a member j can keep at least its emission level in the non-cooperative world, the coalition is profitable for member j.*

Proof. As proven in Lemma 4, $e_j^S(S) \geq e_j^O(S\backslash\{j\})$ iff

$$\frac{\Phi_j}{\Phi^S} \geq 1 - \frac{\Psi_j^S - 2\Psi_j + \Phi_j \sum_{k \in S} \frac{1}{\beta_k}}{1 + \Psi^O + \Psi^S}.$$

Since $\frac{\Phi_j}{\Phi^S} < 1, \frac{\Phi_j^2}{(\Phi^S)^2} < \frac{\Phi_j^2 + \beta_j \Phi_j}{(\Phi^S)^2 + \beta_j \Phi_j}$.

$$\frac{\Phi_j^2 + \beta_j \Phi_j}{(\Phi^S)^2 + \beta_j \Phi_j} > \frac{\Phi_j^2}{(\Phi^S)^2} \geq \left(1 - \frac{\Psi_j^S - 2\Psi_j + \Phi_j \sum_{k \in S} \frac{1}{\beta_k}}{1 + \Psi^O + \Psi^S}\right)^2$$

From Lemma 8, $\Gamma_j^S(S) > 0$. $\square$

In (E.1), profitability of a country is composed of the change of the benefit of emissions and change of climate change costs. If a member's emission level is no lower than the non-cooperative outcome, the benefit of emissions is at least as much as the non-cooperative level. Moreover, since the world emission level is always lower with a larger IEA, the member's climate change cost is lower than without an IEA. Thus for such a signatory to an IEA, it has higher welfare than if no IEA is formed. However, if a signatory needs to reduce its emissions compared to the non-cooperative outcome, the profitability of

Types	Conditions	Emission Change	Cooperative Incentives
I	$\left(\frac{1+\Psi}{1+\Psi^O+\Psi^S}\right)^2 \leq \left(\frac{\Phi_j}{\Phi^S}\right)^2 < \frac{\Phi_j\Psi_j+\Phi_j}{\Phi^S\Psi_j^S+\Phi_j}$	$e_j^S(S) \geq e_j$	$\Delta w_j > 0$
II	$\left(\frac{\Phi_j}{\Phi^S}\right)^2 < \left(\frac{1+\Psi}{1+\Psi^O+\Psi^S}\right)^2 \leq \frac{\Phi_j\Psi_j+\Phi_j}{\Phi^S\Psi_j^S+\Phi_j}$	$e_j^S(S) < e_j$	$\Delta w_j \geq 0$
III	$\left(\frac{\Phi_j}{\Phi^S}\right)^2 < \frac{\Phi_j\Psi_j+\Phi_j}{\Phi^S\Psi_j^S+\Phi_j} < \left(\frac{1+\Psi}{1+\Psi^O+\Psi^S}\right)^2$	$e_j^S(S) < e_j$	$\Delta w_j < 0$

Table E.6: Emissions and welfare changes from non-cooperative to coalition equilibrium

the IEA to the country depends on whether its reduced climate change cost is enough to compensate to the foregone benefit of emissions. A detailed relationship between emissions change profitability can be obtained from Lemma 4 and Lemma 8. Table E.6 shows the relationship between emission change and profitability, given each country's parameters..

Type I are highly vulnerable countries and is described in Lemma 9 and have to reduce their emissions. Type II countries can be moderately vulnerable to climate change. These countries still have to reduce their emissions, but the welfare rises as the IEA is formed becasue the reduced climate change cost is enough to compensate the foregone benefit of emissions. Countries with low vulnerability compose Type III, in which countries need reduce significant amount of emissions but benefit little from global emissions reduction. The grand coalition is definitely profitable for Type I countries, wealy profitable for Type II, and non-profitable for Type III. Thus, a stable coalition can only have Type I and Type II countries.

Lemma 10. *A given coalition S is less profitable for a less vulnerable member j. If a member j with relatively low vulnerability which satisfies the condition for Type III, the coalition cannot be formed.*

Proof. For a given coalition, all coalition-level parameters, i.e. Φ^O, Φ^S, Ψ^O and Ψ^S, are fixed. Let j be any arbitrary member in the coalition.

$$\frac{\partial \Delta w_j}{\partial \Phi_j} = \frac{\overline{E}^2}{2}\left[\frac{2\Psi_j}{(1+\Psi)^2} + frac1(1+\Psi)^2 - \frac{1}{1+\Psi^O+\Psi^S}\right] > 0$$

Note that $1+\Psi < 1+\Psi^O+\Psi^S$.

If there exist a member with very low $\frac{\Phi_j}{\Phi^S}$ such that $\left(\frac{\Phi_j}{\Phi^S}\right)^2 < \frac{\Phi_j\Psi_j+\Phi_j}{\Phi^S\Psi_j^S+\Phi_j} < \left(\frac{1+\Psi}{1+\Psi^O+\Psi^S}\right)^2$, as stated in Lemma 8, the coalition is profitable for country j and hence is not stable. $\square$

With heterogeneous agents, a stable coalition consists only Type II countries. However, with heterogeneity countries, if gaps in vulnerability is large between countries, Type I and Type III countries can emerge, especially in the formation of the grand coalition. To address the impact of heterogeneity in adaptation, temporarily assume countries are identical on the benefit side but heterogeneous in natural vulnerability and adaptation. Suppose $\alpha_i = \alpha$, $\beta_i = \beta$, $\forall i \in N$. Net vulnerability, Φ_i, varies across countries because of heterogeneous v_i, θ_i and c_i. For a given coalition, all coalition-level parameters, i.e. Φ^O and Φ^S, are fixed. The condition that a coalition is profitable for country $j \in S$ becomes

$$\frac{\Phi_j^2 + \Phi_j\beta}{\Phi^{S2} + \Phi_j\beta} > \frac{(\beta+\Phi)^2}{(\beta+\Phi^O+s\Phi^S)^2} \tag{E.2}$$

where s is the size of the coalition S.

The right hand side is fixed at a value between $[\frac{1}{s^2}, 1]$ given a set of countries N and a coalition S. The left hand side is country-specific and is higher for a member with higher Φ_j. Note that $\lim_{\Phi_j \to 0} = 0$ and $\lim_{\Phi_j \to \Phi_S} = 1$. Let Φ^m be the value at which $\frac{\Phi_j^2 + \Phi_j \beta}{\Phi^{S2} + \Phi_j \beta} = \frac{(\beta + \Phi)^2}{(\beta + \Phi^O + s\Phi^S)^2}$. As shown in Figure E.3, for those whose vulnerability is smaller than Φ^m, according to Lemma 8, the coalition is not profitable for them. The further disperse the vulnerability is, the more likely that some member's vulnerability is smaller than Φ^m. Therefore, large gap in adaptation cost and effectiveness may prevent a large coalition.
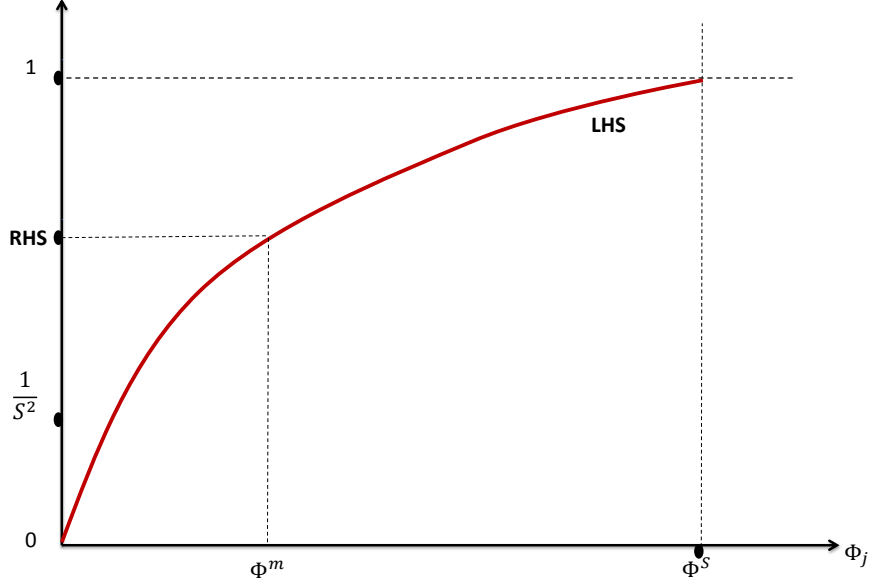

Figure E.3: Vulnerability and profitability of a member country

Appendix E.1. Internal Stability and Profitability

Lemma 11. *(Sufficient condition for profitability) If a coalition S is internal stable, it is also profitable for all members.*

Proof. From Proposition 8, the profitability condition of a coalition is equivalent to the following,

$$\frac{\Phi_j \Psi_j + \Phi_j}{\Phi^S \Psi_j^S + \Phi_j} \geq \left(\frac{1 + \Psi}{1 + \Psi^O + \Psi^S}\right)^2, \forall j \in S.$$

From Lemma 5, the internal stability condition is equivalent to the following,

$$\frac{\Phi_j \Psi_j + \Phi_j}{\Phi^S \Psi_j^S + \Phi_j} \geq \frac{(1 + \Psi^O(S \backslash \{j\}) + \Psi^S(S \backslash \{j\}))^2}{(1 + \Psi^O + \Psi^S)^2}, \forall j \in S.$$

Note $1 + \Psi^O(S\backslash\{j\}) + \Psi^S(S\backslash\{j\}) \geq 1 + \Psi$ for any existing coalition S:

$$1 + \Psi^O(S\backslash\{j\}) + \Psi^S(S\backslash\{j\}) = 1 + \Psi^O + \Psi^S + 2\Psi_j - \Psi_j^S - \Phi_j \sum_{k \in S} \frac{1}{\beta_k}$$

$$= 1 + \sum_{i \in O} \frac{\Phi_i}{\beta_i} + \sum_{k \neq j \in S} \frac{\Phi^S - \Phi_j}{\beta_k} + \frac{\Phi_j}{\beta_j}$$

$$\geq 1 + \sum_{i \in O} \frac{\Phi_i}{\beta_i} + \sum_{k \neq j \in S} \frac{\Phi_k}{\beta_k} + \frac{\Phi_j}{\beta_j} = 1 + \Psi.$$

Thus if a coalition S is internal stable, the profitability condition is satisfied as well:

$$\frac{\Phi_j \Psi_j + \Phi_j}{\Phi^S \Psi_j^S + \Phi_j} \geq \frac{(1 + \Psi^O(S\backslash\{j\}) + \Psi^S(S\backslash\{j\}))^2}{(1 + \Psi^O + \Psi^S)^2} \geq \left(\frac{1 + \Psi}{1 + \Psi^O + \Psi^S}\right)^2, \forall j \in S.$$

$\square$

Internal stability is a sufficient condition to profitability for any coalition. Thus, in the text we only focus on stability conditions as constraints for a stable coalition. Nevertheless, if there exists some pivotal countries such that an IEA on mitigation will either formed with the participation of these countries or not formed at all, profitability condition becomes a constraint to a stable coalition as well. Pivotal countries' decisions are based on profitability: a pivotal country will choose to join the coalition if it gains from forming the coalition as compared to the non-cooperation equilibrium. From our results in this section, profitability condition cannot be satisfied if countries differ much in terms of vulnerability, especially given a large coalition. If gaps in net vulnerability among pivotal countries, or between pivotal countries and the rest of the world, are very large, an IEA cannot be formed since the coalition is not profitable for pivotal countries. The Kyoto Protocol is queried since the 'big emitters', such as the U.S., China and India, did not participate, and their decisions greatly influence other countries' decisions. Our result has an implication to IEAs on mitigation of climate change: reduce gaps in vulnerability, among countries, e.g. provide vulnerable countries with adaptation technology, may foster cooperation on mitigation of climate change.

Appendix E.2. Profitability of the Grand Coalition

If we consider countries are asymmetric in all parameters $(\phi_i, \beta_i, \alpha_i)$, the general conclusion is that the more different they are in terms of vulnerability, the more welfare gain is after a grand coalition formed. The aggregate welfare change is given by,

$$\Delta W = \sum_{k \in N} \Delta w_k = \frac{\overline{E}^2}{2}\left[\frac{\sum\limits_{k \in N}(\Psi_k \Phi_k) + \Phi}{(1 + \Psi)^2} - \frac{\Psi^G \Phi + \Phi}{(1 + \Psi^G)^2}\right] \tag{E.3}$$

Lemma 12. *The aggregate profitability of the grand coalition is higher when members are heterogeneous with respect to adaptation parameters.*

Proof.

$$\Delta W = \frac{\overline{E}^2}{2(\beta + \Phi)^2(\beta + n\Phi)}\left[\left(\beta\sum_{k \in N}\Phi_k^2 + \beta^2\Phi\right)(\beta + n\Phi) - \beta\Phi(\beta + \Phi)^2\right]$$

$$\geq \frac{\overline{E}^2}{2(\beta + \Phi)^2(\beta + n\Phi)}\left[\left(\beta n\overline{\Phi}^2 + \beta^2\Phi\right)(\beta + n\Phi) - \beta\Phi(\beta + \Phi)^2\right] = \Delta W^m$$

xxi

Thus with heterogeneity in adaptation (embodied in residual vulnerability Φ_i), the aggregate welfare is always greater than the mean preserving homogeneous world.

$$\frac{1}{n}\sum_{k\in N}\Phi_k^2 = \frac{1}{n}\sum_{k\in N}\left(\Phi_k - \overline{\Phi}\right)^2 + \overline{\Phi}^2 = var\left(\Phi_i\right) + \left(mean\left(\Phi_i\right)\right)^2$$

For mean preserving Φ_i for n countries, the higher the variance of Φ_i the higher the ΔW is. Thus heterogeneity in adaptation increases the total profitability of the grand coalition. $\square$