Climate Change Adaptation and International Mitigation Agreements with Heterogeneous Countries

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Abstract

Global cooperation with respect to greenhouse gas emissions mitigation is contingent on finding common ground in addressing the problem of adaptation to climate change impacts. This paper uses a non-cooperative game theory model to investigate the relationship between adaptation technology and the formation of emission-reducing International Environmental Agreements (IEAs) on climate change, with countries that are heterogeneous with respect to the benefits and costs of both mitigation and adaptation. While differences in climate vulnerability are a deterrent for cooperation, increasing the effectiveness of adaptation in highly vulnerable countries can foster an IEA. Both traditional free-riding on climate change mitigation efforts, and free-riding on adaptation technology among members of an IEA can be reduced by transfers of adaptation technology within the IEA. A numerical example with parameters estimated from climate change data is used to simulate stable coalitions and demonstrate how the transfer 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 projected (Stern, 2008; Kousky, 2012). Over the past few 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 programs aimed at reducing CO_2 emissions, and adaptation measures involving adjustments in ecological and socio-economic systems meant to reduce climate change impacts are two major approaches to address climate change. However, such global efforts have to date been grossly inadequate. The *Working Group II* contribution to the Fifth Assessment Report IPCC titled 'Climate Change 2014: Impacts, Adaptation and Vulnerability' and many other reports paint a dire picture in terms of the timing and magnitude of the projected impacts around the world. One consequence of the sharper recent focus on climate change impacts is that mitigation and adaptation are no longer considered alternative strategies. Due to climate hysteresis and other factors, such as disparities in adaptation capability among countries, they are increasingly seen as policy complements (Bayramoglu et al., 2016). Indeed, one fact the recent COPs made exceedingly clear was that a global agreement adhered to by both developing and developed countries would have to include both adaptation and mitigation provisions.

GHGs are global pollutants, since a country's emissions impose a negative externality on other countries by contributing to climate change. When countries choose emission levels non-cooperatively, the global GHG emissions exceed the globally efficient level, defined as the fully cooperative outcome where every country chooses its own emissions to maximize global welfare. Thus conceptually, international coordination is required in order to mitigate global GHG emissions effectively. Yet, 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 competitiveness. In addition, many have judged the Kyoto Protocol's emission reduction targets and the Paris Agreement's Intended Nationally Determined Contributions to be inadequate for slowing down climate change (UNEP, 2012, 2017). 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 of climate change.[2]

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

[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

This paper studies the interaction between climate change adaptation technology and incentives to participate in an International Environmental Agreement on GHG emissions mitigation (referred to as an IEA), in the presence of cross-country heterogeneity. We focus on the incentives to free ride for each country, given their specific economic and environmental parameters, and we look at the way these incentives respond to exogenous changes in adaptation technology and net vulnerability to climate change impacts. The importance of accounting for country differences in benefits and damages from emissions cannot be overemphasized: different levels of development, technology, resource endowment and economic structure translate into markedly different economic benefits per unit of carbon emitted, while differences in geography, infrastructure preparedness and institutional capacity also yield substantially different projected economic impacts 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 fully heterogeneous benefits and costs of both mitigation and adaptation on a country's incentives with respect to optimal climate change policy and international cooperation.

Adaptation is typically seen as a private good.[3] However, asymmetric costs and benefits of both mitigation and adaptation across countries further complicate the relationship between mitigation, adaptation and cooperativeness. In particular, a country with low adaptation costs and/or low exposure to climate change but high mitigation costs 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 literature. This paper explores the relationship between mitigation and adaptation with heterogeneous countries, focusing on the effects of adaptation technology on the formation and stability of an IEA aimed at GHGs mitigation.

To preview the main results, exogenous technological progress in adaptation creates positive spillovers within the IEA, compared to it being strictly a private good outside of an IEA. Besides the usual free-riding in mitigation, free-riding with respect to adaptation technology emerges among members of an international mitigation agreement. Using two coalition stability concepts, we find that large gaps in vulnerability to climate change prevent the formation of a large IEA. [4] Thus, technological progress in adaptation occurring in (or transferred to) highly vulnerable countries can act as a partial equalizer of vulnerability and can help form a broader international agreement on mitigation. The results also suggest that free-riding in an international mitigation agreement can

to defend against rising sea levels, changing crop types, and even relocating population from vulnerable areas.

[3] One major exception is geo-engineering, which is a global public good (Weitzman, 2015; Moreno-Cruz, 2015; Keith, 2013). Nonetheless, we restrict our focus here to less controversial and more widely practiced measures of adaptation, which means both its costs and benefits are private to the respective country.

[4] Please see section 4 below - in particular Proposition 3 - for a formal characterization of the link between disparities in vulnerability and countries' cooperative incentives.

be reduced through the transfer of new technologies in adaptation to less innovative 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.

It is generally accepted that adaptation cannot reduce climate change damages to zero, neither could mitigation entirely revert the underlying trends driving climate change. In this sense, adaptation and mitigation are broadly complementary policies.[5] Still, as a country invests more in adaptation, it will suffer less damage from climate change, making internalization of the global externality through mitigation less attractive. Moreover, as countries reduce GHG emissions, the speed of climate change may decelerate, making adaptation efforts less worthwhile. Thus, at least if we abstract from non-linearities and high-risk low-probability events, mitigation and adaptation may also be substitutes. Despite these policy interactions, the interplay between GHG-emission mitigation policies and adaptation activities has not received sufficient attention in the literature. The existing work on international cooperation on GHG emissions mitigation mostly analyzes the incentives to join emission-reducing IEAs and their stability. A small body of work looking at adaptation and mitigation mostly exploits the trade-off between the two for identical countries. Only a handful of studies allow for heterogeneity across countries in either mitigation or adaptation, and even fewer undertake such analysis in a comprehensive manner, as discussed below.

A substantial part of the existing literature on IEAs analyzes the formation and stability of an IEA using non-cooperative game theory. Since there does not exist a supranational institution that can enforce participation in an IEA, it must be *self-enforcing*, in the sense of D'Aspremont et al. (1983), where the concepts of internal and external stability of a coalition are introduced. Barrett (1994) studies the stability of an IEA and shows that a self-enforcing IEA may sustain a large number of countries only when the net gain of moving from noncooperation to full cooperation is very small. Subsequent papers (Barrett, 1997a; Pavlova and de Zeeuw, 2013) have similarly reached conclusions, suggesting that IEAs that aim to coordinate GHG emissions mitigation may not achieve much, and the real world experience to date seems to confirm these pessimistic findings.[6] In a recent paper, Battaglini and Harstad (2016) show how coalitions can be enlarged when considering technological investments in green technologies under incomplete contracting. When the agreement focuses on internalizing the positive externality of investments in clean technology R&D rather than on mitigation, El-Sayed and Rubio (2014) show that a small stable coalition is feasible. However, clean technologies aimed at reducing carbon emissions do not necessarily enhance cooperation on mitigation. As demonstrated in Benchekroun and Chaudhuri (2015), the adoption of cleaner

[5] In a two-player framework, Eisenack and Kähler (2016) show that considering adaptation may lead to an improved likelihood that unilateral emission reductions can be welfare-improving.

[6] e.g. despite Kyoto's relatively large membership, only a few signatories actively curbed emissions.

technologies does not always improve the odds of achieving a stable coalition.[7]

Only a small number of recent papers look explicitly at the interaction between adaptation and mitigation, and this sub-literature can be categorized into two strands. The first highlights the trade-off between mitigation and adaptation across countries. The second 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 mitigation-coalition formation. Benchekroun et al. (2017) develop a model based on Barrett (1994) with adaptation as a policy instrument additional to mitigation. With identical adaptation and mitigation across countries, more effective adaptation measures may diminish a member's incentive to leave an emission-reducing IEA and lead to larger stable coalitions. Thus, while adaptation and mitigation are normally considered substitutes, their conclusion is that adaptation efficiency increases and IEAs on mitigation are complements. We generally confirm these results in this paper, while also outlining the role of cross-country heterogeneity with respect to vulnerability. Our framework also allows us to be more precise in describing the effects of technological progress in adaptation, depending on the membership status and idiosyncratic characteristics of the innovation adopter. While in reality costs and benefits of both mitigation and adaptation differ widely across countries, most studies in the sizable 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. (2016) assume two types of adaptation costs and analyze the incentives to join an IEA on mitigation with and without carbon leakage. The article shows that considering adaptation may not discourage the formation of a mitigation agreement, and details cases when exogenous reductions in the cost of adaptation differences among countries have positive or negative effects on cooperation. A recent working paper by Bayramoglu et al. (2016) also brings together climate change mitigation and adaptation to analyze conditions for a more successful climate agreement. While their work generally follows the assumption of ex-ante symmetric players, some of their results around the order of adaptation and mitigation and the cooperation-enhancing potential of adaptation could be extended to asymmetric players. Our focus on adaptation technology, on the specific ways in which countries differ with respect to their vulnerability to climate change impacts, as well as on the 'club-goods' nature of adaptation technology improvements within an IEA makes our work complementary to theirs.

To summarize, the main contribution of the paper is to be the first - to the best of our knowl-

[7] Several ways to overcome this predicament have been explored, notably Nkuiya et al. (2015) show how endogenous uncertainty can increase IEA participation. Focusing on intellectual property rights (IPRs) of clean technologies, Goeschl and Perino (2017) show that a global system of IPRs on clean technologies can undermine the size and the abatement goal of an IEA. Finus and Rübbelke (2013) show that while accounting for ancillary benefits of mitigation may increase the likelihood of reaching an international agreement, the size of the resulting coalition may in fact be smaller.

edge - 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 emissions mitigation coalitions. We obtain results on the likelihood of cooperation which are contingent on these country-specific characteristics, and which can be used to inform policy. For example, technology transfers aimed at reducing country-specific vulnerability to climate impacts are shown to be cooperation-enhancing. We are also flexible in terms of the timing of adaptation, by studying cases in which it takes place both prior to and simultaneous with (or, equivalently, subsequent to)[8] the choice of emission reductions. Additionally, we extend our model to show how shared technological advances in adaptation among the members of an IEA has the potential to increase cooperation, and we derive conditions involving the assumed country-specific parameters for the enhanced potential of such coalitions. Finally, unlike the received literature, numerical simulations we use to solve for the stable coalitions employ empirically-estimated parameters, based on a dataset assembled for this purpose. In our view, the paper's chief limitations are the assumed exogeneity of technological progress and the essentially static nature of the game, and these are left as topics of future research.

The rest of the paper proceeds as follows. The model with heterogeneous agents is presented in section two. Section three characterizes the coalition equilibrium of the model. The incentive to participate in an IEA will be analyzed in section four. Section five tackles coalition stability, section six presents 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, considered to be both more realistic and more general than cooperative games.[9] The game structure is based on McGinty (2007) and Benchekroun et al. (2017), and it includes a standard coalition formation game theory setting which we augment with 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 country-specific.

Let $N = \{1, ..., n\}$ denote the set of all countries. Emissions e_i of a global pollutant (e.g. a GHG) is the by-product of consumption and production activities of each country i. While most of the literature confines the analysis to positive emission choices, we allow for negative net country emissions, which would correspond to processes like carbon sequestration.[10] Global emissions of

[8] See discussion in Appendix D.

[9] A literature survey by Finus (2008) states that 'the potential for explaining real world phenomena of IEAs is much higher for the non-cooperative than for the cooperative approach,' due to the absence 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.

[10] Such 'negative emissions' are consistent with the 2016 Paris Agreement, which projects the need for negative

the global pollutant are aggregated over all countries, $E \equiv \sum_{i=1}^{n} e_i$. For 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 $B_i(e_i)$ represent the benefit that country i derives from its own emissions-generating production and consumption activities:

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

with $\alpha_i, \beta_i > 0$. The marginal benefit of emissions is given by $\frac{dB}{de_i} = \alpha_i - \beta_i e_i$, and hence the benefit $B_i(e_i)$ is monotonically increasing over $(-\infty, \overline{e_i}]$, where the maximum emissions level is defined as $\overline{e_i} \equiv \frac{\alpha_i}{\beta_i}$.[11] The marginal benefit of emissions diminishes with the amount of emissions, since $\frac{d^2B}{de_i^2} = -\beta_i < 0$.

While the benefits of emissions are private, the effects of emissions represent a global public bad: the damage is imposed to all countries, albeit differentially. The actual damage to country i is assumed to be a convex function of global emissions and country-specific vulnerability (v_i) and adaptation (θ_i) parameters:

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

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 natural vulnerability to climate change. This 'ex-ante' vulnerability is an exogenously given parameter, characteristic to each country, and should be distinguished from a country's actual or 'ex-post' vulnerability to climate change impacts, which takes into account the actual equilibrium level of emissions and the optimal level of adaptation. The second term in (2) represents the country-specific damage-reduction effect or '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. (2017) 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.

Note three main features of the the damage function defined in (2). First, whenever there are positive damages from climate change - which we assume in order to avoid a trivial solution-,[12] D

emissions in order to keep the temperature increase under 2°C. An additional technical 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, and thus artificially tilting the table towards cooperation. Still, for simplicity of exposition, we do assume that the *combined* world emissions are positive, i.e. $E > 0$.

[11] This ceiling ensures that higher emissions - as a proxy for a higher scale of beneficial consumption and/or production activities - continue to bring about positive marginal benefits. The condition under which individual country emissions are in this range is provided in (4) below.

[12] $D > 0 \iff E > 2\theta_i a_i / v_i \Rightarrow E > \theta_i a_i / v_i \iff D_E > 0$.

is strictly increasing and convex in global emissions and it is decreasing in adaptation. Second, the marginal damage from emissions $\frac{\partial D(E,a_i)}{\partial E} = v_i E - \theta_i a_i$ is decreasing in adaptation. Third, the marginal benefit of adaptation $-\frac{\partial D(E,a_i)}{\partial a_i} = \theta_i E$ is increasing in global emissions: the higher the global emissions, the more valuable adaptation activities are.

The convex cost of adaptation for country i is:

$$C_i(a_i) \equiv \frac{c_i}{2} a_i^2, \tag{3}$$

where $c_i > 0$ and with differences in adaptation costs across countries captured by parameter c_i. Technological progress in adaptation can affect both the effectiveness and the cost of adaptation activities: either θ_i rises and/or c_i drops.[13]

Climate change is costly for an economy in terms of both direct net damages given its adaptive measures $D_i(E, a_i)$, and in terms of the cost of those adaptive efforts. We call this 'the total climate cost': $CC_i(E, a_i) \equiv D_i(E, a_i) + C_i(a_i)$, and by using (2) and (3) and with a_i optimally chosen, the marginal climate cost can be written as $MCC_i = E\left(v_i - \frac{\theta_i^2}{c_i}\right)$. Notice that if adaptation is very effective and/or its cost is very low, this marginal cost of climate change can turn negative, in what might be termed 'profitable over-adaptation'. To rule out this less interesting scenario, the following is assumed to hold:

$$v_i > \frac{\theta_i^2}{c_i}. \tag{4}$$

Technically, the purpose of this assumption is twofold. First, the marginal cost of global emissions for country i, 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 optimal emission level. Therefore, the optimal emissions level of a country i is always smaller than its maximum emission level: $e_i \leq \overline{e_i} \equiv \frac{\alpha_i}{\beta_i}$.

The social welfare of country i is determined as the benefits of emissions, net of climate-induced damages given own adaptation efforts, and net of the cost of these efforts, where the last two terms are jointly defined above as the cost of climate change:

$$w_i(e_i, a_i, E) \equiv B_i(e_i) - D_i(E, a_i) - C_i(a_i) = B_i(e_i) - CC_i(E, a_i).^{14} \tag{5}$$

[13] We depart here from Benchekroun et al. (2014) in using both θ and c as parameters. While both essentially represent differences in adaptation across countries, economies may in fact differ from each other with respect to either one, or both. The two adaptation parameters also yield different implications for both private investment and policy, which may target the effectiveness of adaptation θ and the costs of adaptation c separately.

[14] While all functions are country-specific, as indicated so far by the i subscripts, we omit these in the following analysis, in order to simplify notation.

3. Equilibrium

We consider a model based on a two-stage, simultaneous-move, open membership game.[15] In the first stage, countries choose whether to participate in the international agreement on abatement, and in the second stage they concomitantly choose their level of emissions/abatement and adaptation. We assume a monocentric setting, where countries decide simultaneously not just their levels of mitigation and adaptation, but also on whether to participate in the agreement, and we do not allow for side-payments. Since most of the assumptions we maintain throughout the paper are standard in the literature, we relegate a lengthier explanation to Appendix A.1. Here we briefly discuss the last two, which have particular implications in our context.

The timing of the game presents an interesting possibility in our context. Given that many adaptation projects require substantial infrastructure investment,[16] which may take a long time to complete, it is likely for some prospective IEA members to have already committed significant amounts of funds to such purposes *before* a mitigation agreement is reached. We look at this option in Appendix D, and as expected, countries have lower incentives to join the coalition (more incentives to free ride) if they have already decreased their *de facto* vulnerability via adaptation. Equivalently, should an IEA be formed eventually, countries over-adapt. On side-payments, the practical logistics of such transfers are problematic in a world in which the most vulnerable countries - which benefit the most from an IEA, benefit the least from emissions and are often among the poorest - would have to compensate the richer, less vulnerable, industrialized countries in order to induce them to join the IEA.

We first study the two polar opposite cases of *no cooperation* and of *full cooperation*, and the complete results are provided in Appendix C. While these two cases are relevant, they are examined in the existing literature and are particular applications of the more general *partial cooperation* case. Here we proceed directly with the general case of a coalition with any number of members.

3.1. Coalition Formation

Let S denote the set of signatories of a coalition, or an IEA, and let O denote the set of non-signatories. Let $E^O(S)$ denote the aggregate emissions by non-signatories, and $E^O_{-i}(S)$ the emissions by all non-signatories other than i. Let $E^S(S)$ denote the aggregate emissions by the set of signatories and $E^S_{-j}(S)$ the emissions by all signatories other than j. Let $E^N(S) \equiv E^O(S) + E^S(S)$ be the global emissions, given the existence of a coalition S.

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

[16] Note that adaptation through infrastructure investments may be emission-generating as well, although here we do not highlight this aspect, for simplicity.

3.1.1. Non-signatories

A non-signatory i behaves like a singleton and maximizes its payoff, given other countries' emissions:

$$\max_{e_i,a_i} w_i\left(e_i,a_i,E^N\right) = B_i(e_i) - D_i\left(E^N,a_i\right) - C_i\left(a_i\right). \tag{6}$$

The first order conditions are given by: $\alpha_i - \beta_i e_i - v_i\left(E^O+E^S\right)+\theta_i a_i = 0$ and $\theta_i\left(E^O+E^S\right) - c_i a_i = 0$. While adaptation is a private good, an increase in the amount of adaptation in a country a_i - other things equal - allows it to have higher equilibrium emissions, which then generate spillover effects for all other countries, impacting their own optimal adaptation and emission decisions.

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

$$e_i = \frac{\alpha_i - \Phi_i\left(E^S+E^O_{-i}\right)}{\beta_i+\Phi_i}, \tag{7}$$

$$a_i = \frac{\theta_i}{c_i}\frac{\alpha_i + \beta_i\left(E^S+E^O_{-i}\right)}{\beta_i+\Phi_i}, \tag{8}$$

where $\Phi_i \equiv v_i - \frac{\theta_i^2}{c_i}$ is the net vulnerability in the presence of adaptation, and is always positive, given (4). As a result of technological progress in adaptation in country i, θ_i rises and/or c_i drops and country i's net vulnerability decreases. Substituting e_i and a_i from (7) and (8) into (2), we obtain the net marginal damage from emissions: $\frac{dD(E)}{dE} = \Phi_i E^N$.

From (7), the aggregate emissions best response function of all non-signatories $E^O\left(S\right)$, given the aggregate emissions by signatories E^S, is given by the following:

$$E^O\left(S\right) = \frac{\overline{E}^O - \Psi^O E^S}{1+\Psi^O}, \tag{9}$$

where $\overline{E}^O \equiv \sum\limits_{i\in O}\bar{e}_i$, $\Psi^O \equiv \sum\limits_{i\in O}\Psi_i$, and $\Psi_i \equiv \frac{\Phi_i}{\beta_i}$.

3.1.2. Signatories

Each signatory to the agreement j maximizes the joint welfare of the coalition S, given the emissions by non-signatories E^O.

$$\max_{e_j,a_j}\sum_{j\in S} w_i\left(e_j,a_j,E^N\right) = \sum_{j\in S}\left[B_i(e_j) - D_i\left(E^N,a_j\right) - C_i\left(a_j\right)\right] \tag{10}$$

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

$$e_j = \frac{\alpha_j - \Phi^S\left(E^S_{-j}+E^O\right)}{\beta_j+\Phi^S}, \tag{11}$$

$$a_j = \frac{\theta_j}{c_j}\frac{\alpha_j + \beta_j\left(E^S_{-j}+E^O\right)}{\beta_j+\Phi^S}, \tag{12}$$

where $\Phi^S \equiv \sum_{j \in S} \Phi_j$. Using (9), (11) and (12), global and individual emissions levels can be derived. The emission level of a non-signatory and a signatory are given as follows:

$$e_i^O = \overline{e_i} - \Psi_i E^N = \overline{e_i} - \frac{\Psi_i}{1 + \Psi^O + \Psi^S} \overline{E}, \tag{13}$$

$$e_j^S = \overline{e_j} - \Psi_j^S E^N = \overline{e_j} - \frac{\Psi_j^S}{1 + \Psi^O + \Psi^S} \overline{E}, \tag{14}$$

where $\Psi_j^S \equiv \frac{\Phi^S}{\beta_j}$, $\Psi^S \equiv \sum_{j \in S} \Psi_j^S$. $\overline{E} \equiv \sum_{k \in N} \overline{e_k} = \sum_{k \in N} \frac{\alpha_k}{\beta_k}$ is the maximum level of world's emissions. Note that Φ_i is the slope of the marginal damage from emissions net of adaptation, while β_i is the slope of the marginal benefit of emissions. Therefore, Ψ_i is the relative rate of change for marginal damage to marginal benefit. A non-signatory's emission level, as given by (13), 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. A signatory's emissions in (14) can be interpreted in a similar way. Nonetheless, the abatement indicator of 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. Hence a member always abates more than a comparable non-member.[17]

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

$$E^N(S) = E^S(S) + E^O(S) = \frac{\overline{E}}{1 + \Psi^O + \Psi^S}. \tag{15}$$

If a non-signatory i joins coalition S, the denominator of world emissions increases by $(\frac{\Phi^S}{\beta_i} + \Phi_i \sum_{j \in S} \frac{1}{\beta_j})$. 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.

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

$$a_i = \frac{\theta_i}{c_i} E^N, \forall i \in N. \tag{16}$$

With the assumption of heterogeneous countries, we are able to identify the different impacts of exogenous technological progress in adaptation being adopted in non-member and in member countries as follows:

Proposition 1. *Given an existing coalition S, the impact of exogenous technological progress in adaptation depends on whether it is adopted in a non-member or a member country:*

[17] This result is standard in the literature. Nonetheless, one opposite case is demonstrated in Goeschl and Perino (2017), where a member may abate less than a non-member country in the presence of intellectual property rights of new clean technology.

i. *given adaptation technological progress in a non-member of the coalition, the country will pollute more and adapt more in equilibrium. All other non-members and all members respond by reducing emissions and adapting more;*

ii. *given adaptation technological progress in a coalition member, all members will pollute more and adapt more in equilibrium. Every non-member responds by reducing emissions and adapting more in equilibrium.*

Proof. See Appendix A.2 □

Technological progress in adaptation in a country that is not a member of the coalition reduces its 'ex-post' or actual vulnerability to climate change, and that country's optimal emission level rises as a result. However, the externality of its increased emissions is imposed on other countries, both signatories and non-signatories, which will respond by reducing their emissions, in order to partially offset the damages. Thus, emission levels are *strategic substitutes*. However, given that the coalition behaves like one agent, technological progress in adaptation in one member country reduces the overall vulnerability of the coalition, and all members can afford higher equilibrium emission levels. Members' emissions choices are *strategic complements* in the presence of new adaptation technology adopted in a member country.

Proposition 2. *Given an existing coalition S, technological progress in adaptation is a private good in non-member countries; however, it induces a positive externality in a coalition.*

i. *If technological progress in adaptation is adopted in a non-member country, it benefits from raising its emission level. The negative externality of emissions is imposed on other countries.*

ii. *If technological progress in adaptation is adopted in a member country j, it generates a positive externality for other members; their welfare increases when $\Phi_k\beta_k < \frac{\Phi^S}{\sum_{j\in S}\frac{1}{\beta_j}}\left(1+\sum_{i\in O}\frac{\Phi_i}{\beta_i}\right)$, $k \neq j \in S$, and the welfare of the coalition always rises. A non-member's welfare decreases.*

Proof. See Appendix A.3 □

An interesting implication of Propositions 1 and 2 is that unlike when it occurs outside an IEA, technological progress in adaptation induces a positive externality inside the coalition. Intuitively, the positive externality of technological progress inside the agreement is due to the fact that maximizing the welfare of a now less vulnerable coalition requires less costly mitigation from members. Moreover, as shown in Appendix A.3, the intuition for the positive externality condition can be understood as follows. A member country that highly benefits from emissions (i.e. has a low β_k) and is less vulnerable to climate change (i.e. has a low Φ_k) is most likely to gain from technological progress in adaptation occurring inside the agreement. Coalition-wide gains in adaptation effectiveness allows such a member to benefit by increasing its benefits from emissions proportionately more than the associated increase in climate damages. However, contrary to the case for non-members, adaptation technological progress in a member country j is not always beneficial to j, that is, the sign of the welfare effect $\frac{dw(e_j^S)}{d\Phi_j}$ depends on the members' characteristics. Hence inside a coalition, technological progress in adaptation in a member country may not always be adopted, even though such progress is always beneficial for the coalition as a whole. An intriguing further implication is that non-member countries are more in favor of adopting technological progress in adaptation, while member countries may suppress the adoption of such progress. Furthermore, since technological progress in adaptation is always beneficial to a country outside the coalition, a member country experiencing negative welfare effects following this technological progress if it remains in the agreement is more likely to back out of the IEA.

Another important implication of Proposition 2 is that the location of innovation adoption on adaptation is crucial to the welfare gain of the coalition. Note that $\frac{dw(e_k^S)}{d\Phi_j} < 0$ if $\Phi_k\beta_k < \frac{\Phi^S}{\sum\limits_{j\in S}\frac{1}{\beta_j}}\left(1+\sum\limits_{i\in O}\frac{\Phi_i}{\beta_i}\right)$, where $k \neq j \in S$. Thus, a member country k with a high benefit from emissions (low β_k) and less vulnerable to climate change (low Φ_k) is most likely to gain from technological progress in adaptation occurring in another member country j. On the contrary, highly vulnerable and less developed member countries are more likely to see welfare reductions if other members experience technological progress in adaptation: such members suffer significantly more damages from higher levels of global emissions, but the gain of increased own emissions is limited. Thus, technological progress in adaptation is not always welfare-increasing for all members. Nevertheless, since $\frac{dw(e_j^S)}{d\Phi_j} < \frac{dw(e_j^S)}{d\Phi_k}$, with $k \neq j \in S$, a member always gains more if technological progress in adaptation occurs in that country. The reason is that technological progress in adaptation in the adopting country reduces its actual vulnerability, while other member countries' vulnerabilities are not affected. If technological progress in adaptation occurs in highly vulnerable less developed countries, the welfare of all individual members increases, and their incentives to cooperate via an IEA become stronger. In contrast, from Proposition 2, a non-member's welfare decreases if a member sees technological progress in adaptation. Thus, non-members will have lower incentives to continue to be free riders. In summary, the location of technological progress in adaptation is crucial to the welfare gains and distribution, hence to the success of an IEA. This finding suggests a role for technological transfers as part of the negotiations leading to an agreement.

Our results so far have focused on vulnerability-reducing technological change. For completeness, we now look at some comparative statics with respect to the parameters of the benefit function. 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, due to shifts in the production structure of the economy induced by international trade, or due to general production process, factor-augmenting, or end-of-pipe innovation (Amir et al., 2008). 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:

Lemma 1. *If country i's marginal benefit of emissions shifts up (i.e. α_i rises) - other things equal -, 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) - other things equal -, its emissions increase. All other countries respond by reducing emissions, yet global emissions increase.*

Proof. See Appendix A.4 □

The benefit of emissions occurs privately to a country regardless of its 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.

Lemma 2. *If no country joins the coalition, i.e. $S = \varnothing$ and $O = N$, then $E^N = E$, which is 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. Global emissions given a coalition of S signatories are between the non-cooperative and full-cooperative levels: $E^G \leq E^N = E^O + E^S \leq E$, and their level falls with the size of the coalition. Adaptation levels are also between the non-cooperative and full-cooperative levels: $a_i^G \leq a_i^N \leq a_i$ for $\forall i \in N$.*

Proof. See Appendix A.5 □

4. Stability

Since no supranational institution that can enforce participation exists, an IEA must be *self-enforcing*. A large part of the existing literature on IEAs (Barrett, 1994, 1997a; McGinty, 2007; Pavlova and de Zeeuw, 2013) analyzes the formation and stability of an IEA using the intuitive internal and external stability conditions defined in D'Aspremont et al. (1983): a coalition is internally stable if no member wants to leave it, and it is externally stable if no non-member wants to join. Most previous studies analyze stability of an IEA assuming limited types of agents and no role for adaptation. To preview the results, with heterogeneous countries, we find that large gaps in vulnerability prevent the formation of a coalition, since in that case, less vulnerable members are better off quitting. The internal stability condition is violated, and a stable coalition cannot be formed with significant disparity of vulnerability among coalition members. This result implies technological progress in adaptation in highly vulnerable countries can help reduce the gaps, and hence foster cooperation in climate change mitigation. Normally three conditions need to be satisfied at a coalition equilibrium: profitability, internal stability and external stability (Hoel, 1992; Finus, 2001; Carraro, 2003). Since internal stability implies profitability in our model (see Appendix E.1), we focus here on internal and external stability conditions.[18]

4.1. Cooperative Incentives and Free-riding Incentives

Let $S\backslash\{j\}$ denote the resulting coalition when signatory j leaves S, and let $S\cup\{i\}$ denote the coalition when non-signatory i accedes to S. For a given coalition S, a signatory j's emission and the world emission levels are given by (14) and (15). Using (13) and (15), a former signatory's emissions if it left the IEA and the world's total emissions are as follows:

$$\begin{aligned} e_j^O(S\backslash\{j\}) &= \overline{e_j} - \frac{\Psi_j}{1+\Psi^O(S\backslash\{j\})+\Psi^S(S\backslash\{j\})}\overline{E} && (17)\\ E^N(S\backslash\{j\}) &= \frac{\overline{E}}{1+\Psi^O(S\backslash\{j\})+\Psi^S(S\backslash\{j\})}, && (18)\end{aligned}$$

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

Define the *cooperative incentive* Γ^S of a member country j as its current welfare less its potential welfare as a non-signatory. From (14), (15), (17) and (18):

$$\begin{aligned} \Gamma_j^S(S) &= w_j^S(S) - w_j^O(S\backslash\{j\})\\ &= \frac{\overline{E}^2}{2}\left[\frac{\Phi_j\Psi_j+\Phi_j}{(1+\Psi^O(S\backslash\{j\})+\Psi^S(S\backslash\{j\}))^2} - \frac{\Phi^S\Psi_j^S+\Phi_j}{(1+\Psi^O+\Psi^S)^2}\right]. && (19)\end{aligned}$$

For a given coalition S, a non-signatory i's emission and the world emission levels are given by (13) and (15). Using (14) and (15), a former non-signatory i's emissions if it joins the IEA and total global emissions are as follows:

$$\begin{aligned} e_i^S(S\cup\{i\}) &= \overline{e_i} - \frac{\Psi_i^S+\Psi_i}{1+\Psi^O(S\cup\{i\})+\Psi^S(S\cup\{i\})}\overline{E} && (20)\\ E^N(S\cup\{i\}) &= \frac{\overline{E}}{1+\Psi^O(S\cup\{i\})+\Psi^S(S\cup\{i\})}, && (21)\end{aligned}$$

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

Define the *free riding incentive* Γ^O of a non-member country i as its current welfare less its potential welfare when becoming a signatory of a coalition.

$$\begin{aligned} \Gamma_i^O(S) &= w_i^O(S) - w_i^S(S\cup\{i\})\\ &= \frac{\overline{E}^2}{2}\left[\frac{(\Phi^S+\Phi_i)(\Psi^S+\Psi_i)+\Phi_i}{(1+\Psi^O(S\cup\{i\})+\Psi^S(S\cup\{i\}))^2} - \frac{\Phi_i\Psi_i+\Phi_i}{(1+\Psi^O+\Psi^S)^2}\right]. && (22)\end{aligned}$$

[18] The profitability condition is explored in Appendix E, as it can be applied to a scenario where an IEA can only be formed when all pivotal countries participate. With some pivotal countries, an IEA will either be formed with the participation of these countries or not be formed at all. Hence participation of pivotal countries depends on profitability. The result implies a large gap in adaptation among pivotal countries may prevent the emergence of an IEA.

It is easy to see that cooperative incentive and free-riding incentive are related: 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 a coalition $S \backslash \{j\}$.

4.2. Coalition Stability

An IEA is said to be stable provided it is both internally and the externally stable, or:

$$\Gamma_j^S(S) \geq 0, \forall j \in S, \tag{23}$$

$$\Gamma_i^O(S) \geq 0, \forall i \in O. \tag{24}$$

(23) is the internal stability condition, which requires a signatory of the IEA to be no worse off than outside of the IEA, and (24) is the external stability condition, which stipulates that any non-signatory should have a higher welfare outside of the coalition 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. *If a member j's emission level is no lower than the level it would be at if it left the coalition, its cooperative incentive for the given coalition is positive.*

Proof. see Appendix A.6 □

With heterogeneous countries, it is not necessary that every member reduces emissions when joining the coalition. If a member would maintain at least the same emission level as when it was a non-member, its cooperative incentive is positive. In other words, this is a sufficient condition for $\Gamma_j^S > 0$. The cooperative incentive of a member (19) can be decomposed into two parts: the change in the benefit of emissions and the change in climate change costs that include damages from emissions and adaptation costs. Since a country's benefit from emissions function increases in own emissions, if a member's emission level is not lower than if it left the coalition, the change of the benefit of emissions is non-negative. Moreover, since the world emissions level is always lower with a larger IEA, the member's climate change cost is lower when it chooses to stay in the IEA. Thus, any signatory that emits more in the coalition equilibrium than its non-cooperation level will certainly benefit from joining the IEA, as stated in the following result:

Lemma 4. *A member's equilibrium emissions level rises by forming the coalition iff $\frac{\Phi_j}{\Phi^S} \geq \frac{1+\Psi}{1+\Psi^O+\Psi^S}$, i.e. iff it is relatively vulnerable among all signatories.*

Proof. See Appendix A.7 □

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 among signatories, and it will benefit by joining the IEA, as stated in Proposition 3.[19] However, if a signatory needs to curb its emissions when joining, its cooperative incentive depends on whether its reduced climate change cost due to the IEA-induced mitigation is sufficient to compensate for the foregone benefit of reduced emissions. Relationships between emission changes and cooperative incentives are illustrated in Table 1.

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[20]

For any given coalition, there may exist three types of members based on their relative net vulnerability and slope of the marginal abatement cost. *Strongly-cooperative* members are described in Lemmas 3 and 4. These countries are highly vulnerable to climate change compared to other members. A very vulnerable country maintains a low emission level in the non-cooperative equilibrium. After joining the IEA, its vulnerability is taken into account by all other members and the IEA as a whole reduces emissions. The global emissions level falls, although emissions reductions by the coalition are partly undermined by non-signatories. As a result, the highly vulnerable country can afford a higher emission level, and receives more benefit from emissions and less climate change damages. A *weakly-cooperative* member needs to reduce its emissions if it chooses to join the coalition, yet its total welfare rises: the reduced climate change cost by joining the coalition is enough to compensate for the foregone benefits of emissions. While with homogeneous countries, a stable coalition consists only of weakly-cooperative members, when countries are allowed to differ according to the various parameters of their benefit, damage and cost functions, a stable coalition may include a mix of strongly-cooperative and weakly-cooperative members. *Non-cooperative* countries can be less vulnerable than other members of the coalition. Such countries need to reduce a significant amount of emissions but benefit little from global emissions reduction, hence their welfare declines if they choose to join the coalition. Thus, non-cooperative countries cannot belong to a stable coalition since the free-riding on the coalition dominates.

[19] Goeschl and Perino (2017) obtain a comparable result in a setting without heterogeneous agents and adaptation, but where there is a hold-up problem due to rent-seeking by innovators.

[20] Exact conditions on Φ and β that define these types are found in Appendix A.8.

4.3. Disparity in Vulnerability and Cooperative Incentives

Actual vulnerability to the impacts of climate change differs greatly across countries. In this section, we focus on the role of this disparity in vulnerability on the formation of an IEA. If the gap in net vulnerability is too large, 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 3. *In any given coalition, countries with a lower equilibrium level of ex-post or net vulnerability have lower cooperative incentives. If there exists at least one member j with relatively low net vulnerability, such that $\frac{\Phi_j^2+\beta_j\Phi_j}{(\Phi^S)^2+\beta_j\Phi_j} < \frac{\left[1+\Psi^O(S\backslash\{j\})+\Psi^S(S\backslash\{j\})\right]^2}{(1+\Psi^O+\Psi^S)^2}$, 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 the benefit side (i.e. all have identical α and β parameter values). From (19), $\lim\limits_{\Phi_j \to 0} \Gamma_j^S(S) < 0$, and $\lim\limits_{\Phi_j \to \Phi^S} \Gamma_j^S(S) > 0$. Thus from continuity, there exists a threshold level $\Phi^* \in (0, \Phi^S)$ 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. The IEA is internally stable if and only if all signatories have vulnerability no less than the threshold level. Thus, from continuity, if the net vulnerability of members differs widely, less vulnerable countries are better off outside the coalition and an IEA cannot be formed.

This result implies that policies which assist vulnerable countries with adaptation technology can help reduce the gaps and foster a broader international cooperation on mitigation. Thus aid initiatives like the Green Climate Fund, which is meant to assist developing countries with adaptation may also be instrumental in forming a broad IEA on climate change mitigation.

5. Transfer of Adaptation Technology

Free-riding on the mitigation efforts of members is the main problem preventing the formation of a large IEA (Yi, 1997; Finus, 2008). As a result, the size of a stable IEA is found in the literature to be typically small, or - as mentioned in the introduction - a high degree of cooperation can be achieved only when the gains of cooperation are small (Barrett, 1994, 1997a; Pavlova and de Zeeuw, 2013). The literature on IEA formation has suggested several ways to extend cooperation (Carraro and Siniscalco, 1993; Hoel and Schneider, 1997; McGinty, 2007; Barrett, 1997b; Wagner, 2016; Fuentes-Albero and Rubio, 2010), including side-payments, dispute settlement, trade sanctions and monitoring mechanisms. However, as previously explained, the logistics of transfers and moral hazard issues make them problematic. Carraro and Siniscalco (1994) suggest that a cooperative technological innovation policy linked with an IEA can increase the size of the coalition, as the positive externality offsets the free-riding incentives, yet much of the previous research linking technological innovation and IEAs focuses on technology that reduces carbon emissions (Benchekroun and Chaudhuri, 2015; Goeschl and Perino, 2017). While a cooperative strategy on adaptation technology - such as a technology transfer - has been encouraged by the UNFCCC, its theoretical impact on the formation of an IEA has not been sufficiently investigated.

So far, technological progress was assumed to occur exogenously. In this section, we extend our framework by considering the possibility of technology transfer, to argue that technological progress in adaptation, provided as an excludable 'club good' to members of an IEA, can reduce free-riding with respect to mitigation. In practice, if the IEA is accompanied by an R&D hub on adaptation technology, any innovation from the hub will be transferred to and adopted by members only.

Technological progress in adaptation in a country increases its effectiveness and/or reduces its cost of adaptation activities (θ_i rises and/or c_i falls), and hence reduces the net vulnerability to climate change Φ_i. New general adaptation technologies are transferred to members, and their vulnerability to climate change is reduced if the new adaptation technology can be adopted. Nevertheless, the new adaptation technologies invented somewhere else need to be adapted by each non-inventor country to its specific adaptation needs. In keeping with our previous full-heterogeneity approach, the extent to which a country can benefit from the general adaptation technology also varies across countries. Suppose the net vulnerability becomes $r_j\Phi_j$ for a member that has access to the technology, where $r_j \in [0,1]$ is a country-specific coefficient measuring adoption costs. 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 technology transfer. If a member j leaves the IEA, its access to the technology transfer arrangement ceases, and its net vulnerability reverts to Φ_j. 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. The possibility of technology transfers has implications for IEA formation and stability.

Proposition 4. *If $\beta_i >> \Phi_i$, $\forall i \in N$, incentives to free ride on an IEA increase in the adoption cost; conversely, the more a country benefits from adaptation technology transfer, the lower its incentive to free ride on an IEA.*

Proof. See Appendix A.10 □

Incentives to free ride on an IEA can be reduced by a coalition which shares technological progress on adaptation among its members. A numerical example illustrating Proposition 4 is provided in Section 6. The opposite case to $\beta_i >> \Phi_i, \forall i \in N$ is trivial since it implies that the damage from emissions is much greater than the benefit from emissions and the net welfare can be negative for all countries.[21] Free riding on an international mitigation agreement can be reduced or

[21] The exact condition for $\frac{\partial \Gamma_i^O}{\partial r_i} > 0$ can be found in Appendix A.10.

even eliminated with the transfer of adaptation technology inside an IEA since the incentive to free ride is offset by the benefits stemming from the technology transfer.[22] International cooperation on mitigation can be fostered by the formation of an R&D hub on adaptation technology which shares technological progress in adaptation.[23]

6. Simulation

Previous work on coalition theory and IEAs has shown that even when using identical agents, analytical solutions for the size of stable coalitions are typically not available in closed form with non-linear benefit and damage functions (Barrett, 1997a; McGinty, 2007; Finus, 2008; Botteon and Carraro, 1997, 2001). Thus, simulation has been heavily relied upon to analyze the stability of coalitions, and we follow the same strategy here for the first stage of the membership game. However, most studies focusing on formation and stability of an IEA assume arbitrary parameters (Barrett, 1997a; McGinty, 2007; Pavlova and de Zeeuw, 2013). Following Finus (2008)'s suggestion that simulations based on estimated parameters are particularly worthy, we focus on coalition stability and technology transfer using parameter *estimated* from climate change data.

6.1. Data and Estimation

The benefit of emissions function is estimated for each country using data on GDP and GHG emissions. GDP (current US dollars) is obtained from the World Bank (2014). The GHG emissions (kt of CO_2 equivalent) are aggregated from CO_2, Methane emissions, Nitrous oxide emissions, and other greenhouse gas emissions (HFC, PFC and SF6), which are collected from the World Bank (2014).[24] Parameters α_i and β_i are estimated for each country using the above data from 1960 to 2010, as follows:

$$GDP_{it} = \alpha_i e_{it} - \frac{\beta_i}{2} e_{it}^2. \tag{25}$$

To the best of our knowledge, there exists no comprehensive measure of cross-country cost and effectiveness of adaptation. Nevertheless, parameters in the damage function and cost of adaptation are integrated into net vulnerability, $\Phi_i \equiv v_i - \frac{\theta_i^2}{c_i}$, and Φ_i can be estimated using damages from climate change and the world's total GHG emissions from World Bank (2014). A caveat is that

[22] Notice that technological progress in adaptation which is shared only inside the coalition plays a double role in inducing non-members to behave in a more cooperative manner: first, due to the positive welfare externality reaped by members only and described in Proposition 2, their cooperative incentive increases and secondly their free riding incentive (of remaining outside of the coalition) decreases, since they are faced with the need to reduce their own emissions as an optimal response to the coalition increasing theirs.

[23] As a caveat, due to the constraints to this paper, this simple exercise does not offer a complete treatment of endogenous technology transfer, and is tantamount to treating it as exogenous. As already mentioned, we plan to endogenize technological progress, adoption and its diffusion in future research.

[24] Once observations with negative α_i or βi are dropped, we are left with 143 countries. Summary statistics and details of estimation can be found in Table B.3.

the estimated net vulnerability is likely to be below the actual vulnerability for two reasons: first, although the output side of adaptation is considered in estimating climate change costs, adaptation costs are not included due to lack of data; second, various indirect impacts of climate change can be large but are difficult to measure. Thus, our simulation exercise provides a conservative estimation of the role of vulnerability and the welfare gain potential of international cooperation on climate change. Using climate change costs in 2010 from DARA International (2012)[25] and the world's total GHG emissions from World Bank (2014), net vulnerability Φ_i is estimated for each country:

$$climate\_change\_cost_i = \Phi_i E^2. \tag{26}$$

Using the estimated α_i, β_i, and Φ_i, countries are clustered into 10 groups for computational simplicity. This is done using the *k-means* method, whereby a representative country whose parameters are equal to the group mean is created for each group. Net vulnerability Φ_i is estimated using the actual global emission level; however this figure is much higher than the resulting emission level in the hypothetical 10 representative country world. To account for this discrepancy, Φ_i needs to be re-scaled using the climate change cost and the aggregate emission level of 10 representative countries. With these estimated parameters, α_i, β_i, and the re-scaled Φ_i, we simulate stable coalitions and the impact of adaptation technology transfers. Parameter values are reported in Table B.5 and they vary substantially across the 10 representative countries. For example, country 2 has a high emissions level and is the most vulnerable to climate change. It represents primarily a group of large developing countries, such as China and India. Country 3 represents developed countries that have high emissions levels and are less vulnerable to climate change, such as Canada.

6.2. Results

As shown in Table B.6, the largest stable coalition consists of four representative countries, $S = \{2, 4, 5, 6\}$, and it leads to a 2.4% fall in global emissions. With a grand coalition, the world's emission level drops by 7.4% and the welfare rises by 0.7% compared to the non-cooperative equilibrium. Again, results should be viewed as conservative, in light of the fact that there are only 10 representative countries and their net vulnerability is under-estimated, as explained before.

As stated in Proposition 4, incentives to free ride on an IEA can be effectively reduced with a coalition where adaptation technology is shared among its members. Figure 1 illustrates this result from Section 5: given the largest stable coalition, $S = \{2, 4, 5, 6\}$, non-members' free-riding incentives decrease as the adoption costs of new adaptation technology decrease. As a result of adaptation technology transfers within the IEA, if a non-member decides to join the IEA, its net vulnerability can be reduced to $r_i\Phi_i$. When $r_i = 1$ (the right end of Figure 1), new technology is

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

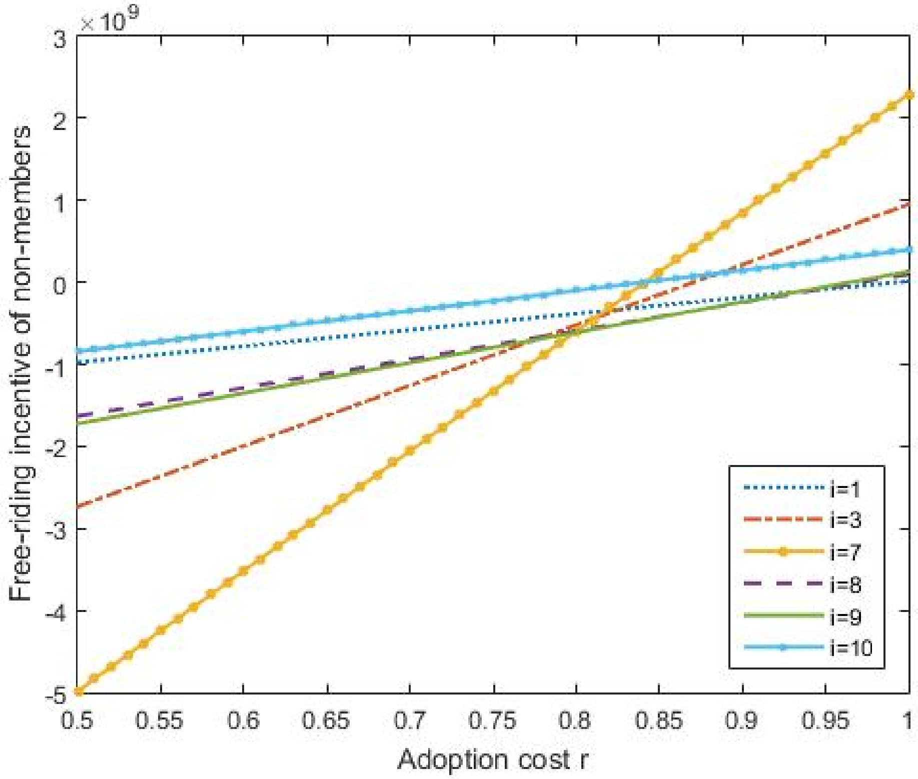

Figure 1: Free-riding incentives and technological progress transfers: $\Gamma_i^O(r_i)$

not adopted due to high adoption cost, and the net vulnerability remains Φ_i if the non-member i joins the IEA. This implies that such non-member countries do not benefit from the technology transfer if they choose to join the IEA. Therefore, non-members' free-riding incentives are positive (as shown in Figure 1 when $r_i = 1$), and they remain outside of the IEA.[26] However, when $r_i < 1$, which indicates that non-member i can benefit from the technology transfer and can reduce its vulnerability if it joins the IEA, country i's free-riding incentive decreases. As shown in Figure 1, the lower the adoption cost index r_i, the lower its free-riding incentive. Eventually, free-riding incentives of a non-member turn negative if the adoption cost is low enough. For example, for representative country $i = 7$ (red line in Figure 1), its free-riding incentive becomes negative when $r_7 = 0.85$. This result indicates that country $i = 7$ joins the IEA if its net vulnerability can be reduced by 15% as a result of the technology transfers within the IEA. In summary, a non-member is willing to join the IEA if it benefits sufficiently from the transfer of adaptation technology as a member of the IEA.

[26] This case is equivalent to the model in Section 2, where technology transfers are not considered.

7. Conclusion

This paper investigates the impact of adaptation technology on a country's incentive to participate in international GHG emissions-reducing 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 impacts of climate change. The paper focuses on the relationship between vulnerability-reducing adaptation technology and the formation of an IEA. We borrow and build on the general modeling framework introduced in Benchekroun et al. (2017), and we confirm the potential coalition-broadening role of technological progress in adaptation. In addition, we find that differences among countries in their net climate change vulnerability have important implications for cooperation. Exogenous technological progress in adaptation in highly vulnerable countries can foster an IEA on mitigation. If an IEA exists, advances in adaptation technology create a positive externality among members. Furthermore, the transfer of adaptation technology among members of an existing agreement can reduce 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 adaptation technology transfers reduce free-riding on the mitigation efforts of 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 generally stressing global participation in emission reduction pledges, the latter insist on adaptation funding for the poorer and more vulnerable countries. The primary focus of the COP21 in Paris in 2015 was to reach a treaty on mitigation, in which the responsibility of reducing GHG emissions is shared between 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 or the Green Climate Fund) can bring the negotiating positions of the two groups closer together, fostering cooperation between vulnerable and less vulnerable countries.

Second, mitigation and adaptation should be considered jointly. Mitigation of GHG emissions is a global public good, and hence countries have an incentive to free ride rather than to participate in a costly emission-reducing agreement. However, this type of free-riding incentives can be reduced by the transfer 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 shares new technology only to members. Moreover, the paper shows that progress in adaptation technology in a member country generates a positive externality for other members. Thus, if an R&D hub on adaptation is formed and sponsored within an international mitigation agreement, the cooperation incentives are enhanced just as free riding on adaptation innovation is reduced. In practice, the UNFCCC established the Climate Technology Centre and Network (CTCN) after COP 16 in Cancun. The CTCN provides technical assistance at the request of member countries and promotes transfers of climate technologies. The emerging network has provided technology transfer on mitigation and adaptation to nearly 60 countries. Our results provides support for the importance of adaptation technology transfer between member countries as a crucial pillar of climate change cooperation.

If a major country withdrew from the IEA, the consequence can be derived from our model by comparing equilibrium emissions and adaptation in Section 3. When a high-emissions country leaves the IEA, global emissions increase and the implication is that all countries - both members of the coalition and non-members - need to adapt more and/or pollute less, in equilibrium. This result further implies that in the case of a major country withdrawing from the global agreement, other countries will tend to rely more on adaptation. Therefore, enhancing the effectiveness of adaptation activities increases in prominence as part of an individual country's climate change strategy. Moreover, as we suggest in the paper, adaptation technology as a club good effectively enlarges the coalition. Since cooperation and individual incentives around innovation in adaptation are mutually reinforcing, we believe that enhancing the effectiveness of adaptation activities is likely to become more prominent in the global efforts to tackle climate change.

To take a concrete example, the withdrawal from the Paris Climate Agreement of an important GHG emitter[27] is indeed likely to create such negative international mitigation and adaptation externalities for the rest of the world, as signatories to the Agreement. Additionally, it may also induce further negative repercussions by providing an example or a pretext for other marginal members to not fulfill their INDCs. On the flip side, faced with a higher level of total global emissions and an intensification of likely damages from climate change impacts, the cooperative coalition will potentially see higher cooperative incentives and especially more reasons to develop and adopt new adaptation technologies within the coalition.

In future work we plan to more closely model the membership decision when technology adoption and transfers are endogenous to the model.

[27] like the specter of US withdrawal under the Trump administration - which would take place in 2020 at the earliest, according to the letter of the accord.

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ONLINE Appendix:

Appendix A. Assumptions, Proofs and Tables

Appendix A.1. Discussion of assumptions

While some version of the model developed in this paper is common in the literature, a brief discussion of the most important assumptions and some alternatives may be useful for the reader. First, it should be noted that we assume a monocentric setting, i.e. that a single (global) agreement is under consideration, as opposed to several competing ones.[28] Second, any country is eligible to join, i.e. there 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. Finus (2008) reviews the sub-literature that takes a sequential approach and points out that this modelling choice is not clearly superior, as it involves a tradeoff between increased realism and loss of 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.[29]

Fourth, players also make the abatement and adaptation decisions simultaneously, also a widely used assumption in the literature.[30] 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.[31] De Bruin et al. (2011) examine the effects of proactive adaptation on the size and welfare of the stable coalitions with calibration of a three-stage model. Proactive adaptation can be applied strategically by one or more countries to affect the IEA outcome.

Lastly, in order to keep the model comparable to our benchmarks, we do not allow for side-payments. It is well known that transfers, dispute settlement and monitoring mechanisms can extend cooperation,[32] however we aim to focus here on the main incentives in the absence of such schemes. [33] Transfers have rarely been used in existing IEAs due to moral hazard issues between donors and recipients, according to Finus (2000).

Appendix A.2. Proof of Proposition 1

Proof. Suppose that a non-member country $i \in O$ experiences a technological progress in adaptation (i.e. adaptation measures become more effective and cost less: θ_i rises and/or c_i falls).

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

[28] A few studies discuss that multiple agreements can be an alternative to a single agreement on climate change, such as Carraro (1999) and Asheim et al. (2006).

[29] See Finus (2008), p. 49-51 for a discussion of existence of equilibrium and other issues in this context.

[30] See Carraro and Siniscalco (1993), Barrett (1994), Pavlova and de Zeeuw (2013)

[31] This is also pointed out in Benchekroun et al. (2017), p. 4. and shown more generally in Bayramoglu et al. (2016), p. 15.

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

[33] 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.

All other countries respond in the opposite way:

$$\frac{de_k^O}{d\Phi_i} = \frac{\Psi_k}{\beta_i\left(1+\Psi^O+\Psi^S\right)^2}\overline{E} < 0, k \neq i \in O,$$
$$\frac{de_j^S}{d\Phi_i} = \frac{\Psi_j^S}{\beta_i\left(1+\Psi^O+\Psi^S\right)^2}\overline{E} > 0, j \in S,$$
$$\frac{dE^N}{d\Phi_i} = -\frac{1}{\beta_i\left(1+\Psi^O+\Psi^S\right)^2}\overline{E} < 0.$$

The adaptation level is given by (16). The change in the equilibrium adaptation level of country i in the effectiveness and/or cost of adaptation are given by:

$$\begin{aligned}
\frac{da_i^O}{d\theta_i} &= \frac{\partial a_i}{\partial \theta_i} + \frac{\partial a_i}{\partial E^N}\frac{dE^N}{d\Phi_i}\frac{d\Phi_i}{d\theta_i} = \frac{E^N}{c_i}\left[1+\frac{\theta_i^2}{c_i}\frac{2}{\beta_i\left(1+\Psi^O+\Psi^S\right)^2}\right] > 0,\\
\frac{da_i^O}{dc_i} &= \frac{\partial a_i}{\partial c_i} + \frac{\partial a_i}{\partial E^N}\frac{dE^N}{d\Phi_i}\frac{d\Phi_i}{dc_i} = \frac{\theta_i^2}{c_i}E^N\left[\frac{\theta_i^2}{c_i}\frac{1}{\beta_i\left(1+\Psi^O+\Psi^S\right)^2}-1\right]\\
&< \frac{\theta_i^2}{c_i}E^N\left[\frac{\Psi_i}{\beta_i\left(1+\Psi^O+\Psi^S\right)^2}-1\right] < 0.
\end{aligned}$$

Since technological progress in adaptation is associated with positive change of θ_i and negative change of c_i, adaptation level of country i increases.

Adaptation levels of other countries $k \neq i \in N$ increase as well,

$$\begin{aligned}
\frac{da_k}{d\theta_i} &= \frac{\partial a_k}{\partial E^N}\frac{dE^N}{d\Phi_i}\frac{d\Phi_i}{d\theta_i} > 0,\\
\frac{da_k}{dc_i} &= \frac{\partial a_k}{\partial E^N}\frac{dE^N}{d\Phi_i}\frac{d\Phi_i}{dc_i} < 0.
\end{aligned}$$

Suppose a member country j experiences technological progress in adaptation. Country j and all other members can now afford higher emission levels:

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

Non-member countries respond in an opposite fashion compared to members, by decreasing their equilibrium emissions:

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

World emissions level changes in the same direction as for member country j:

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

The change of adaptation level of country j with the effectiveness and/or cost of adaptation are:

$$\begin{aligned}
\frac{da_j^S}{d\theta_j} &= \frac{\partial a_j^S}{\partial\theta_j} + \frac{\partial a_j^S}{\partial E^N}\frac{dE^N}{d\Phi_j}\frac{d\Phi_j}{d\theta_j} = \frac{E^N}{c_j}\left[1 + \frac{\theta_j^2}{c_j}\frac{2\sum_{j\in S}\frac{1}{\beta_j}}{(1+\Psi^O+\Psi^S)^2}\right] > 0, \\
\frac{da_j^S}{dc_j} &= \frac{\partial a_j^S}{\partial c_j} + \frac{\partial a_j^S}{\partial E^N}\frac{dE^N}{d\Phi_j}\frac{d\Phi_j}{dc_j} = \frac{\theta_j^2}{c_j}E^N\left[\frac{\theta_j^2}{c_j}\frac{\sum_{j\in S}\frac{1}{\beta_j}}{(1+\Psi^O+\Psi^S)^2} - 1\right] \\
&< \frac{\theta_j^2}{c_j}E^N\left[\frac{\Psi^S}{(1+\Psi^O+\Psi^S)^2} - 1\right] < 0.
\end{aligned}$$

Adaptation levels of other countries $k \neq j \in N$ increase as well,

$$\begin{aligned}
\frac{da_k}{d\theta_j} &= \frac{\partial a_k}{\partial E^N}\frac{dE^N}{d\Phi_j}\frac{d\Phi_j}{d\theta_j} > 0, \\
\frac{da_k}{dc_j} &= \frac{\partial a_k}{\partial E^N}\frac{dE^N}{d\Phi_j}\frac{d\Phi_j}{dc_j} < 0.
\end{aligned}$$

□

Appendix A.3. Proof of Proposition 2

Proof. The welfare of a country i is given by,

$$w\left(e_i, a_i, E\right) = e_i\left(\alpha_i - \beta_i\frac{e_i}{2}\right) - \frac{1}{2}\Phi_i\left(E^N\right)^2.$$

For a non-member country $i \in O$, the welfare increases if its own vulnerability decreases:

$$\begin{aligned}
\frac{dw(e_i^O)}{d\Phi_i} &= \beta_i\left(\bar{e}_i - e_i\right)\frac{de_i^O}{d\Phi_i} - \Phi_i\frac{dE^N}{d\Phi_i}E^N - \frac{1}{2}\left(E^N\right)^2 \\
&= \left[\frac{\Psi_i\left(\Psi_i - \Psi^O - \Psi^S\right)}{1+\Psi^O+\Psi^S} - \frac{1}{2}\right]\left(E^N\right)^2 < 0.
\end{aligned}$$

For other non-member countries $k \neq i \in O$, their welfare drops:

$$\begin{aligned}
\frac{dw(e_k^O)}{d\Phi_i} &= \beta_k\left(\bar{e_k} - e_k\right)\frac{de_k^O}{d\Phi_i} - \Phi_k\frac{dE^N}{d\Phi_i}E^N \\
&= \beta_k\Psi_k E^N\frac{\Psi_k}{\beta_i\left(1+\Psi^O+\Psi^S\right)}E^N + \frac{\Phi_k}{\beta_i\left(1+\Psi^O+\Psi^S\right)}\left(E^N\right)^2 \\
&= \frac{\Psi_k}{\beta_i}\frac{1+\Psi_k}{1+\Psi^O+\Psi^S}\left(E^N\right)^2 > 0.
\end{aligned}$$

The welfare of all member countries $j \in S$ decreases as well:

$$\begin{aligned}
\frac{dw(e_j^S)}{d\Phi_i} &= \beta_j\left(\bar{e_j} - e_j\right)\frac{de_j^S}{d\Phi_i} - \Phi_j\frac{dE^N}{d\Phi_i}E^N \\
&= \beta_j\Psi_j^S E^N\frac{\Psi_j^S}{\beta_i\left(1+\Psi^O+\Psi^S\right)}E^N + \frac{\Phi_j}{\beta_i\left(1+\Psi^O+\Psi^S\right)}\left(E^N\right)^2 \\
&= \frac{\Phi^S\Psi_j^S + \Phi_j}{\beta_i\left(1+\Psi^O+\Psi^S\right)}\left(E^N\right)^2 > 0.
\end{aligned}$$

If a member country $j \in S$ experiences technological progress in adaptation, its welfare change depends on its parameters relative to the coalition's.

$$\begin{aligned}\frac{dw(e_j^S)}{d\Phi_j} &= \beta_j\left(\bar{e_j}-e_j\right)\frac{de_j^S}{d\Phi_j}-\Phi_j\frac{dE^N}{d\Phi_j}E^N-\frac{1}{2}\left(E^N\right)^2\\ &= -\beta_j\Psi_j^S E^N\frac{1+\Psi^O}{\beta_j\left(1+\Psi^O+\Psi^S\right)}E^N+\frac{\Phi_j\sum\limits_{j\in S}\frac{1}{\beta_j}}{1+\Psi^O+\Psi^S}\left(E^N\right)^2-\frac{1}{2}\left(E^N\right)^2\\ &= \left[\frac{\Phi_j\sum\limits_{j\in S}\frac{1}{\beta_j}-\Psi_j^S\left(1+\Psi^O\right)}{1+\Psi^O+\Psi^S}-\frac{1}{2}\right]\left(E^N\right)^2.\end{aligned}$$

The same holds for the welfare changes of other members $k \neq j \in S$.

$$\begin{aligned}\frac{dw(e_k^S)}{d\Phi_j} &= \beta_k\left(\bar{e_k}-e_k\right)\frac{de_k^S}{d\Phi_k}-\Phi_j\frac{dE^N}{d\Phi_j}E^N\\ &= -\beta_k\Psi_k^S E^N\frac{1+\Psi^O}{\beta_k\left(1+\Psi^O+\Psi^S\right)}E^N+\frac{\Phi_k\sum\limits_{j\in S}\frac{1}{\beta_j}}{1+\Psi^O+\Psi^S}\left(E^N\right)^2\\ &= \frac{\Phi_k\sum\limits_{j\in S}\frac{1}{\beta_j}-\Psi_k^S\left(1+\Psi^O\right)}{1+\Psi^O+\Psi^S}\left(E^N\right)^2.\end{aligned}$$

Note that $\frac{dw(e_k^S)}{d\Phi_j} < 0$ if $\Phi_k\sum\limits_{j\in S}\frac{1}{\beta_j}-\Psi_k^S\left(1+\Psi^O\right)<0$, which is equivalent to $\Phi_k\beta_k < \frac{\Phi^S\left(1+\Psi^O\right)}{\sum_{j\in S}\frac{1}{\beta_j}}$.

Moreover, $\frac{dw(e_j^S)}{d\Phi_j} < \frac{dw(e_j^S)}{d\Phi_k}$, which implies a member country always gains more if the technological progress in adaptation is originated in the country.

Although the welfare change for individual member depends on each member's parameters, the welfare of the coalition always raises as a result of technological progress in adaptation adopted in any member country:

$$\sum_{k\in S}\frac{dw(e_k^S)}{d\Phi_j} = -\left(\frac{\Psi^O\Psi^S}{1+\Psi^O+\Psi^S}+\frac{1}{2}\right)\left(E^N\right)^2<0, j\in S.$$

Finally, a non-member's welfare decreases as a result of its reduced emissions level and the rising global emissions:

$$\begin{aligned}\frac{dw(e_i^O)}{d\Phi_j} &= \beta_i\left(\bar{e_i}-e_i\right)\frac{de_i^O}{d\Phi_j}-\Phi_j\frac{dE^N}{d\Phi_i}E^N\\ &= \frac{\left(1+\Psi_i\right)\Phi_i\sum\limits_{j\in S}\frac{1}{\beta_j}}{1+\Psi^O+\Psi^S}\left(E^N\right)^2>0.\end{aligned}$$

□

Appendix A.4. 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:

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

Suppose a member j's α_j changes, then member j's emission level rises in response:

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

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,

$$\begin{aligned}\frac{\partial e_k^S}{\partial \beta_j} &= \frac{1}{\beta_j}\frac{\Psi_k^S}{1+\Psi^O+\Psi^S}e_j^S, k \neq j \in S,\\ \frac{\partial e_i^O}{\partial \beta_j} &= \frac{1}{\beta_j}\frac{\Psi_i}{1+\Psi^O+\Psi^S}e_j^S, i \in O,\\ \frac{\partial E^N}{\partial \beta_j} &= -\frac{1}{\beta_j\left(1+\Psi^O+\Psi^S\right)}e_j^S.\end{aligned}$$

Additionally, from (16) adaptation level always goes to the same direction as the global emission level does. $\square$

Appendix A.5. Proof of Lemma 2

Proof. Suppose $S = \varnothing$ [34] and $O = N$. $\Psi^O = \sum_{i \in N} \frac{\Phi_i}{\beta i} = \Psi$, and $\Psi^S = 0$. From (C.6),

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

Suppose $S = N$ and $O = \varnothing$. $\Phi^O = 0$ and $\Phi^S = \sum_{j\in S}\frac{\Phi_j}{\beta_j} = \Psi^G$. From (C.12),

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

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

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

From (15), the world's total emissions is given by,

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

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

$$E^N(S\cup\{i\}) = \frac{\overline{E}}{1+\Psi^O+\Psi^S+\Psi_i^S+\Phi_i\sum_{k\in S}\frac{1}{\beta_k}}, \tag{A.2}$$

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 (16), $a_i^G \leq a_i^N \leq a_i$, $\forall i \in N$. $\square$

[34] 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 Lemma 3

Proof. From (19), $\Gamma_j^S(S) \geq 0$ is equivalent to the following,

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

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

For a member j in S, from (14) and (17), 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 $1 + \Psi^O(S \backslash \{j\}) + \Psi^S(S \backslash \{j\}) = 1 + \Psi^O + \Psi^S + 2\Psi_j - \Psi_j^S - \Phi_j \sum_{k \in S} \frac{1}{\beta_k}$.

$$\begin{aligned} e_j^S(S) > e_j^O(S \backslash \{j\}) &\Leftrightarrow \frac{\Psi_j}{\Psi_j^S} > \frac{1 + \Psi^O(S \backslash \{j\}) + \Psi^S(S \backslash \{j\})}{1 + \Psi^O + \Psi^S} \\ &\Leftrightarrow \frac{\Phi_j}{\Phi^S} > 1 - \frac{\Psi_j^S - 2\Psi_j + \Phi_j \sum_{k \in S} \frac{1}{\beta_k}}{1 + \Psi^O + \Psi^S}. \end{aligned}$$

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

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

Hence, $\Gamma_j^S(S) > 0$. □

Appendix A.7. Proof of Lemma 4

Proof. Suppose a coalition exists, $S \neq \varnothing$. From (C.4) and (13),

$$\begin{aligned} &e_i^O(S) - e_i = \left(\frac{1}{1 + \Psi} - \frac{1}{1 + \Psi^O + \Psi^S}\right) \Psi_i \overline{E}, i \in O, \\ &1 + \Psi^O + \Psi^S = 1 + \Psi + \sum_{j \in S} \left(\Psi_j^S - \Psi_j\right) > 1 + \Psi, \\ &\Rightarrow e_i^O(S) > e_i. \end{aligned}$$

From (C.4) and (14),

$$\begin{aligned} &e_j^S(S) - e_j = \left(\frac{\Psi_j}{1 + \Psi} - \frac{\Psi_j^S}{1 + \Psi^O + \Psi^S}\right) \overline{E}, j \in S, \\ &e_j^S(S) \geq e_j \Leftrightarrow \frac{\Phi_j}{\Phi^S} \geq \frac{1 + \Psi}{1 + \Psi^O + \Psi^S}. \end{aligned}$$

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

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

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.8. Emissions and cooperative incentives

From Appendix A.6 (the proof of Lemma 3), conditions defining the three types of countries in a coalition can be derived and is given in the following table.

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 and Proof of Proposition 3

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.

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

Since $(1+\Psi_j)(2-\sum_{k\in S}\frac{\beta_j}{\beta_k}) < (1+\Psi_j) < 1+\Psi^O+\Psi^S$, the first term in the square brackets is positive. Also note that $1+\Psi^O+\Psi^S > 1+\Psi^O(S\backslash\{j\})+\Psi^S(S\backslash\{j\})$. The second and third term together is positive. Therefore, $\frac{\partial\Gamma_j^S(\Phi_j,\beta_j;S)}{\partial\Phi_j} > 0$, i.e. the higher the net vulnerability a member has, the higher cooperative incentives. If two signatories have the same β, whoever is more vulnerable has more incentives to cooperate.

From (19), if there exists at least one member j with relatively low vulnerability, such that

$$\frac{\Phi_j^2+\beta_j\Phi_j}{(\Phi^S)^2+\beta_j\Phi_j} < \frac{\left[1+\Psi^O(S\backslash\{j\})+\Psi^S(S\backslash\{j\})\right]^2}{(1+\Psi^O+\Psi^S)^2},$$

$\Gamma_j^S(S) < 0$, which implies its cooperation incentive is negative and the coalition is not stable.

□

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.

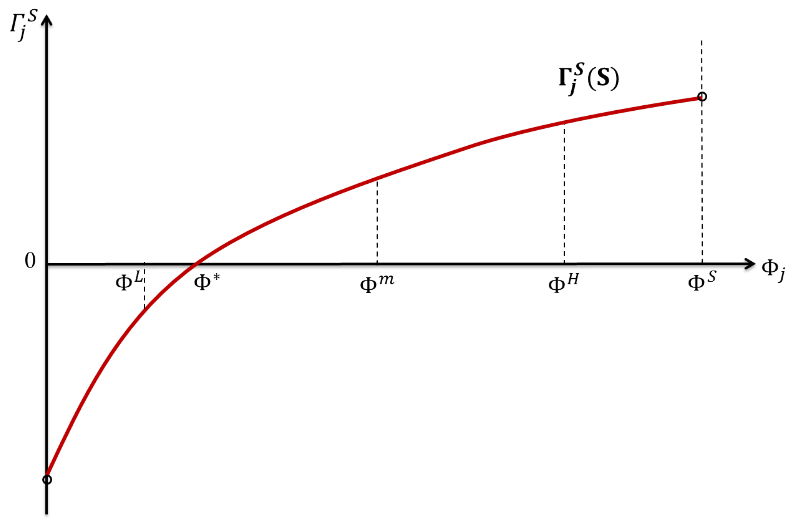

Figure A.2: Cooperative incentives for member countries

Appendix A.10. Proof of Proposition 4

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

$$\begin{aligned} e_i^O(S) &= \overline{e_i} - \frac{\Psi_i}{1+\Psi^O+\Psi^S}\overline{E} \\ e_i^S(S\cup\{i\}) &= \overline{e_j} - \frac{\Psi_i^S + r_i\Psi_i}{1+\Psi^O+\Psi^S+\Psi_i^S+r_i\Phi_i\sum\limits_{j\in S}\frac{1}{\beta_j}+r_i\Psi_i-\Psi_i}\overline{E} \end{aligned}$$

The free riding incentive is given as the following,

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

Take derivative of Γ_i^O with respect to r_i,

$$\begin{aligned} \frac{\partial\Gamma_i^O}{\partial r_i} =& \frac{\beta_i\overline{E}^2}{2}\Bigg\{\frac{2\Psi_i(\Psi_i^S+r_i\Psi_i)+\Psi_i}{(1+\Psi^O+\Psi^S+\Psi_i^S+r_i\Phi_i\sum\limits_{j\in S}\frac{1}{\beta_j}+r_i\Psi_i-\Psi_i)^2} \\ &-\frac{2[(\Psi_i^S+r_i\Psi_i)^2+r_i\Psi_i](\Phi_i\sum\limits_{j\in S}\frac{1}{\beta_j}+\Psi_i)}{(1+\Psi^O+\Psi^S+\Psi_i^S+r_i\Phi_i\sum\limits_{j\in S}\frac{1}{\beta_j}+r_i\Psi_i-\Psi_i)^3}\Bigg\}. \end{aligned}$$

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

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

As $\beta_i \to +\infty$, the limits of left and right hand side are given as following,

$$\begin{aligned}\lim_{\beta_i \to +\infty} LHS &= \frac{1}{2r_i}, \\ \lim_{\beta_i \to +\infty} RHS &= 0.\end{aligned}$$

If in general $\beta_i >> \Phi_i$ for all $i \in N$, 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 $\beta_i >> \Phi_i$, $\forall i \in N$.

□

From (C.4), (C.5), and (C.6), the welfare for a country i is given by:

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

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 A.11. Proof of Proposition 5

Proof. For country i, from (C.4) and (C.6),

$$\begin{aligned} \frac{\partial e_i}{\partial \Phi_i} &= -\frac{1+\Psi-\Psi_i}{\beta_i\left(1+\Psi\right)^2}\overline{E} < 0, \\ \frac{\partial e_j}{\partial \Phi_i} &= \frac{\Psi_j}{\beta_i\left(1+\Psi\right)^2}\overline{E} > 0, j \neq i \in N, \\ \frac{\partial E}{\partial \Phi_i} &= -\frac{1}{\beta_i\left(1+\Psi\right)^2}\overline{E} < 0. \end{aligned} \tag{A.4}$$

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 (C.6) into (C.5), the adaptation level of country i is given by,

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

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:

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

□

Appendix A.12. Proof of Proposition 6

Proof. From (C.10) and (C.12),

$$\frac{\partial e_i^G}{\partial \Phi_i} = -\frac{1}{\beta_i\left(1+\Psi^G\right)^2}\overline{E} < 0 \tag{A.5}$$
$$\frac{\partial e_j^G}{\partial \Phi_i} = -\frac{1}{\beta_j\left(1+\Psi^G\right)^2}\overline{E} < 0 \tag{A.6}$$
$$\frac{\partial E^G}{\partial \Phi_i} = -\left(\sum_{k\in N}\frac{1}{\beta_k}\right)\frac{1}{\left(1+\Psi^G\right)^2}\overline{E} < 0 \tag{A.7}$$

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,

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

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:

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

□

Appendix A.13. Proof of Lemma 5

Proof. For emission and adaptation levels,

$$\begin{aligned} \frac{E^G}{E} &= \frac{1+\Psi}{1+\Psi^G} < 1, \\ a_i^G &= \frac{\theta_i E^G}{c_i} < a_i = \frac{\theta_i E}{c_i}. \end{aligned}$$

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:

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

□

Appendix B. Simulation Statistics

A country's net vulnerability is calculated as a ratio of its climate change cost and the square of the world's total GHG emissions (see expression (26)). The estimated climate change costs in 2010 are reported in DARA (2012) for 172 countries, and the world's total GHG emissions in 2010 is obtained from the World Bank Open Data. Summary statistics for GDP, total GHG emissions, and climate change cost are provided in Table B.3:

Table B.3: Summary Statistics

Variable	Obs	Mean	Std. Dev.	Min	Max
GDP (million US $)	7883	125734.33	676972.81	9.12	14958300
totalGHG (kt of CO2 equivalent)	8723	104581.70	489075.60	-80.67	10728810.00
Climate_change_cost (million US $)	172	3333.564	10345.37	5.00	90000.00

The parameters of the benefit of emissions function (α_i and β_i) are estimated from GDP and GHG emissions in country i. We constructed a cross-country dataset from 1960 to 2010 using GDP and GHG emission data from the World Bank. Equation (25) is estimated by ordinary least squares (OLS) for each country. The coefficients of emissions and the quadratic term are transformed to α_i and β_i (i.e. β_i is calculated by two times the inverse of the coefficient of the quadratic term). In the model, we assume positive α_i and β_i: the benefit (GDP) is increasing in emissions but the marginal benefit is diminishing. Therefore, regression results with negative α_i or β_i were dropped (85 out of 174 countries). Sample regression results from three countries, Argentina, Germany, and Thailand are given in Table B.4.

Table B.4: Regressions of GDP on GHG Emissions

	(1) Argentina	(2) Germany	(3) Thailand
$totalGHG$	1287848.9***	9368656.0***	830387.5***
	(173789.3)	(1860152.2)	(73681.4)
$totalGHG^2$	-1.033	-7.501**	-0.439
	(0.758)	(2.140)	(0.244)
N	49	21	51
R^2	0.824	0.959	0.945

The table reports regression results for three countries, Argentina, Germany, and Thailand. The dependent variable is GDP in a country. Regression results include standard errors in parentheses; * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

The estimated α_i, β_i, and net vulnerability ϕ_i, are obtained for 89 countries, and these countries are clustered into 10 groups by k-means clustering. A representative country with parameters equal to the group mean is created for each of the 10 groups. Note that the net vulnerability needs to be rescaled to the hypothetical world with 10 representative countries, otherwise climate change damage would be substantially underestimated. First, the GHG emissions of the 10 representative countries is aggregated to the hypothetical world emissions. The net vulnerability is recalculated as a ratio of its climate change cost and the square of the hypothetical world emissions. Next, parameters (α_i, β_i, and the rescaled net vulnerability ϕ_i) of the 10 representative countries are utilized to generate emission levels and welfare of each country under every possible coalition scenario. Note that the computation complexity here is of the scale of $N \times 2^N$, and consequently countries are clustered to 10 representative countries in order to limit computation costs. Finally, free-riding and cooperative incentives are generated to find equilibria of the two-stage game.

Appendix C. Two Polar Cases

Note: This material has been developed in many of the existing papers in the literature and is only provided here for context and as a benchmark.

Appendix C.1. The Non-cooperative Outcome

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

$$\max_{e_i,a_i} w\left(e_i, a_i, E\right) = B(e_i) - D\left(E, a_i\right) - C\left(a_i\right). \tag{C.1}$$

Table B.5: Estimated Parameters for 10 Representative Countries

	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 B.6: World's Emissions and Welfare

	World's emissions (kt of CO2 equivalent)	Welfare (Billion US$)
Non-cooperative equilibrium	2.7938×10^6	1.2563×10^9
Full-cooperative equilibrium	2.5867×10^6	1.2653×10^9
With stable coalition {2,4,5,6}	2.7273×10^6	1.2591×10^9

*: compared to the non-cooperative equilibrium

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

$$e_i = \frac{\alpha_i - \Phi_i E_{-i}}{\beta_i + \Phi_i} \tag{C.2}$$

$$a_i = \frac{\theta_i}{c_i}\left(\frac{\alpha_i + \beta_i E_{-i}}{\beta_i + \Phi_i}\right), \tag{C.3}$$

where $\Phi_i \equiv v_i - \frac{\theta_i^2}{c_i}$ is the net vulnerability in the presence of adaptation. Substituting a_i from (C.3) into (2), we obtain the net marginal damage from emissions: $\frac{dD(E)}{dE} = \Phi_i E$, where Φ_i is always positive from (4). Note that as a result of technological progress in adaptation in country i, θ_i rises and/or c_i drops and country i's net vulnerability decreases.

We add up (C.2) for all countries to derive global emissions and country i's emission and adaptation level, which are given by,

$$e_i = \overline{e_i} - \frac{\Psi_i}{1+\Psi}\overline{E} \tag{C.4}$$

$$a_i = \frac{\theta_i}{c_i}E, \tag{C.5}$$

where $\Psi_i \equiv \frac{\Phi_i}{\beta_i}$ and $\Psi \equiv \sum\limits_{k \in N} \Psi_k$. 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 (C.4), 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. A highly vulnerable country chooses a high abatement level to reduce the damage from climate change. Moreover, 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 (C.4), one can see that abatement is undertaken even though no IEA is formed since natural vulnerability to climate change cannot be neutralized by adaptation ($\Phi_i > 0$).[35]

The global emission level is given by,

$$E = \frac{\sum\limits_{k=1}^{n} \frac{\alpha_k}{\beta_k}}{1 + \sum\limits_{k=1}^{n} \frac{\Phi_k}{\beta_k}} = \frac{1}{1+\Psi}\overline{E}, \tag{C.6}$$

where $\overline{E} \equiv \sum\limits_{k \in N} \overline{e_k} = \sum\limits_{k \in N} \frac{\alpha_k}{\beta_k}$ 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'.[36] From (C.4), (C.5) and (C.6), any change in the abatement indicator Ψ_i in a country, i.e. β_i and Φ_i, can affect emission and adaptation levels in all countries. Our assumption of heterogeneous countries allows us to investigate the impact of a change in Φ_i as a result of technological progress in adaptation in a country on its own emission levels as well as others'.

[35] In the extreme case that the damage can be fully countered by adaptation (i.e. $\Phi_i = 0$), the country does not abate (its abatement factor $\Psi_i \equiv \frac{\Phi_i}{\beta_i} = 0$), and its emissions achieve the maximum level $\overline{e_i}$.

[36] 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.

Proposition 5. *When countries behave non-cooperatively, if country i's net vulnerability Φ_i decreases,*[37] *it will choose to emit more and adapt more. All other countries respond optimally by emitting less and adapting more, and global emissions rise.*

Proof. See Appendix A.11 □

After country i experiences technological progress in adaptation, its net vulnerability to climate change is reduced, and its marginal damage of emissions falls. Thus, country i affords a higher emission level. However, the negative externality of the increased emissions in country i is imposed to other countries, and marginal damage of emissions of the rest of the world rises. Hence all other countries need to reduce their emissions. Regarding adaptation, the marginal benefit of adaptation increases for each country as the world's emissions rise. For country i, the increase in the marginal benefit of adaptation may also rise from changes in θ_i, and the marginal cost may fall as a result of a fall in exogenous cost parameter c_i. As a result, all countries increase adaptation investments. In summary, only the country which experiences technological progress in adaptation benefits from it, while other countries abate more emissions and suffer more damage from climate change.

Appendix C.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,

$$\max_{e_i,a_i} \sum_{i\in N} w\left(e_i, a_i, E\right) = \sum_{i\in N} \left[B(e_i) - D\left(E, a_i\right) - C\left(a_i\right)\right] \tag{C.7}$$

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

$$e_i = \frac{\alpha_i - \sum\limits_{k\in N} \Phi_k E_{-i}}{\beta_i + \sum\limits_{k\in N} \Phi_k} \tag{C.8}$$

$$a_i = \frac{\theta_i}{c_i}\left(\frac{\alpha_i + \beta_i E_{-i}}{\beta_i + \sum\limits_{k\in N} \Phi_k}\right) \tag{C.9}$$

The global emissions and the individual emission levels can be derived from (C.8) and (C.9). Country i's emission and adaptation level are given by:

$$e_i^G = \overline{e_i} - \frac{\Psi_i^G}{1+\Psi^G}\overline{E} \tag{C.10}$$

$$a_i^G = \frac{\theta_i}{c_i} E^G \tag{C.11}$$

where $\Psi_i^G \equiv \frac{\Phi}{\beta_i}$.[38] Similar to (C.4), the second term in (C.10) is the abatement level. However, a country's abatement indicator Ψ_i^G in (C.10) is much larger than in the non-cooperation case Ψ_i since it 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,

$$E^G = \frac{1}{1+\Psi^G}\overline{E}, \tag{C.12}$$

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

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

where $\Psi^G \equiv \sum_{k \in N} \Psi_k^G$ is the global abatement indicator under the grand coalition. With international cooperation on mitigation of emissions, the impact of technological progress in adaptation is very different from the non-cooperation case.

Proposition 6. *When all countries behave cooperatively, if country i's net vulnerability Φ_i decreases, it pollutes more and adapts more. All other countries respond by emitting more and adapting more and global emissions rise.*

Proof. See Appendix A.12 □

It is worth noting that when a country's net vulnerability changes, the emissions response by other countries under full-cooperation is the opposite to the non-cooperation case. Under non-cooperation, more effective adaptation technologies in country i lower its net vulnerability, and hence affording it a higher emission level. All other countries reduce emissions to offset part of the damage caused by the emissions increase by country i. However, with full cooperation, if technological progress in adaptation in one country lowers its vulnerability to climate change, not only does that country's equilibrium emission level rise, but so do other countries' emissions. The underlying reason is that the damage from climate change is internalized and shared by all countries under the grand coalition. Hence the benefit of a lowered net vulnerability in one country is shared by all: all countries afford higher emissions. An interesting implication of Proposition 6 is that technological progress in adaptation induces positive externality in the grand coalition, compared to being a pure private good in the non-cooperation case.

Lemma 5. *Under full cooperation, the world emission level is lower than in the non-cooperative case, i.e. $E^G < E$. Adaptation levels are lower for all countries, while individual emissions of country i are lower (higher) iff $\frac{\Phi_i}{\Phi} \leq (\geq) \frac{1+\Psi}{1+\Psi^G}$.*

Proof. See Appendix A.13 □

In the non-cooperation case, a highly vulnerable country keeps a low emission level due to high marginal damage from emissions. In full-cooperation 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: $\frac{1+\Psi}{1+\Psi^G} = \frac{1+\sum_{k \in N} \frac{\Phi_k}{\beta_k}}{1+\sum_{k \in N} \Phi_k \sum_{k \in N} \frac{1}{\beta_k}} \approx \frac{1}{n}$. Hence $e_i^G > e_i$ if the following is satisfied:

$$\Phi_i > \frac{\sum_{k \in N} \Phi_k}{n}.$$

Therefore, with full cooperation, a country's emissions are likely to rise compared to its ex-ante level if its net vulnerability is greater than the global 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. An IEA on mitigation is beneficial to countries with high net vulnerability to climate change (e.g. highly vulnerable to climate change and less capable of adaptation).

Appendix D. Timing of Adaptation

Adaptation activities typically include investments in infrastructure which may have 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 potential damage of induced by climate change. If adaptation decisions are undertaken prior to mitigation (De Bruin et al., 2011; Benchekroun et al., 2017) countries can use adaptation strategically to reduce their own mitigation effort at the expense of others', pointing to a substitution relationship between adaptation and mitigation. To address the timing of adaptation decision, here we model the decision to adapt to climate change preceding the formation of an IEA. In stage zero (or prior to the first stage of the game) countries choose the level of adaptation independently. The first stage is the 'open membership game' where countries decide simultaneously whether to participate in an IEA. The second stage is the 'emission game' in which IEA signatories and non-signatories choose their emission levels simultaneously. In keeping with the sequencing described above, we first solve the stage zero, and then use backward induction to solve the second and the first stage.

Here we modify the standard model by adding a *stage zero* in order to highlight investments in *adaptation* as a private good that addresses the consequences of climate change. While a fully specified three-stage strategic interaction in which the sequence of stages is to first choose adaptation levels, then make the membership decision, then choose emission levels/mitigation would be a more complete treatment of that problem, such a treatment exceeds the available space here. The purpose of including this alternative timing for adaptation is to show that our framework can be easily extended to that chronology, and that the analysis would not be significantly different. For that reason, we present the simpler case of the first stage adaptation investments being taken under the assumption of non-cooperation on mitigation. However, we do believe that a model in which countries behave strategically in all three stages of the game is potentially very interesting, and we plan to address that alternative scenario in future research.

The first stage is the 'open membership game' in which countries decide whether to participate in an IEA. The second stage is the 'emissions game' in which the IEA and non-signatories choose their emissions 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 existing studies on IEA and adaptation rely on the assumption of simultaneous adaptation and emissions choices. (Benchekroun et al., 2017; Lazkano et al., 2016).

Appendix D.1. Stage Zero

The first stage is equivalent to the non-cooperative outcome presented in Appendix (C.4), (C.5) and (C.6):

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

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 Second 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.

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

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

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

Emission levels of all countries are affected by the adaptation levels chosen in the first stage. In particular, from (16), 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,

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

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 chosen after an IEA. 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.

$$
\begin{aligned}
\frac{\partial e_i^O(S,a)}{\partial a_i} &= \frac{\theta_i}{\beta_i}\left(1-\frac{\frac{v_i}{\beta_i}}{1+\sum_{i\in O}\frac{v_i}{\beta_i}+\sum_{j\in S}\frac{1}{\beta_j}\sum_{j\in S} v_j}\right) > 0, i \in O, \\
\frac{\partial e_i^O(S,a)}{\partial a_k} &= -\frac{v_i}{\beta_i}\frac{\theta_k}{\beta_k}\frac{1}{1+\sum_{i\in O}\frac{v_i}{\beta_i}+\sum_{j\in S}\frac{1}{\beta_j}\sum_{j\in S} v_j} < 0, k \neq i \in O, \\
\frac{\partial e_i^O(S,a)}{\partial a_j} &= -\frac{v_i}{\beta_i}\left(\theta_j \sum_{j\in S}\frac{1}{\beta_j}\right)\frac{1}{1+\sum_{i\in O}\frac{v_i}{\beta_i}+\sum_{j\in S}\frac{1}{\beta_j}\sum_{j\in S} v_j} < 0, j \in S.
\end{aligned}
$$

A member's 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 that members take account of the aggregate vulnerability of the IEA.

$$
\begin{aligned}
\frac{\partial e_j^S(S,a)}{\partial a_j} &= \frac{\theta_j}{\beta_j}\left(1-\frac{\sum_{j\in S}\frac{v_j}{\beta_j}}{1+\sum_{i\in O}\frac{v_i}{\beta_i}+\sum_{j\in S}\frac{1}{\beta_j}\sum_{j\in S} v_j}\right) > 0, j \in S, \\
\frac{\partial e_j^S(S,a)}{\partial a_k} &= \frac{\theta_k}{\beta_j}\left(1-\frac{\sum_{j\in S}\frac{v_j}{\beta_j}}{1+\sum_{i\in O}\frac{v_i}{\beta_i}+\sum_{j\in S}\frac{1}{\beta_j}\sum_{j\in S} v_j}\right) > 0, k \neq j \in S, \\
\frac{\partial e_j^S(S,a)}{\partial a_i} &= -\frac{\theta_i}{\beta_i}\frac{\sum\limits_{j\in S} v_j}{\beta_j}\frac{1}{1+\sum\limits_{i\in O}\frac{v_i}{\beta_i}+\sum\limits_{j\in S}\frac{1}{\beta_j}\sum\limits_{j\in S} v_j} < 0, i \in O.
\end{aligned}
$$

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 as its adaptation level is higher, and thus its net vulnerability is lower. The reason is that emissions are chosen based on relative, not absolute vulnerability ((13) and (14)). If all countries increase adaptation levels, each country will be less vulnerable to climate change in absolute terms. However, a country who may become more vulnerable relative to other countries, will in equilibrium choose to cut more emissions. If Stage 1 adaptation decision is exogenous, the more a country invests in adaptation, the more emissions it can 'afford.'

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

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

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. Similar with Proposition 2, adaptation technology has a positive externality 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.

As explained in Section 6, analytical solutions for the size of stable coalitions are not available even with homogeneous countries. Therefore, to analyze the impact of adaptation level in the first stage on stable coalitions (outcomes in the second stage), a simulation of all three stages is required. The impact is expected to be ambiguous depending on parameters, according to De Bruin et al. (2011).

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 exist 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*

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

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 4, 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 6. *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,

$$\begin{aligned}
\Delta w_j =& \left[\alpha_j\left(e_j^S - e_j\right) - \frac{\beta_j}{2}\left(e_j^{S2} - e_j^2\right)\right] - \frac{1}{2}\left(v_j - \frac{\theta_j^2}{c_j}\right)\left(E^{N2} - E^2\right) \\
=& \frac{\beta_j}{2}\left[\left(\frac{\Psi_j}{1+\Psi}\right)^2 - \left(\frac{\Psi_j^S}{1+\Psi^O+\Psi^S}\right)^2\right]\overline{E}^2 - \frac{\Phi_j}{2}\left[\left(\frac{1}{1+\Psi^O+\Psi^S}\right)^2 - \left(\frac{1}{1+\Psi}\right)^2\right]\overline{E}^2 \\
=& \frac{\overline{E}^2}{2}\left[\frac{\Phi_j\Psi_j + \Phi_j}{(1+\Psi)^2} - \frac{\Phi^S\Psi_j^S + \Phi_j}{(1+\Psi^O+\Psi^S)^2}\right].
\end{aligned}$$

Thus the coalition is profitable for j iff,

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

□

Lemma 7. *(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. From the proof of Lemma 3, $e_j^S(S) \geq e_j^O(S\backslash\{j\})$ 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 6, $\Gamma_j^S(S) > 0$. □

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 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 the proof of Lemma 3 and Lemma 6. Table E.7 shows the relationship between emission change and profitability, given each country's parameters..

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.7: Emissions and welfare changes from non-cooperative to coalition equilibrium

Type I are highly vulnerable countries and is described in Lemma 7 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 8. *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.

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

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 6, the coalition is profitable for country j and hence is not stable. □

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 $\lim\limits_{\Phi_j \to 0} = 0$ and $\lim\limits_{\Phi_j \to \Phi_S} = 1$. 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 6, 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.

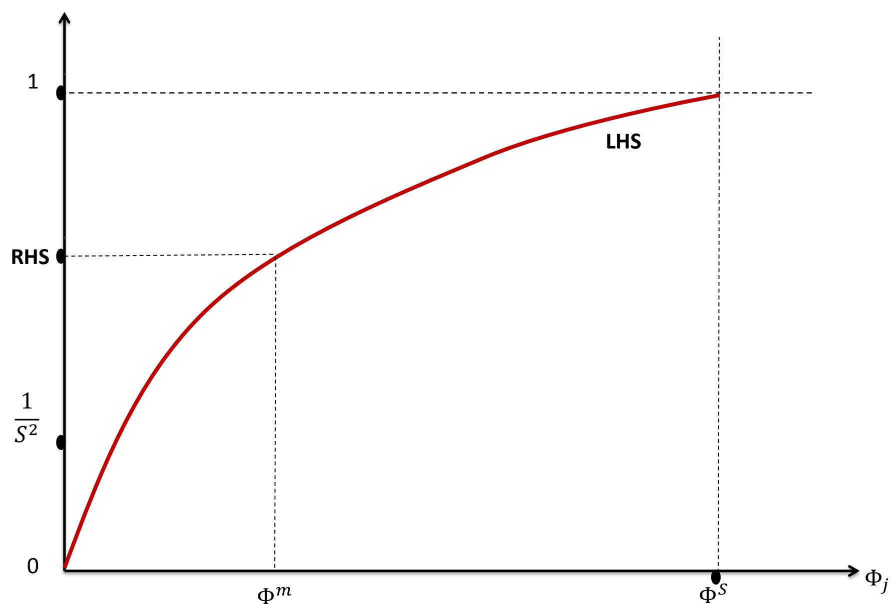

Figure E.3: Vulnerability and profitability of a member country

Appendix E.1. Internal Stability and Profitability

Lemma 9. *(Sufficient condition for profitability) If a coalition S is internal stable, it is also profitable for all members.*

Proof. From Proposition 6, 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 (22), 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:

$$\begin{aligned}1+\Psi^O(S\backslash\{j\})+\Psi^S(S\backslash\{j\}) &= 1+\Psi^O+\Psi^S+2\Psi_j-\Psi_j^S-\Phi_j\sum_{k\in S}\frac{1}{\beta_k}\\ &= 1+\sum_{i\in O}\frac{\Phi_i}{\beta_i}+\sum_{k\neq j\in S}\frac{\Phi^S-\Phi_j}{\beta_k}+\frac{\Phi_j}{\beta_j}\\ &\geq 1+\sum_{i\in O}\frac{\Phi_i}{\beta_i}+\sum_{k\neq j\in S}\frac{\Phi_k}{\beta_k}+\frac{\Phi_j}{\beta_j}=1+\Psi.\end{aligned}$$

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

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

□

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

Proof.

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

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. □