# Adaptation to Climate Change and International Mitigation Agreements with Heterogeneous Countries☆

Hongxiu Li[1,*], Horatiu A. Rus[2]

**Abstract**

This paper investigates the impact of adaptation on a country's incentive to participate in emission-reducing International Environmental Agreements (IEAs) on climate change. We develop a framework where heterogeneity across countries is introduced with respect to the benefits and costs of both mitigation of emissions and adaptation to reduce the impact of climate change. The paper uses two coalition stability concepts and numerical simulations to look at stable coalitions. We also study the effect of an within-coalition increase in the efficiency of adaptation on emissions and on countries' incentives to cooperate. Our main findings are: first, investment in adaptation technology has a public good feature inside the coalition, compared to being strictly a private good in the non-cooperation case. Second, a large coalition cannot be achieved if countries differ much in terms of vulnerability. Third, cooperation incentives can be enhanced by a coalition which diffuses technological progress on climate change adaptation among its members.

*JEL*: H41, Q54, Q59

*Keywords:* Climate Change, Mitigation, Adaptation, International Environmental Agreements, Heterogeneous Agents, Coalition Stability

*This version: October 16, 2014*

☆This is an *incomplete* draft of the paper. Comments are welcome. Please do not cite without permission.

*Corresponding author

[1]Department of Economics, University of Waterloo, 200 University Ave. W., Waterloo, ON, Canada N2L 3G1. Tel: +1(519) 781 7584 Email: h254li@uwaterloo.ca

[2]Department of Economics, University of Waterloo, 200 University Ave. W., Waterloo, ON, Canada N2L 3G1. Tel: +1(519) 888 4567 ext.38338 Email: hrus@uwaterloo.ca

## 1. Introduction

According to rapidly accumulating evidence, increasing concentrations of greenhouse gases (GHGs) is a major driver of climate change, with major expected consequences (Stern, 2007, 2008; Kousky, 2012). Over the past several decades, jurisdictions across the world have been experimenting with ways to tackle climate change. Mitigation policies such as command and control mechanisms, carbon taxes and cap-and-trade systems aimed at reducing carbon emissions, and adaptation measures involving adjustments in ecological, social and economic systems meant to reduce climate change damage are two major approaches to address climate change. The recently released *Working Group II* contribution to the Fifth Assessment Report IPCC titled 'Climate Change 2014: Impacts, Adaptation and Vulnerability' paints a dire picture in terms of the timing and magnitude of the projected impacts around the world. One consequence of the sharper focus on climate change impacts is that mitigation and adaptation are no longer considered alternative strategies. Increasingly, due to climate hysteresis and other factors, they are seen as being required simultaneously.

This paper focuses on the interaction of adaptation, emissions and the incentive to participate in an International Environmental Agreement (IEA) on emissions mitigation, in the presence of cross-country heterogeneity. The importance of accounting for the differences in assessing both benefits and damages from GHG emissions cannot be overemphasized: different levels of development, technology and resource endowment translate into markedly different economic benefits per unit of carbon emitted, while differences in geography, local conditions and subjective evaluation practices also yield different to substantially different economic damages around the world. Differences among countries are introduced here through four parameters of the model, referring to the benefits and costs of both mitigation and adaptation. To our knowledge, this study is the first to investigate systematically the effect of heterogeneous benefits and costs of both mitigation and adaptation on a country's incentives with respect to optimal climate change policy and international cooperation.

GHGs are global pollutants, which implies that a country's emissions impose a negative externality on other countries by exacerbating climate change. When countries choose emission levels non-cooperatively, the global GHG emissions exceed the globally efficient level, defined as the full cooperative outcome where every country chooses own emissions to maximize the joint welfare. Thus international coordination is required in order to mitigate global GHG emissions effectively. International environmental initiatives, targeting at mitigation of GHGs through international cooperation, have been initiated for the past two decades. In 1997, the Kyoto Protocol was adopted by members of the UNFCCC,[1] and it sets binding obligations on industrialized countries to reduce emissions of GHG. These so-called Annex I countries, including the EU and 37 other industrialized countries, agreed to reduce their GHG emissions by 5.2% on average during the first commitment period 2008-2012. The protocol was amended in 2012 with a second commitment period from 2012-2020. While the Kyoto Protocol has compelled some signatory countries to make some progress in reducing the global GHG emissions, there have been questions over its effectiveness, especially with respect to the large and increasing relative economic importance of non-participating countries. Several major emitters of GHG in the world including the U.S. (which signed the Protocol but failed to ratify it), India and China do not participate in the protocol. Canada withdrew from the Kyoto Protocol in 2011, and New Zealand, Russia and Japan refused to sign the extension of the Kyoto Protocol in 2012.

Without participation from major emitters, any mitigation agreement is undermined by the free-rider problem from nonparticipating countries, exacerbated potentially via the 'carbon leakage' effect.[2] Moreover, 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, some have argued that the emission reduction target set by the Kyoto Protocol may be inadequate

[1] The United Nations Framework Convention on Climate Change (UNFCCC) is an international environmental forum aimed at reducing the impact of human activities on global climate. It was initiated in 1992 and currently has 194 signatories.

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

for slowing down climate change (UNEP, 2012). The ongoing concerns about the feasibility and effectiveness of global IEAs indicate that mitigation of GHG emissions cannot be the only policy response to climate change. Indeed in recent years, besides mitigation of GHGs, countries have increasingly considered undertaking adaptive measures to reduce the impact climate change.[3] Adaptation is mostly seen as a private good, which means both its costs and benefits are private to the respective country.

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. 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 and low-probability events, mitigation and adaptation may also be regarded as substitutes. This research explores the relationship between mitigation and adaptation and specifically it focuses on effects of adaptation on formation and stability of an IEA aimed at mitigation of GHGs.

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

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

studied in the extant literature on climate change and IEAs.

To preview the main results, in the non-cooperative case, a country with higher efficiency in adaptation or benefit of emissions tends to pollute more and adapt more, augmenting the negative externality of GHG emissions for other countries. As a result, all other countries pollute less and invest more in adaptation in order to reduce the damage from climate change. This result also implies that very exposed countries, unless highly effective in adaptation or benefits generated from emissions measures, have to maintain a low level of GHG emissions. Thus, highly vulnerable countries are most likely to benefit from joining an IEA since they can pollute more than their non-cooperative levels and invest less in adaptation. As for the impact of adaptation on the incentive to participate in an IEA, if a country's adaptation becomes more effective, its incentive to join the coalition may fall or rise, depending on the coalition size and the characteristics of the members. If the number of signatories is small, a highly vulnerable country may have more incentives to stay in the IEA as its adaptation measures become more effective. Nevertheless, a member may have more incentives to leave the IEA as its effectiveness in adaptation rises, if the IEA is large. The results differ from the paper on a similar topic by Benchekroun et al. (2014) in that adaptation and an IEA on mitigation may be complements or substitutes, depending on the coalition size and the characteristics of the members.

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

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

A few studies highlight the importance of heterogeneity across countries, albeit in a limited way. Barrett (1997) explores the stability of an IEA when there are two types of countries, and finds that no more than three countries can sustain an IEA. Thus the conclusion is similar to Barrett (1994): IEAs can achieve little in the effort to combat climate change. McGinty (2007) generalizes the benchmark model of IEAs by incorporating heterogeneity in mitigation across countries and allowing for transfer payments. He finds that heterogeneity reduces the incentive of a member to leave an IEA by introducing gains from an emission permit trading system. With heterogeneous countries and transfers available, the size of a stable IEA varies and the net gain between noncooperation and coalition can be large.

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

The main contribution of our paper is to be one of the first to allow for the full set of mitigation and adaptation parameters to be country-specific, as it studies the incentives of countries to join international GHG emission mitigation coalitions. Additionally, we show how shared technological advances in adaptation among the members of an IEA has the potential to increase cooperation. Another element that differentiates our paper from existing contributions is that we consider the choice of adaptation both prior to and simultaneous with (or, equivalently, subsequent to[4]) the choice of emission reductions. Finally, unlike the received literature, numerical simulations used to solve for the stable coalitions employ empirically accurate parameters, based on a dataset specifically assembled for this purpose.

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

## 2. The Model

We model a non-cooperative IEA membership game, which is considered in the literature to be both more realistic and more general than cooperative games. According to a comprehensive literature survey by Finus (2008), 'the potential for explaining real world phenomena

[4] See discussion in section 3 and Appendix.

of IEAs is much higher for the noncooperative than for the cooperative approach.'[5] The game structure is based on McGinty (2007) and Benchekroun et al. (2014), and it includes a standard coalition formation game theory setting with added heterogeneous costs and benefits of adaptation across countries. In this paper, the full set of parameters characterizing both mitigation costs (i.e. benefits of emissions) and net damage costs (including natural vulnerability and adaptation effectiveness) are assumed to be country-specific.

Let $N = \{1, ..., n\}$ denote the set of all countries. The emissions of a global pollutant (like GHG) is the by-product of the consumption and production activities of each country. Country $i$ emits $e_i$. While most of the literature is restricted to positive emission choices, we also allow for negative net country emissions, which would correspond to processes like carbon sequestration.[6] Global emissions are aggregated over all countries, $E \equiv \sum_{i=1}^{n} e_i$. For $i$, the sum of all others' emissions is $E_{-i} \equiv \sum_{j \neq i \in N} e_j$. While the benefits of emissions are private to a country, the effects of emissions are a global public bad: the damage is imposed to all countries, albeit differentially. Let $B(e_i)$ represent the benefit that country $i$ derives from its own emissions:

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

with $\alpha_i, \beta_i > 0$. The first order derivative is given by $\frac{dB}{de_i} = \alpha_i - \beta_i e_i$. The benefit $B(e_i)$ is monotonically increasing in $(-\infty, \overline{e_i}]$, $\overline{e_i} \equiv \frac{\alpha_i}{\beta_i}$.[7] Note that $\frac{d^2B}{de_i^2} = -\beta_i < 0$, which indicates that the marginal benefit of emissions is diminishing.

The damage to country $i$ from emissions is assumed to be a convex function of global

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

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

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

emissions and country-specific vulnerability and adaptability parameters:

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

with $v_i, \theta_i > 0$. While expression (2) is based on the damage function adopted in Benchekroun et al. (2014) in the way in which adaptation enters the damage function, we differ in that both the vulnerability and the adaptability parameters are heterogeneous across countries. The first term in (2) is the damage caused by global emissions, with $v_i$ denoting the country's vulnerability to climate change. The second term in (2) represents the 'benefit' from adaptation, which is country-specific as well. The adaptation level chosen by country $i$ is denoted by $a_i$ and is assumed to be private, i.e. it reduces the climate-induced damage of pollution for country $i$ only. $\theta_i$ denotes the effectiveness of adaptation, or 'adaptability.' The damage function in (2) has three features. First, it is strictly increasing and convex in global emissions. Second, both the damage and the marginal damage from emissions are decreasing in adaptation and adaptability. Third, the marginal benefit of adaptation, given by $-\frac{\partial D(E,a_i)}{\partial a_i} = \theta_i E$, increases with global emissions. Thus, a country that is less vulnerable and more adaptable to climate change suffers less from the impact of GHG emissions. Moreover, the higher the global emissions are, the more valuable the adaptation activities are.

The marginal damage from emissions is given by $\frac{\partial D(E,a_i)}{\partial E} = v_i E - \theta_i a_i$. Thus, if adaptation is very effective and/or the adaptation level is very high, the marginal damage from emissions could turn negative, in what we term the 'productive over-adaptation' case. To rule out this less interesting scenario, the following is assumed to hold,

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

This implies practically that adaptation cannot reduce natural vulnerability to climate change impacts to zero. Technically, it ensures two things. First, the marginal damage of global emissions for country $i$,[8] as derived in the following optimization problems under different

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

cooperation scenarios, is always positive. Thus the 'productive over-adaptation' case is rule out. Second, this also guarantees a positive marginal benefit from emissions at the the optimal emission level. Therefore, the optimal emissions level of a country is always smaller than its maximum emission level defined above: $e_i \leq \overline{e_i} \equiv \frac{\alpha_i}{\beta_i}$.

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

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

with $c_i > 0$. The differences in adaptation costs across countries is captured by parameter $c_i$.

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

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

## 3. Equilibrium

The model considered here is based on a two-stage, simultaneous-move open membership (in an IEA) game.[9] In the first stage, countries choose whether to participate or not in the international agreement on abatement, and in the second stage they concomitantly choose their level of emissions/abatement and adaptation. While some version of this is the most prevalent type of game in the literature we are contributing, a brief discussion of these assumptions and some alternatives seems warranted at this point. First, it should be noted that we consider a single (global) agreement is under consideration, as opposed to several competing ones. Secondly, any country is eligible to join, i.e. there is no exclusivity clause.

Thirdly, countries decide simultaneously on their participation in the agreement, i.e. the Cournot-Nash assumption. In reality there is a sequential element to many agreements, whereby a small group of countries may initiate a regime that subsequently incorporates new members. However, as shown in Finus (2008), the results in the existing papers adopting a Stackelberg model for instance, are mixed and not sufficiently different to justify the loss

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

in explanatory power. Moreover, these sequential games assume identical countries. In our heterogeneous countries setup, allowing for a sequential structure of the game would require endogenizing the order in which countries decide on their participation, substantially increasing the array of strategic options and further diluting the results.[10] In addition, players make the abatement and adaptation decisions simultaneously here, also an assumption which is widely used in the literature[11]. While there are several papers adopting a sequential model for the choice of emissions, they all assume symmetric countries and we leave this extension for future research.

Fourthly, countries also choose both adaptation and emissions at the same time in the second stage. This assumption is less restrictive than it may appear at first. According to Zehaie (2009), this scenario is equivalent to one in which the (private) adaptation decisions are made subsequent to (global) abatement choices, as also pointed out in Benchekroun et al. (2014).[12] However, there is another interesting possibility in the context of our setup. Given that many adaptation projects require substantial infrastructure investment which may take a long time to complete, it is likely for some prospective IEA members to have already committed significant amounts of funds to such purposes *before* any mitigation agreement is reached. We look at this option in the Appendix, by assuming that countries choose their level of adaptation by taking the non-cooperative level of global emissions as given. The expected result is that countries have less of an incentive to join the coalition (more of an incentive to free ride) if they have already decreased their de facto vulnerability via adaptation investment. In other words, should an IEA be formed eventually, countries over-adapt compared to the efficient level.

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

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

anisms can extend cooperation,[13] however we aim here to focus on the main incentives in the absence of such schemes. Moreover, the logistics of such transfers, in a world in which the most vulnerable countries, having the most to benefit from an IEA, are also the ones who benefit the least from emissions and are the poorest, would conceivably have to compensate the richer, less vulnerable industrialized countries in order to induce them to join the IEA is problematic.[14] Transfers have rarely been used in existing IEAs due to moral hazard issues between donors and recipients, according to Finus (2000). Nevertheless, if allowing for country heterogeneity with respect to all dimensions related to abatement and adaptation increases the chances of cooperation, an optimally designed transfer scheme could further improve those odds.

*3.1. Non-cooperative Outcome*

In the non-cooperative case, each country chooses emissions ($e_i$) and adaptation ($a_i$) levels to maximize own welfare, taking as given the sum of the other countries' emissions $E_{-i}$:

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

The first order conditions are given by

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

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

The best response functions of emissions and adaptation for country $i$ are given by the following:

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

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

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

[14] 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.

where $\Phi_i \equiv v_i - \frac{\theta_i^2}{c_i}$. Substituting (8) in (2), we obtain the marginal damage from emissions net of adaptation: $\frac{dD(E)}{dE} = \Phi_i E$. $\Phi_i$ is the rate at which the net of adaptation marginal damage increases, and hence it presents the net vulnerability in the presence of adaptation. From our assumption in (3), $\Phi_i$ is always positive. The net vulnerability is increasing in the 'natural' vulnerability $v_i$ and adaptation cost $c_i$, and is decreasing in adaptability $\theta_i$.

In (7), sum over $i$ for all countries to derive global emissions and country $i$'s emission and adaptation level. Country $i$'s emission and adaptation level are given by,

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

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

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

From (11), abatement is undertaken even though no IEA is formed since natural vulnerability to climate change cannot be neutralized by adaptation ($\Phi_i > 0$). In a extreme case that the damage can be fully countered by adaptation, i.e. $\Phi_i = 0$, the country will not abate ($\Psi_i \equiv \frac{\Phi_i}{\beta_i} = 0$), and its emissions will achieve the maximum level $\overline{e_i}$. Moreover, in the non-cooperative case, a country abates more if it has higher relative rate of marginal change $\Psi_i$ than others.

The global emission level is given by,

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

where $\overline{E} \equiv \sum_{k \in N} \overline{e_k} = \sum_{k \in N} \frac{\alpha_k}{\beta_k}$. The fraction multiplying the maximum level of the world's emissions $\overline{E}$ is decreasing in $\Psi$ and thus - as expected - the actual aggregate emission are lower when countries (and the world as a whole) have higher 'abatement indicators'.[15]

From (11), (12) and (13), any change in relative rate of marginal change $\Psi_i$ (i.e. net vulnerability $\Phi_i$ and/or $\beta i$) will affect emission and adaptation level in all countries.

**Proposition 1.** *When countries behave non-cooperatively, if country i's net vulnerability $\Phi_i$ decreases (i.e. adaptation measures become more effective: $\theta_i$ rises and/or $c_i$ falls, and/or its natural vulnerability to climate impacts falls: $v_i$ decreases), it will choose to emit more and adapt more. All other countries respond by reducing emissions and adapting more, while the global emissions rise.*

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

$$\begin{aligned} \frac{\partial e_i}{\partial \Phi_i} &= -\frac{1+\Psi-\Psi_i}{\beta_i (1+\Psi)^2}\overline{E} < 0, \\ \frac{\partial e_j}{\partial \Phi_i} &= \frac{\Psi_j}{\beta_i (1+\Psi)^2}\overline{E} > 0, j \neq i \in N, \\ \frac{\partial E}{\partial \Phi_i} &= -\frac{1}{\beta_i (1+\Psi)^2}\overline{E} < 0. \end{aligned} \tag{14}$$

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

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

The net vulnerability change may be caused by change(s) of any of $\theta_i$, $c_i$, and $v_i$.

[15] 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.

$$\frac{da_i}{d\theta_i} = \frac{E}{c_i}\left(1 + \frac{1}{1+\Psi}\frac{\theta_i}{\beta i c_i}\right) > 0,$$
$$\frac{da_i}{dc_i} = -\frac{\theta_i}{c_i^2}E\left(1 + \frac{\theta_i^2}{c_i}\frac{1}{1+\Psi}\right) < 0,$$
$$\frac{da_i}{dv_i} = -\frac{\theta_i}{\beta_i c_i}\frac{1}{1+\Psi}E.$$

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

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

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

□

As country $i$'s adaptation measures become more effective, or the natural vulnerability of climate change decreases, the marginal damage of emissions on country $i$ falls. Thus the emission level of country $i$ rises. For all other countries, the emission levels fall since their marginal damage of emissions rises as a result of the increase in $i$'s emissions. The global emissions rise. Regarding adaptation, the marginal benefit of adaptation increases for every country as the world's emissions rise (for country $i$, the increase will be caused by changes in $v_i$ or $\theta_i$ as well), but the marginal cost remains the same (for country $i$, it may fall as a result of a fall in exogenous $c_i$). As a result, all countries increase adaptation investments. In summary, for the country experiencing an improvement in adaptation effectiveness and/or in natural vulnerability, mitigation and adaptation are substitutes. For all other countries, mitigation and adaptation are complements.

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

**Lemma 1.** *When countries behave non-cooperatively, if country i's marginal benefit of emissions shifts up (i.e. $\alpha_i$ rises), its emissions level increases. All other countries respond by reducing emissions and adapting more, and global emissions rise. If country i's marginal benefit of emissions becomes flatter (steeper), that is $\beta_i$ falls (increases), the absolute value of its emissions increases (decreases). All other countries will respond in the opposite way, yet the global emissions change in the same direction as country i's emission change.*

*Proof.* If $\alpha_i$ changes, country i's emissions rise:

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

Any other country $j \neq i \in N$ will choose to decrease emissions,

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

while the global emission level still increases:

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

If $\beta_i$ changes,

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

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

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

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

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

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

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

The responses in the adaptation level to a shift and a slope change in the marginal benefit of emissions are:

$$\frac{\partial a_i}{\partial \alpha_i} = \frac{da}{dE}\frac{\partial E}{\partial \alpha_i} = \frac{\theta i}{c_i}\frac{\partial E}{\partial \alpha_i} > 0,$$
$$\frac{\partial a_i}{\partial \beta_i} = \frac{da}{dE}\frac{\partial E}{\partial \beta_i}, \forall i \in N,$$

thus $a_i$ goes in the same direction as the global emissions, in response to changes in parameters $\alpha_i$ and $\beta_i$.

□

*3.2. Full-cooperative Outcome (A Grand Coalition)*

Suppose all nations are signatories to an IEA and choose simultaneously $e_i$ and $a_i$ to maximize the joint welfare,

$$\max_{e_i, a_i} \sum_{i \in N} w(e_i, a_i, E) = \sum_{i \in N} \left[ B(e_i) - D(E, a_i) - C(a_i) \right] \tag{15}$$

The first order conditions are given by,

$$e_i : \alpha_i - \beta_i e_i - \sum_{i \in N} v_i E + \sum_{i \in N} \theta_i a_i = 0 \tag{16}$$

$$a_i : \theta_i E - c_i a_i = 0 \tag{17}$$

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

$$e_i = \frac{\alpha_i - \sum_{k \in N} \Phi_k E_{-i}}{\beta_i + \sum_{k \in N} \Phi_k} \tag{18}$$
$$a_i = \frac{\theta_i}{c_i}\left( \frac{\alpha_i + \beta_i E_{-i}}{\beta_i + \sum_{k \in N} \Phi_k} \right)$$

From (16) and (17), the global emissions and individual emission level can be derived. Country $i$'s emission and adaptation level are given by,

$$e_i^G = \overline{e_i} - \frac{\Psi_i^G}{1 + \Psi^G}\overline{E} \tag{19}$$

$$a_i^G = \frac{\theta_i E^G}{c_i} \tag{20}$$

where $\Psi_i^G \equiv \frac{\Phi}{\beta_i}$ (the superscript denotes the 'grand coalition'). Similar to (11), the second term in (19) is the abatement level. However, compared to (11), a country's abatement indicator $\Psi_i^G$ in (19) is much larger than the non-cooperation one $\Psi_i$, since in the grand coalition, every country takes the joint vulnerability $\Phi$ into account instead of its own vulnerability $\Phi_i$. The underlying reason is that in the grand coalition, every country maximizes joint welfare and takes aggregate damages from global emissions into account.

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

$$E^G = \frac{1}{1 + \Psi^G}\overline{E}, \tag{21}$$

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

Any change in benefit of emissions or residual vulnerability in one country will cause each country's emission level and adaptation level changes. In the full-cooperation case, the impact of changes in vulnerability is very different from the non-cooperation outcome.

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

*Proof.* From (19) and (21),

$$\frac{\partial e_i^G}{\partial \Phi_i} = -\frac{1}{\beta_i\left(1 + \Psi^G\right)^2}\overline{E} < 0 \tag{22}$$

$$\frac{\partial e_j^G}{\partial \Phi_i} = -\frac{1}{\beta_j\left(1 + \Psi^G\right)^2}\overline{E} < 0 \tag{23}$$

$$\frac{\partial E^G}{\partial \Phi_i} = -\left(\sum_{k \in N} \frac{1}{\beta_k}\right)\frac{1}{\left(1 + \Psi^G\right)^2}\overline{E} < 0 \tag{24}$$

where $j \neq i \in N$, and $\Phi_i \equiv v_i - \frac{\theta_i^2}{c_i}$.

From (20) and (21), the impact of vulnerability change on adaptation of can be derived as the following,

$$da_i^G = \frac{\partial a_i^G}{\partial \theta_i} d\theta_i + \frac{\partial a_i^G}{\partial c_i} dc_i + \frac{\partial a_i^G}{\partial \Phi_i} \left( \frac{\partial \Phi_i}{\partial v_i} dv_i + \frac{\partial \Phi_i}{\partial c_i} dc_i + \frac{\partial \Phi_i}{\partial \theta_i} d\theta_i \right) < 0,$$

if $dv_i \leq 0, d\theta_i \geq 0, dc_i \leq 0$.

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

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

□

It is worth noting that in Proposition 2, when a country's net vulnerability changes, the response by other countries under full-cooperation is the opposite to the non-cooperation case. With full cooperation, if one country's net vulnerability falls, not only does that country's emission level rise, but so do all other countries' emissions. However, from (14) and (22), $\frac{\partial e_i}{\partial \Phi_i} < \frac{\partial e_i^G}{\partial \Phi_i} < 0$, which implies an emission rise that is lower with full-cooperation than with non-cooperation. If countries behave non-cooperatively, country i enjoys its reduction in vulnerability on its own and affords a higher emission level. All other countries reduce emissions to offset part of the damage caused by the emissions increase by country i. However, if all countries cooperate, the damage from climate change is internalized and shared by all countries. The damage caused by an increase in vulnerability of one country is shared by all countries, and the benefit from a decrease in the vulnerability of one country is also shared by all.

An interesting implication of Proposition 2 is that investment in adaptation technology now has a public good feature (compared to a private good in the non-cooperation case). Suppose a member invests in adaptation technology and experiences a vulnerability decrease. Its emission level increases less compared to the non-cooperation case. However, unlike in non-cooperation outcome where all other countries have to reduce emissions, they afford higher emission levels with full cooperation among countries. Thus with a grand coalition, all countries benefit from private investment of adaptation technology by a countries.

**Lemma 2.** *When all countries behave cooperatively, if country i's marginal benefit of emissions shift up (i.e. $\alpha_i$ rises), its emission level will increase. All other countries respond by reducing emissions and adapting more, and global emissions rise. If country i's marginal benefit of emissions becomes flatter (i.e. $\beta_i$ falls), the absolute value of its emissions increases. All other countries will respond oppositely, and yet the global emissions change in the same direction as country i's emission change.*

*Proof.* If $\alpha_i$ changes,

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

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

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

For the global emission level,

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

If $\beta_i$ changes,

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

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

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

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

For the global emission level,

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

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

For adaptation level, $\forall i \in N$,

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

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

□

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

*Proof.* For emission and adaptation levels,

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

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

The difference in emission level is given by,

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

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

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

□

In the non-cooperation case, a country with high vulnerability $\Phi_i$ emits at a low emission level due to high marginal damage from emissions. In the cooperative case, all countries choose emissions according to the aggregate damage. Low 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 $\sum_{j\in N}\Phi_j$ are sufficiently large, and $\beta$ is identical for all countries. $\frac{1+\Psi}{1+\Psi^G} = \frac{1+\sum_{k\in N}\frac{\Phi_k}{\beta_k}}{1+\sum_{k\in N}\Phi_k\sum_{k\in N}\frac{1}{\beta_k}} \approx \frac{1}{n}$. $e_i^G > e_i$ if the following is satisfied:

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

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

*3.3. Coalition Formation*

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

*3.3.1. Non-signatories*

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

$$\max_{e_i, a_i} w\left(e_i, a_i, E^N\right) = B(e_i) - D\left(E^N, a_i\right) - C\left(a_i\right) \tag{25}$$

First order conditions are given by,

$$e_i : \alpha_i - \beta_i e_i - v_i \left(E^O + E^S\right) + \theta_i a_i = 0, \tag{26}$$

$$a_i : \theta_i \left(E^O + E^S\right) - c_i a_i = 0. \tag{27}$$

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

$$e_i = \frac{\alpha_i - \Phi_i \left(E^S + E^O_{-i}\right)}{\beta_i + \Phi_i}, \tag{28}$$

$$a_i = \frac{\theta_i}{c_i} \frac{\alpha_i + \beta_i \left(E^S + E^O_{-i}\right)}{\beta_i + \Phi_i}. \tag{29}$$

From (28), the aggregate best response function of emissions of all non-signatories, given $E^S(S)$ is given by the following:

$$E^O(S) = \frac{\overline{E}^O - \Psi^O E^S(S)}{1+\Psi^O}, \tag{30}$$

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

*3.3.2. Signatories*

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

$$\max_{e_j,a_j} \sum_{j\in S} w\left(e_j, a_j, E^N\right) = \sum_{j\in S} \left[B(e_j) - D\left(E^N, a_j\right) - C\left(a_j\right)\right] \tag{31}$$

First order conditions are given as follows,

$$e_j : \alpha_j - \beta_j e_j - \sum_{j\in S} v_j \left(E^S + E^O\right) + \sum_{j\in S} \theta_j a_j = 0, \tag{32}$$

$$a_j : \theta_j \left(E^S + E^O\right) - c_j a_j = 0. \tag{33}$$

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

$$e_j = \frac{\alpha_j - \Phi^S\left(E^S_{-j} + E^O\right)}{\beta_j + \Phi^S}, \tag{34}$$

$$a_j = \frac{\theta_j}{c_j} \frac{\alpha_j + \beta_j\left(E^S_{-j} + E^O\right)}{\beta_j + \Phi^S}, \tag{35}$$

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

Using (32), (33) and (30), the world emission level and individual emission level can be derived. The emission level of a non-signatory and a signatory are given as follows,

$$e^O_i = \overline{e_i} - \Psi_i E^N = \overline{e_i} - \frac{\Psi_i}{1+\Psi^O+\Psi^S}\overline{E}, \tag{36}$$

$$e^S_j = \overline{e_j} - \Psi^S_j E^N = \overline{e_j} - \frac{\Psi^S_j}{1+\Psi^O+\Psi^S}\overline{E}, \tag{37}$$

where $\Psi_j^S \equiv \frac{\Phi^S}{\beta_j}$. The emission levels differ across non-signatories, depending on the effectivess of benefit of emissions and of residual vulnerability, while the emission level for all signatories depends only on the effectivness of benefit of emissions.

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

$$E^N(S) = E^S(S) + E^O(S) = \frac{\overline{E}}{1 + \Psi^O + \Psi^S}. \tag{38}$$

As mentioned in the full-cooperative case, countries with higher residual vulnerability are more willing to join the coalition. Suppose all countries with high residual vulnerability are signatories of the IEA that is, $\frac{\Phi^S}{s} >> \frac{\Phi^O}{n-s}$, where $\Phi^O \equiv \sum_{i \in O} \Phi_i$. If a non-signatory with relatively low residual vulnerability join the IEA, the world's total emissions still can be decreased by a substantial amount. This can be seen from (38), for a non-signatory $i$ leaving $O$ and joining $S$, the denominator of the world emissions will increase by $\left(\frac{\Phi^S}{\beta_i} + \Phi_i \sum_{j \in S} \frac{1}{\beta_j}\right)$. If the IEA contains a large number of members, the world emission level could fall by a substantial amount. Thus the size of the coalition is crucial to the impact of an IEA.

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

$$a_i = \frac{\theta_i E^N}{c_i}, \forall i \in N \tag{39}$$

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

*Proof.* Suppose a non-member country i experiences a vulnerability decrease (i.e. adaptation measures become more effective: $\theta_i$ rises and/or $c_i$ falls, and/or its natural vulnerability to climate impacts falls: $v_i$ decreases).

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

All other countries respond oppositely:

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

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

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

Non-member countries respond oppositely to members:

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

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

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

The adaptation level change for the country with vulnerability change is given by,

$$da_i = \frac{\partial a_i}{\partial \theta_i}d\theta_i + \frac{\partial a_i}{\partial c_i}dc_i + \frac{\partial a_i}{\partial \Phi_i}\left(\frac{\partial \Phi_i}{\partial v_i}dv_i + \frac{\partial \Phi_i}{\partial c_i}dc_i + \frac{\partial \Phi_i}{\partial \theta_i}d\theta_i\right) < 0, i \in N$$

if $dv_i \leq 0, d\theta_i \geq 0, dc_i \leq 0$.

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

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

□

An intriguing implication of Propositions 2 and 4 is that investment in adaptation technology has a public good feature inside the coalition, compared to being strictly a private good in the non-cooperation case. All signatories increase emissions in response to a member's decrease in net vulnerability, while non-signatories have to reduce emissions and suffer more damage from climate change. If a signatory invests in adaptation technology to reduce its net vulnerability, the benefit of this investment is shared by all members. In other words, free-riding on adaptation technological progress emerges inside an IEA on mitigation, and private investment in adaptation technology is discouraged inside the IEA. One solution to this problem is to incorporate R&D spending on adaptation technology in the IEA, and to require all members to contribute. For example, a research hub on adaptation technology can be established and funded by all members of an IEA. Related to this, Proposition 7 below shows that if technological progresses from R&D on adaptation can be made excludable as a club good inside an IEA, the free-riding incentives of non-signatories can be significantly reduced. These insights form some of the most interesting implications derived from our model.

**Lemma 3.** *The impact of change in the benefit of emissions (The change in abatement cost) are the same regardless of whether it originates in a non-member or a member country. If country i's marginal benefit of emissions shifts up (i.e. $\alpha_i$ rises), its emissions level will increase. All other countries respond by reducing emissions and adapting more, and global emissions rise. If country i's marginal benefit of emissions becomes flatter (i.e. $\beta_i$ falls), the absolute value of its emissions increases. All other countries will respond in the opposite way, yet the global emissions change in the same direction as country i's emission change.*

*Proof.* First, suppose a country's $\alpha$ changes. A non-member i's emissions rise if its $\alpha_i$ 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 $\alpha_i$:

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

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

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

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

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

The global emission level always rises no matter which country experiences reduced $\alpha$:

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

Second, suppose $\beta$ changes in a country. If a non-member i's $\beta_i$ 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 $\beta_j$ drops. The member j increases its emission level:

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

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

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

Additionally, from (39) adaptation level always goes to the same direction as the global emission level does. □

Notice that similar results as presented in Lemma 1 and 3 are obtained under all three scenarios: non-cooperation, full-cooperation and partial cooperation, when it comes to exogenous changes in the benefit function parameters ($\alpha$ and $\beta$). The underlying reason is that countries in an IEA take into account the aggregate damage of the coalition. The benefit of emissions is still private to a country regardless of the membership status. Thus the impact of exogenous changes in the benefit side is similar across countries regardless of the existing coalition and a country's membership status. However, something interesting can be said about differences between signatories and non-signatories in the partial-cooperation equilibrium: i.e. the increase in emissions of signatories is less pronounced than for non-signatories, following an exogenous rise in the marginal benefit of emissions (as $\alpha$ rises and/or $\beta$ falls).

**Lemma 4.** *If no country joins the coalition, i.e. $S = \varnothing$ and $O = N$, $E^N = E$, the non-cooperative global emission level. If all countries are members of the coalition, $E^N = E^G$, which is the global emission level in the presence of the grand coalition. The global emissions $E^G \leq E^N \leq E$, and the adaptation investments $a_i^G \leq a_i^N \leq a_i$ for $\forall i \in N$.*

*Proof.* Suppose $S = \varnothing$ [16] and $O = N$. $\Psi^O = \sum_{i \in N} \frac{\Phi_i}{\beta i} = \Psi$, and $\Psi^S = 0$. From (13),

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

Suppose $S = N$ and $O = \varnothing$. $\Phi^O = 0$ and $\Phi^S = \sum_{j \in S} \frac{\Phi_j}{\beta_j} = \Psi^G$. From (21),

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

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

□

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

*Proof.* Suppose a coalition exists, $S \neq \varnothing$. From (11) and (36),

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

From (11) and (37),

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

[16] 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.

From Lemma 4, $E^N < E$ if $S \neq \varnothing$.

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

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

If a coalition is formed, the coalition as a whole cuts emissions. Facing a lower level of world emissions, a non-member country responds by increasing emissions due to a reduced damage from climate change. The world emission level still decreases, and every country pays less climate change cost than in the non-cooperation equilibrium. In a world with heterogeneous countries, a signatory to an IEA may be able to emit more if it is relatively more vulnerable than other signatories. Combined with the fact that every country suffers less damages from climate change, a signatory that emits more than its non-cooperation level will certainly benefit from forming the coalition.

## 4. Stability

Free-riding is the main problem preventing a large coalition being formed: a large coalition usually is not internally stable since a member can increase emissions and free ride on emission cuts by other members if it leaves the coalition. The literature on IEA formation has suggested many ways to extend the cooperation. Most of the studies assume homogeneous agents and no role of adaptation. Lazkano et al. (2014) assume carbon leakage and incorporate adaptation in the model. With identical adaptation cost, no large coalition is formed. If two types adaptation costs are assumed, the paper shows that such limited heterogeneity in adaptation cost may extend the coalition size, even to the grand coalition. Their result implies that policies aiming at reducing the gap in adaptation cost - for example by encouraging the diffusion of technology - may negatively affect an IEA on climate change.

However, by assuming countries are different in net vulnerability, we show that a coalition cannot be achieved when members differ much from each other with respect to their vulnerability. If a member's adaptation cost is very low (and/or its adaptation activities are very effective) compared to other members (so its vulnerability is low), the member is better off by leaving the coalition, and the internal stability condition is violated. This result implies large gaps in adaptation cost and effectiveness may prevent forming a large coalition, but also the opposite policy implication with respect to adaptation technology differences: sharing cost-saving adaptation technologies fosters cooperation in climate change mitigation.

Three conditions need to be met in a coalition equilibrium: profitability, internal stability and external stability. Since internal stability implies profitability in our model (as shown in the appendix), we focus on internal and external stability conditions in this section. Nevertheless, profitability condition is explored in the appendix, and can be applied to the pivotal-countries case where an IEA can only be formed when pivotal countries all participate. The result implies a large gap in adaptation among pivotal countries may prevent forming an IEA.

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

Without transfer, the stability conditions are given by,

$$w_j^S(S) - w_j^O(S\backslash\{j\}) \geq 0, \forall j \in S \quad (40)$$

$$w_i^O(S) - w_i^S(S\cup\{i\}) > 0, \forall i \in O, \quad (41)$$

where (40) is the internal stability condition, which requires a signatory of the IEA to have a higher welfare than if it leaves the IEA. (41) is the external stable condition, which says any non-signatory will have a lower welfare if it joins the IEA. In summary, the coalition is stable if no member wants to leave it and no singleton wants to join it.

Define the cooperative incentive for a signatory as the current welfare minus the welfare of being a non-signatory, and define the free-riding incentive for a non-member country as the current welfare minus welfare of being a signatory of a coalition. The internal and external stable conditions are equivalent to (42) and (43):

$$\Gamma_j^S(S) = w_j^S(S) - w_j^O(S \backslash \{j\}) \geq 0, \forall j \in S \tag{42}$$

$$\Gamma_i^O(S) = w_i^O(S) - w_i^S(S \cup \{i\}) > 0, \forall i \in O \tag{43}$$

*4.1. Cooperative Incentives of Signatories*

For a given coalition $S$, a signatory j's emission and the world emission levels are given by (37) and (38). From (36), a signatory's emissions if it leaves the IEA is given by (44). The world's total emissions can be derived from (38), and is given by (45).

$$e_j^O(S \backslash \{j\}) = \overline{e_j} - \frac{\Psi_j}{1 + \Psi^O(S \backslash \{j\}) + \Psi^S(S \backslash \{j\})}\overline{E} \tag{44}$$

$$E(S \backslash \{j\}) = \frac{\overline{E}}{1 + \Psi^O(S \backslash \{j\}) + \Psi^S(S \backslash \{j\})} \tag{45}$$

where $1 + \Psi^O(S \backslash \{j\}) + \Psi^S(S \backslash \{j\}) = 1 + \Psi^O + \Psi^S + 2\Psi_j - \Psi_j^S - \Phi_j \sum_{k \in S} \frac{1}{\beta_k}, j \in S$. The world emission level rises after the signatory leaves the coalition since $1 + \Psi^O + \Psi^S > 1 + \Psi^O(S \backslash \{j\}) + \Psi^S(S \backslash \{j\})$.

From (37), (38), (44) and (45), the cooperative incentive for a signatory is given by,

$$\begin{aligned} \Gamma_j^S(S) &= \alpha_j \left[e_j^S(S) - e_j^O(S \backslash \{j\})\right] - \frac{\beta_j}{2}\left[e_j^S(S)^2 - e_j^O(S \backslash \{j\})^2\right] \\ &\quad - \frac{1}{2}\Phi_j \left[E(S)^2 - E(S \backslash \{j\})^2\right] && (46) \\ &= \frac{\overline{E}^2}{2}\left[\frac{\Phi_j \Psi_j + \Phi_j}{(1 + \Psi^O(S \backslash \{j\}) + \Psi^S(S \backslash \{j\}))^2} - \frac{\Phi^S \Psi_j^S + \Phi_j}{(1 + \Psi^O + \Psi^S)^2}\right]. && (47) \end{aligned}$$

*4.2. Free-riding Incentives of Non-signatories*

For a given coalition $S$, a non-signatory's emission and the world emission levels are given by (36) and (38). From (37), a non-signatory's emissions if it joins the IEA is given by (48). The world's total emissions can be derived from (38), and is given by (49).

$$e_i^S(S \cup \{i\}) = \overline{e_i} - \frac{\Psi_i^S + \Psi_i}{1 + \Psi^O(S \cup \{i\}) + \Psi^S(S \cup \{i\})}\overline{E} \tag{48}$$

$$E(S \cup \{i\}) = \frac{\overline{E}}{1 + \Psi^O(S \cup \{i\}) + \Psi^S(S \cup \{i\})} \tag{49}$$

where $1+\Psi^O(S\cup\{i\})+\Psi^S(S\cup\{i\}) = 1+\Psi^O+\Psi^S+\Psi_i^S+\Phi_i\sum_{k\in S}\frac{1}{\beta_k}$, $i\in O$. The world's emission level falls if the non-signatory joins the IEA since $1+\Psi^O(S\cup\{i\})+\Psi^S(S\cup\{i\}) > 1+\Psi^O+\Psi^S$.

The free-riding incentive for a non-signatory is given by,

$$\begin{aligned}\Gamma_i^O(S) &= \alpha_i\left(e_i^O(S)-e_i^S(S\cup\{i\})\right)-\frac{\beta_i}{2}\left[e_i^O(S)^2-e_i^S(S\cup\{i\})^2\right]\\ &\quad -\frac{1}{2}\Phi_i\left[E(S)^2-E(S\cup\{i\})^2\right] \qquad (50)\\ &= \frac{\overline{E}^2}{2}\left(\frac{(\Phi^S+\Phi_i)(\Psi^S+\Psi_i)+\Phi_i}{(1+\Psi^O(S\cup\{i\})+\Psi^S(S\cup\{i\}))^2}-\frac{\Phi_i\Psi_i+\Phi_i}{(1+\Psi^O+\Psi^S)^2}\right). \qquad (51)\end{aligned}$$

**Lemma 5.** *For a given coalition $S$,*

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

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

*Proof.* For a member $j$ in $S$, from (37) and (44), the change in emissions is given by,

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

For a non-member $i$ in $O$, from (36) and (48), the change in emissions is as following,

$$\begin{aligned}e_i^O(S)-e_i^S(S\cup\{i\}) &= \left(\frac{\Psi_i+\Psi_i^S}{1+\Psi^O+\Psi^S+\Psi_i^S+\Phi_i\sum_{k\in S}\frac{1}{\beta_k}}-\frac{\Psi_i}{1+\Psi^O+\Psi^S}\right)\overline{E}\\ e_i^S(S\cup\{i\})>e_i^O(S) &\Leftrightarrow \frac{\Psi_i+\Psi_i^S}{\Psi_i}>\frac{1+\Psi^O+\Psi^S+\Psi_i^S+\Phi_i\sum_{k\in S}\frac{1}{\beta_k}}{1+\Psi^O+\Psi^S}\\ &\Leftrightarrow \frac{\Phi_i}{\Phi^S}<\frac{1+\Psi^O+\Psi^S}{\Psi_i^S+\Phi_i\sum_{k\in S}\frac{1}{\beta_k}}\end{aligned}$$

□

**Lemma 6.** *For a given coalition S, a member's cooperative incentive is non-negative iff* $\frac{\Phi_j^2+\beta_j\Phi_j}{(\Phi^S)^2+\beta_j\Phi_j} \geq \left(1 - \frac{\Psi_j^S - 2\Psi_j + \Phi_j \sum_{k\in S}\frac{1}{\beta_k}}{1+\Psi^O+\Psi^S}\right)^2$*, $j \in S$. A non-member's free-riding incentive is positive iff* $\frac{\Phi_i^2+\beta_i\Phi_i}{(\Phi^{S\cup\{i\}})^2+\beta_i\Phi_i} < \left(\frac{1+\Psi^O+\Psi^S}{1+\Psi^O+\Psi^S+\Psi_i^S+\Phi_i\sum_{k\in S}\frac{1}{\beta_k}}\right)^2$*, $i \in O$.*

*Proof.* From (47), $\Gamma_j^S(S) \geq 0$ is equivalent to the following,

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

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

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

From(51), $\Gamma_i^O(S) > 0$ is equivalent to the following,

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

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

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

In general, a member with high vulnerability relative to the coalition is more likely to have a positive cooperative incentive, while a non-member with low vulnerability is more likely to free-ride on the coalition.

**Lemma 7.** *(Sufficient condition to internal stability) If a member j's emission level does not rise when it leaves the coalition, its cooperative incentive for the given coalition is positive.*

*Proof.* From Lemma 5, $e_j^S(S) \geq e_j^O(S\backslash\{j\})$ 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, $\Gamma_j^S(S) > 0$. □

Eq. (47) helps interpret Lemma 7. The cooperative incentive of a member is composed of two parts: change of the benefit of emissions(first two terms) and change of climate change cost (the last term). Since a country's benefit of emissions is increasing in its emissions, if a member's emission level is not lower than if it leaves the coalition, the change of the benefit of emissions is non-negative. Moreover, since the world emission level is always lower with a larger IEA, the signatory's climate change cost is lower if it chooses to stay in the IEA. Thus for a given IEA, if the signatory is also able to emit more than if it leaves the IEA, its cooperative incentive is definitely positive. However, if the signatory can afford more emissions when it leaves the IEA, its cooperative incentive depends on, as a member, whether its reduced climate change cost is enough to compensate to the lost in benefit of emissions. A detailed relationship between emission changes and cooperative incentives can be obtained from Lemma 5, 6 and 7, and it is illustrated in Table 1

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

Table 1: Emission Changes and Cooperative Incentives

Given a coalition, member countries can be categorized into three types based on their net vulnerability and slope of marginal benefit of emissions. In general, Type I members are highly vulnerable (e.g. low adaptation cost and/or high effectiveness in adaptation) ones in the coalition. A type I country is characterized by Lemma 7. Type II members have to reduce their emissions if they choose to stay in the coalition, but the welfare rises as the coalition formed. The reason is that the reduced climate change cost by staying in the coalition is enough to compensate for the loss from emission cuts. Type III countries have low vulnerability relative to other members. They have to keep lower emissions levels and the welfare is lower if they choose to stay in the coalition: they need reduce significant amount of emissions but benefit little from global emissions reduction. Thus a stable coalition is composed with only Type II and Type III countries. Type I countries cannot exist in a stable coalition since free-riding on the coalition is a better choice for them. In the next section, we show that if countries differ much in net vulnerability, low vulnerable countries can be Type I countries, and hence a stable coalition cannot be formed.

*4.3. Heterogeneous Vulnerability and Cooperative Incentives*

In this section, we focus on heterogeneous vulnerability and stable coalitions. If the gap in net vulnerability is large enough, low vulnerable countries can be Type I countries and choose to leave the coalition. Thus if countries differ much in net vulnerability, a large stable coalition is not likely to be formed. Our findings implies that Green Climate Funds which assist the developing countries in adaptation may help form an IEA on climate change mitigation.

**Proposition 6.** *In a given coalition, less vulnerable countries have lower cooperative incentives.*

*Proof.* For a given coalition, all coalition-level parameters, i.e. $\Phi^O$, $\Phi^S$, $\Psi^O$ and $\Psi^S$, 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 $\beta_j$ and $\phi_j$.

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

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

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

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

The sign of $\frac{\partial \Gamma_j^S(\Phi_j,\beta_j;S)}{\partial \beta_j}$ is ambiguous without parameter values. However, from Lemma 5, if $e_j^S(S) \geq e_j^O(S\backslash\{j\})$, the first two terms in $\frac{\partial \Gamma_j^S(\Phi_j,\beta_j;S)}{\partial \beta_j}$ is non-positive:

$$\begin{aligned} e_j^S(S) \geq e_j^O(S\backslash\{j\}) \Leftrightarrow & \quad \frac{\Psi_j}{1+\Psi^O+\Psi^S+2\Psi_j-\Psi_j^S-\Phi_j\sum_{k\in S}\frac{1}{\beta_k}} \geq \frac{\Psi_j^S}{1+\Psi^O+\Psi^S} \\ \Leftrightarrow & \quad \frac{\Psi_j^{S2}}{(1+\Psi^O+\Psi^S)^2} - \frac{\Psi_j^2}{(1+\Psi^O(S\cup\{i\})+\Psi^S(S\cup\{i\}))^2} \leq 0\end{aligned}$$

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

□

From Proposition 6, a signatory's cooperative incentive is positively related with vulnerability. It is expected a country's cooperative incentive may be negative if its vulnerability is low enough. To better understand the role of heterogeneous vulnerability in countries' cooperative incentives and the structure of stable coalitions, assume countries are symmetric in benefit side (identical $\alpha$ and $\beta$ for all countries). From Lemma 6, whether a signatory has positive (negative) cooperative incentive is equivalent to:

$$\frac{\Phi_j^2+\Phi_j\beta}{\Phi^S+\Phi_j\beta} > (<) \frac{(1+\Psi^O(S\backslash\{j\})+\Psi^S(S\backslash\{j\}))^2}{1+\Psi^O+\Psi^S}. \tag{52}$$

For a given coalition, all the coalition-level parameters are fixed, and only the vulnerability differs in signatories. The LHS in (52) in increasing in $\Phi_j$ and the RHS is decreasing in $\Phi_j$.

$$\lim_{\Phi_j \to 0} \frac{\Phi_j^2 + \Phi_j\beta}{\Phi^S + \Phi_j\beta} = 0, \lim_{\Phi_j \to \Phi^S} \frac{\Phi_j^2 + \Phi_j\beta}{\Phi^S + \Phi_j\beta} = 1,$$

$$\lim_{\Phi_j \to 0} \frac{(1 + \Psi^O(S\backslash\{j\}) + \Psi^S(S\backslash\{j\}))^2}{1 + \Psi^O + \Psi^S} = \left(1 - \frac{\Phi^S}{\beta + \Phi^O + s\Phi^S}\right)^2,$$

$$\lim_{\Phi_j \to \Phi^S} \frac{(1 + \Psi^O(S\backslash\{j\}) + \Psi^S(S\backslash\{j\}))^2}{1 + \Psi^O + \Psi^S} = \left(1 - \frac{(s-1)\Phi^S}{\beta + \Phi^O + s\Phi^S}\right)^2,$$

where $s \geq 2$ is the coalition size. The LHS and RHS are pictured in Fig.(1).

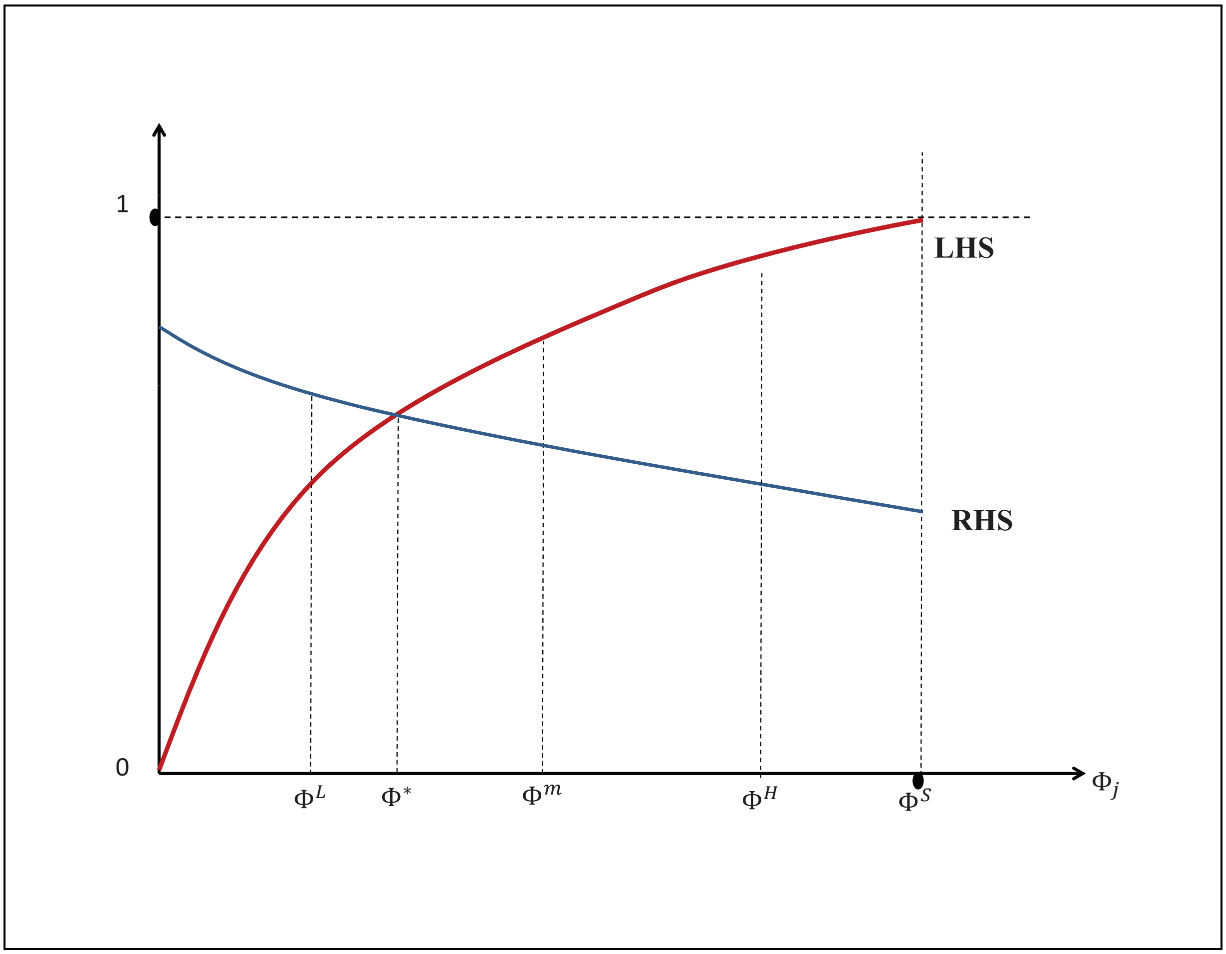


Figure 1: The cooperative incentive for a member country

For countries with vulnerability greater than $\Phi^*$, their cooperative incentives are positive. However, if a signatory's vulnerability is below $\Phi^*$, its welfare rises if it leaves the IEA. Thus the IEA is internally stable if and only if all signatories have vulnerability no less than $\Phi^*$. If countries' vulnerability does not differ much from each other (every country's vulnerability is close to the average level), as shown in Fig.(1) , all countries may have positive cooperative incentives as their vulnerability is close to the average vulnerability $\Phi^m$. However, if two countries substantially vary from each other in vulnerability, for example, as the $\Phi^L$ and $\Phi^H$ in Fig.(1), the one with low vulnerability countries have negative cooperative incentives and will choose to leave the coalition. Hence a stable coalition cannot be formed if members differ much in vulnerability.

Previous literature in IEAs on GHGs mitigation shows that with non-linear marginal benefit and marginal damage functions, the maximum coalition size is two if countries are symmetric. This result applies to the symmetric version of our model. If heterogeneous damage from emissions and/or adaptation are allowed, the maximum coalition size is still two. However, if heterogeneity is extended to all four aspects (benefit of emissions, damage of emissions, benefit of adaptation, and cost of adaptation), the maximum coalition size can be the grand coalition. A numerical example is given in the simulation section.

### *4.4. Technological Progress in Adaptation and Free-riding Incentive*

In this section, we focus on the adaptation effectiveness and the free riding incentives of non-signatories in a heterogeneous world. We show that technological progress in adaptation, provided as a excludable 'club good' to members of an IEA, may reduce the free riding incentives of non-signatories, and hence helps enlarge the coalition. For example, the IEA can be accompanied by the negotiation of an R&D hub on adaptation technology by all members. The technology progress will be shared and implemented by members only. The underlying mechanism is that the free riding incentive by non-members on an IEA will be offset by the benefits stemming from the technology diffusion inside an IEA.

The technological progress in adaptation increase the absolute effectiveness of adaptation and/or reduce the cost of adaptation activities ($\theta_i$ rises and/or $c_i$ falls), and hence reduces a member's net vulnerability $\Phi_i$. Suppose the net vulnerability becomes $r_j\Phi_j$ for a member of the IEA, where $r_j \in [0, 1]$ is the benefit index. Thus the technological progress reduces

$(1 - r_j)$ portion of vulnerability for member j. The technological progress is assumed to be excludable to members of an IEA. Thus for a non-member $i \in O$, its vulnerability remains $\Phi_i$. As noted in Carraro and Siniscalco (1993), enlargement of a coalition requires some form of commitment. We assume the members are committed to the coalition, and try to analyze the free-riding incentive of non-members.

**Proposition 7.** *An increase in effectiveness of adaptation inside an IEA reduce a nonmember i's free-riding incentive iff* $\frac{2\Psi_i(\Psi_i^S + r_i\Psi_i) + \Psi_i}{2[(\Psi_i^S + r_i\Psi_i)^2 + r_i\Psi_i]} > \frac{(\Phi_i \sum_{j\in S}\frac{1}{\beta_j} + \Psi_i)}{(1+\Psi^O+\Psi^S+\Psi_i^S + r_i\Phi_i\sum_{j\in S}\frac{1}{\beta_j} + r_i\Psi_i - \Psi_i)}$. *If* $\beta_i$ *are much larger than* $\Phi_i$, $\forall i \in N$, *technological progress in vulnerability within an IEA is negatively related with non-signatories' free-riding incentives.*

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

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

From (50), the free riding incentive is given as the following,

$$\Gamma_i^O(S) = \frac{\beta_i\overline{E}^2}{2}\left[\frac{(\Psi_i^S + r_i\Psi_i)^2 + r_i\Psi_i}{(1 + \Psi^O + \Psi^S + \Psi_i^S + r_i\Phi_i\sum_{j\in S}\frac{1}{\beta_j} + r_i\Psi_i - \Psi_i)^2} - \frac{\Psi_i^2 + \Psi_i}{(1 + \Psi^O + \Psi^S)^2}\right] \quad (53)$$

Take derivative of $\Gamma_i^O$ with respect of $r_i$,

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

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

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

LHS $\to \frac{1}{\frac{\Phi^S}{\Phi_i} + r_i}$ as $\beta_i \to 0$. LHS $\to \frac{1}{2r_i}$ as $\beta_i \to \infty$. Note $\frac{1}{2r_i} > \frac{1}{\frac{\Phi^S}{\Phi_i} + r_i}$.
RHS $\to \frac{1}{\frac{\Phi^S}{\Phi_i} + r_i - 1}$ as $\beta_i \to 0$. RHS is decreasing in $\beta_i$. □

If countries are symmetric, free-riding incentives of a non-member decreases in the within-coalition technological progress in adaptation (i.e. decreases in $r$). With heterogeneous countries, if in general $\beta$ are much larger than $\Phi$ [17] , technological progress in adaptation within an IEA is negatively related with non-signatories' free-riding incentives.

## 5. Simulation

Previous literature on IEAs has shown that analytical solution of stable coalitions is not available with non-linear functional forms (Barrett (1997), McGinty (2007),Finus (2008)). Thus simulation has been heavily relied upon analyze the stability of coalitions. However, due to the limitation from data and models (not possible to capture all aspects of climate change), all most all studies on IEA focusing on coalition stability assume arbitrary parameters (Barrett (1997), McGinty (2007), Pavlova and De Zeeuw (2013), Lazkano et al. (2014)). As noted in Finus (2008), simulations based on some scientifically estimated parameters should have some merits.

In this section, we focus on two issues: first, parameters in the model will be estimated with data on climate change, and stable coalitions are simulated with those parameters; second, we show the stable coalition can be enlarged effectively by providing technological progress in adaptation within the coalition.

The benefits of emissions function is estimated with GDP and GHG emissions by each country. The data is obtained from the World Bank Data Portal, ranging from 1960-2010.

[17] $\beta$ is expected to be much larger than $\Phi$ since benefit is generated by private emissions, while damage is caused by aggregate emissions of all countries. This is shown in our numerical example.

| Variable | Obs | Mean | Std. Dev. | Min | Max |
|---|---|---|---|---|---|
| GDP | 8486 | 1.34E+11 | 7.20E+11 | 8824746 | 1.62E+13 |
| totalGHG | 11556 | 79452.91 | 427294.6 | -80.674 | 1.07E+07 |
| DARACCcost2010 | 184 | 3322.717 | 10291.83 | 0 | 90000 |

Table 2: Summary Statistics

| | alpha_i | beta_i | vul_i |
|---|---|---|---|
| 1 | 1115731.6250 | -11.0279 | 0.004708 |
| 2 | 2735051.0000 | -259.0875 | 0.000628 |
| 3* | 6543675.5000 | -4941.5771 | 0.000471 |
| 4* | 1539416.0000 | -6.6887 | 0.010984 |
| 5 | 1357744.0000 | -63.8756 | 0.001569 |
| 6 | 570826.8125 | -7.1677 | 0.002354 |
| 7* | 830387.4375 | -0.4390 | 0.031384 |
| 8 | 649539.3125 | -13.4068 | 0.000314 |
| 9 | 1914847.6250 | -34.1568 | 0.001177 |
| 10* | 232675760.0000 | -6619563 | 0.000047 |

*: countries in the largest stable coalition

Table 3: Estimated Parameters

The parameters in damage from emissions and cost of adaptation are integrated into the net vulnerability, $\Phi_i \equiv v_i - \frac{\theta_i^2}{c_i}$, and only $\Phi_i$ is needed to simulate the model. The net vulnerability $\Phi_i$ can be estimated by the damage caused by GHG emissions and the world's total GHG emissions. We use the climate change cost monitored by DARA as a proxy for the damage. The climate change cost by DARA was assessed across four impact areas: environmental disasters, habitat change, health impact, and industry stress.

The estimation proceeds as follows: first, $\alpha_i$ and $\beta_i$ are estimated for each country:

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

Second, the net vulnerability $\Phi_i$ is estimated for each country from climate change cost of 2010 by DARA, and the world's GHG emissions obtained from the World Bank.

$$Climate\_change\_cost_i = \Phi_i E^2$$

Third, countries are clustered into 10 groups by $\alpha_i$, $\beta_i$, and $\Phi_i$ using the k-mean method. A representative country whose parameters are closest to the group mean will be chosen from each group.

Fourth, we keep the 10 representative countries and rescale the net vulnerability $\Phi_i$ to this 'small world.' We then simulate the model and obtain stable coalitions.

| | World's emissions | World's welfare |
|---|---|---|
| Non-cooperative equilibrium | 2.13E+06 | 8.86E+11 |
| Full-cooperative equilibrium | 1.88E+06 | 9.02E+11 |
| | drop 11.6%* | rise 2%* |
| Stable coalition {3,4,7,10} | 2.02E+06 | 8.94E+11 |
| | drop 5.1%* | rise 0.9%* |

*: non-cooperative equilibrium as the baseline

Table 4: Welfare and emissions

Some key statistics of GDP, GHG emissions and the climate change costs are shown in Table 2. The parameter values are given by Table 3. The stable coalition is $\{3, 4, 7, 10\}$ and is the only stable coalition with this set of parameters. As shown in Table 4, the world's emission level drops by 5% and the welfare rises by 0.9% compared to the non-cooperative equilibrium. Lazkano et al. (2014) show that with some heterogeneity in adaptation cost, it is possible to obtain a stable coalition larger than three members. They also find that the grand coalition can be sustained as the largest stable coalition. However, these results are sensitive to parameter values. Similar in our case, the coalition outcome is affected by parameter

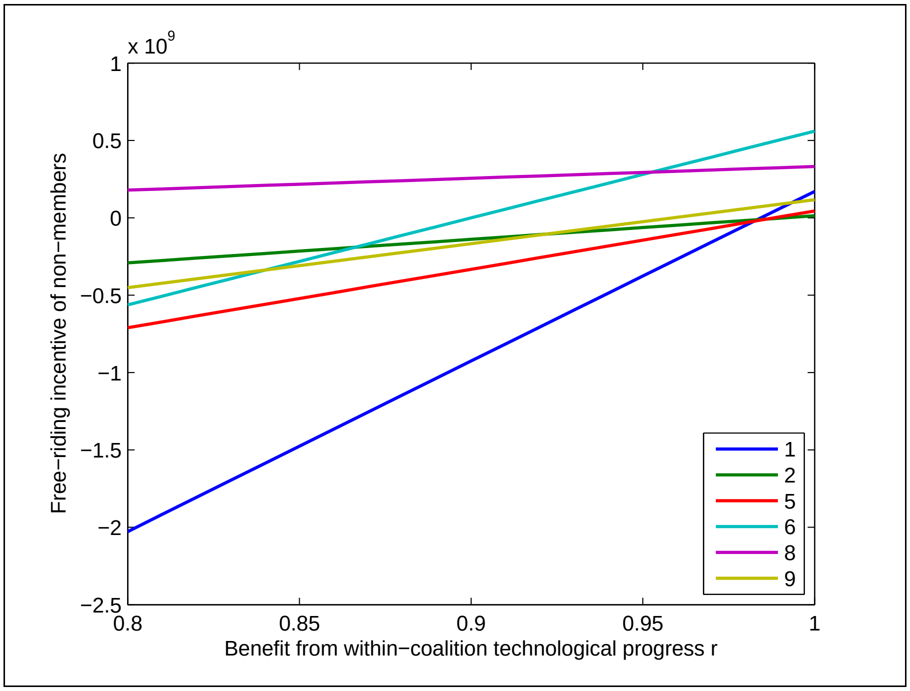


Figure 1: Free-riding Incentive and within-coalition technological progress: $\Gamma_i^O(r_i)$

choice. With heterogeneous benefits and damage and cost function, multiple equilibria may exist and large coalition are expected with some parameter set.

Next we explore the impact of technological progress of adaptation on the free-riding incentive of non-members. The existing coalition is $S = \{3, 4, 7, 10\}$. From (53), the function of free-riding incentive $\Gamma_i^O$ on $r_i$ can be depicted. Figure 1 illustrates $\Gamma_i^O(r_i)$ for $\forall i \in O = \{1, 2, 5, 6, 8, 9\}$, when $r \in [0.8, 1]$. All curves are positively sloped, and the steepness depends on each country's parameters. When $r_i = 1$ for all six countries, we have the prototype that S $=\{3, 4, 7, 10\}$, and the free-riding incentive $\Gamma_i^O(r_i) > 0$, $\forall i \in O$. As $r_i$ increases, the free-riding incentive keep decreasing, and finally $\Gamma_i^O(r_i) < 0$, which implies the country benefits from joining the coalition. Figure 1 shows that with $r = 0.9$, which is 10% decrease in net vulnerability when the country is inside the coalition, five countries are benefit from joining the coalition. The more the country benefits from the technological advancement within the coalition, the free-riding incentive is less. With some form of commitment by existing members, the coalition can be enlarged by providing R&D on adaptation within an IEA.

## 6. Conclusion

This paper investigates the impact of adaptation on a country's incentive to participate in emission-reducing International Environmental Agreements (IEAs) on climate change. We develop a framework where heterogeneity across countries is introduced with respect to the benefits and costs of both mitigation of emissions and adaptation to reduce the impact of climate change. We study the effect of an increase in the efficiency of adaptation on emissions and on countries' incentives to cooperate. The paper uses two coalition stability concepts and numerical simulations to look at the size of the stable coalition.

Our main results have implications for policies aimed at reducing countries' vulnerability to climate change, such as adaptation. Firstly, R&D in adaptation should be done collaboratively within an IEA since the benefit of technological progress in a member country is shared by all members.

Secondly, using coalition profitability and stability concepts we show a large coalition (especially the grand coalition) cannot be achieved if countries differ much in terms of vulnerability and benefit of emissions. Thus policies directed at reducing the gaps in vulnerability to climate-induced damages (e.g. the Cancun Adaptation Fund) and also with respect to abatement costs among countries may help form a larger IEA.

Thirdly, cooperation incentives are significantly enhanced by a coalition which diffuses technological progress on climate change adaptation among its members. Therefore IEAs on climate change mitigation can be enhanced by the negotiation of an R&D hub on adaptation technology by all members.

## References


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

Barrett, S., 1997. International environmental negotiations. Edward Elgar, Ch. Heterogeneous International Environmental Agreements.

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

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

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

Finus, M., 2000. Game Theory and International Environmental Co-operation: A Survey with an Application to the Kyoto-Protocol. Fondazione Eni Enrico Mattei.

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

Kousky, C., 2012. Informing climate adaptation: A review of the economic costs of natural disasters, their determinants, and risk reduction options. Resources for the Future Discussion Paper (12-28).

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

McGinty, M., 2007. International environmental agreements among asymmetric nations. Oxford Economic Papers 59 (1), 45–62.

Parry, M. L., 2007. Climate Change 2007: Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Fourth Assessment Report of the IPCC Intergovernmental Panel on Climate Change. Vol. 4. Cambridge University Press.

Pavlova, Y., De Zeeuw, A., 2013. Asymmetries in international environmental agreements. Environment and Development Economics 18 (01), 51–68.

Stern, N., 2007. The economics of climate change: the Stern review. Cambridge University Press.

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

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

Zehaie, F., November 2009. The Timing and Strategic Role of Self-Protection. Environmental & Resource Economics 44 (3), 337–350.

**APPENDIX:**

## Appendix A. Timing of Adaptation

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

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

### *Appendix A.1. The First Stage*

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

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

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

### *Appendix A.2. The Third Stage*

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

*Appendix A.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,

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

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

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

$$\tag{A.3}$$

Sum (A.2) over all non-signatories. The aggregate emissions of all non-signatories are given by the following:

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

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

*Appendix A.2.2. Signatories*

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

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

The first order condition is given by,

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

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

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

Sum (Appendix A.2.2) over all signatories to obtain the aggregate best response function, then combine with (A.4) to solve for the world emission level and individual emission level.

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

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

$$e_j^S(S,a) = \overline{e}_j - \frac{\sum_{k\in S} v_k}{\beta_j}E^N(S,a) + \frac{\sum_{k\in S}\theta_k a_k}{\beta_j} \tag{A.9}$$

Emission levels of all countries are affected by the adaptation levels chosen in the first stage. Specially, from (39), 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 is chosen after an IEA. Thus overall countries are less vulnerable to climate change and able to emit more. However, the individual emissions may rise or fall compared to those where adaptation is chosen after an IEA, depending on parameters and the given coalition.

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

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

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

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

$$de_j^S(S,a) = \frac{\partial e_j^S(S,a)}{\partial a_j}da_j + \sum_{k\neq j\in S}\frac{\partial e_j^S(S,a)}{\partial a_k}da_k + \sum_{i\in O}\frac{\partial e_j^S(S,a)}{\partial a_i}da_k.$$

The total effect of adaptation level rise is undetermined. If countries are homogeneous, every country's emission level increases given a higher adaptation level. However, if countries are heterogeneous, some countries may decrease emissions even its adaptation level is higher. The reason is that emission is chosen based on relative terms of vulnerability , not absolute value ((36) and (37)). If all countries increase adaptation levels, each country will be less vulnerable to climate change in absolute terms. However, a country may become more vulnerable compared to other countries, and have to cut more emissions.

As a result of undetermined emission changes, changes of profitability and cooperative incentives of signatories varies from country to country. If all countries are homogeneous, the welfare gain by joining an IEA (profitability) is decreasing in adaptation level. In this case, adaptation chosen prior to an IEA discourages the formation of the IEA. (proof can be added)

## Appendix B. Profitability

A basic prerequisite 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. Free-riding is the main problem preventing a large coalition being formed. In other words, internal and external stability conditions are sufficient but not necessary to profitability in most models used in the IEA literature. Therefore, only internal and external stability are extensively used as the definition of a stable coalition in literature of IEA and coalition theory. However, if there exists some pivotal countries such that an IEA on mitigation will either formed with the participation of these countries or not formed at all, a coalition should be formed based on profitability to pivotal countries.

In this section, we show that a coalition can only be achieved when members do not differ much from each other with respect to their net vulnerability. If a member's adaptation cost is very low (and/or its adaptation activities are very effective) compared to other members (so its vulnerability is low), the coalition is not necessarily profitable for the member. This result implies large gaps in adaptation cost and effectiveness may prevent forming a large coalition.

The profitability of a coalition for a member country j is defined as the gains from forming the coalition as compared to the non-cooperation equilibrium.

**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*

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

The profitability of a coalition is defined as the gains from forming the coalition as compared to the non-cooperation equilibrium. (B.1) can be divided into two parts: the first part is the change in benefit of emissions caused by forming the coalition; the second part is the change in the climate change cost (the damage from climate change plus the adaptation cost). The climate change cost will be reduced for every country after a coalition is formed. However, from Proposition 5, a member with relatively low vulnerability compared to other members needs to cut emissions, and the foregone benefit from emissions may far exceed the reduced climate change cost. Therefore with heterogeneous agents, satisfying the profitability condition is insurprisingly difficult.

**Proposition 8.** *With heterogeneous countries, 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 (B.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,

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

□

To address the impact of heterogeneity in adaptation on profitability, let us first assume countries are identical on the benefit side but heterogeneous in natural vulnerability and adaptation (hence vulnerability is heterogeneous). Suppose $\alpha_i = \alpha$, $\beta_i = \beta$, $\forall i \in N$. The vulnerability, $\Phi_i$, varies across countries because of heterogeneous $v_i$,$\theta_i$ and $c_i$. The condition that a coalition is profitable for country $i$ becomes,

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

where s is the size of the coalition $S$.

The right hand side (RHS): $\Phi \to 0, RHS \to 1$; $\Phi \to \infty, RHS \to \frac{1}{s^2}$. For a given world and a given coalition, the RHS is fixed at a value between $[\frac{1}{s^2}, 1]$.

The left hand side (LHS): $\Phi_j \to 0, LHS \to 0$; $\Phi_j \to \Phi_S, LHS \to 1$. The LHS is increasing in $\Phi_j$ since $\frac{dLHS}{d\Phi_j} > 0$ (the curvature depends on $\beta$ and $\Phi^S$: $\frac{d^2 LHS}{d\Phi_j^2} < 0$ iff $\beta > \Phi^S$). Thus the LHS is member specific, and the less vulnerable the member country is, the lower value the LHS is. As shown in Figure B.2, for those whose vulnerability is smaller than $\Phi^m$, according to Proposition 8, the coalition is not profitable for them. The further disperse the vulnerability is, the more likely that some member's vulnerability is smaller than $\Phi^m$. Thus large gap in adaptation cost and effectiveness may prevent a large coalition.

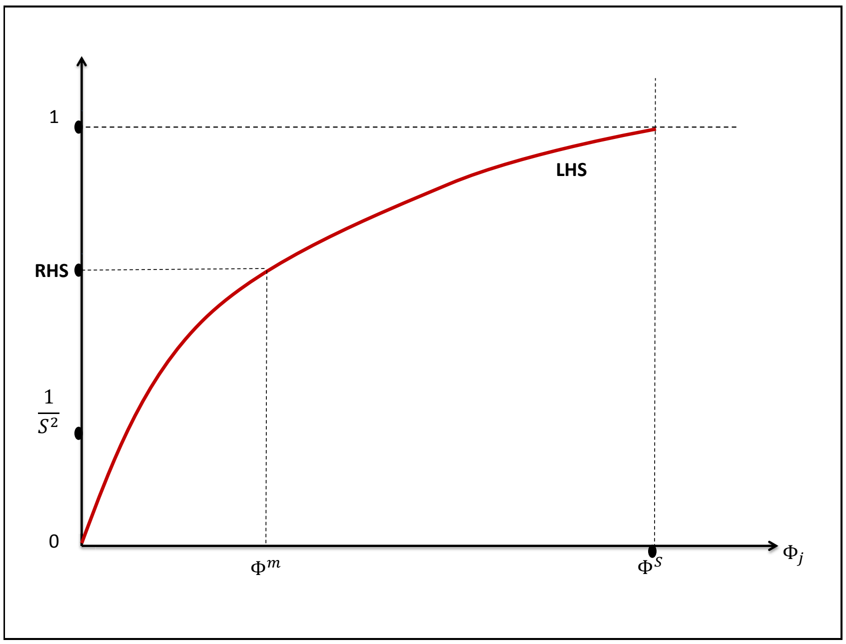


Figure B.2: Profitability for a member country

The welfare change in (B.1) can be divided into two parts: the first part is the change in benefit of emissions; the second part is the change in the climate change cost (the damage from climate change plus the adaptation cost). Since the global emission level falls as an IEA is established, the climate change cost falls for every country. However, the change in the benefit of emissions is not identical. With heterogeneous countries, the emission level of a signatory may rise or fall, depending on its vulnerability relative to other signatories (Lemma 5). If a signatory rises its emission level after the IEA is formed, the IEA must be profitable for it. This is stated in Lemma 9.

**Lemma 8.** *(Sufficient condition for profitability) If a member j's emission rises after the coalition is formed, the coalition is profitable for member j.*

*Proof.* (will be updated to the Latex file later) □

If a signatory's emission level falls after the IEA is formed, profitability depends on whether the reduced climate change cost is enough to compensate the lost in benefit from emissions. A detailed relationship between emissions change profitability can be obtained from Lemma 5 and Proposition 8. Table B.2 shows the relationship between net vulnerability, emission change and profitability.

| Type I | Type II | Type III |
|---|---|---|
| $\left(\frac{\Phi_j}{\Phi^S}\right)^2 < \frac{\Phi_j\Psi_j+\Phi_j}{\Phi^S\Psi_j^S+\Phi_j} < \left(\frac{1+\Psi}{1+\Psi^O+\Psi^S}\right)^2$ | $\left(\frac{\Phi_j}{\Phi^S}\right)^2 < \left(\frac{1+\Psi}{1+\Psi^O+\Psi^S}\right)^2 \leq \frac{\Phi_j\Psi_j+\Phi_j}{\Phi^S\Psi_j^S+\Phi_j}$ | $\left(\frac{1+\Psi}{1+\Psi^O+\Psi^S}\right)^2 \leq \left(\frac{\Phi_j}{\Phi^S}\right)^2 < \frac{\Phi_j\Psi_j+\Phi_j}{\Phi^S\Psi_j^S+\Phi_j}$ |
| $\Delta e_j < 0$ | $\Delta w_j < 0$ | $\Delta w_j \geq 0$ |
| $\Delta w_j \leq 0$ | $\Delta w_j > 0$ | $\Delta w_j > 0$ |
| $\Delta e_j = e_j^S - e_j$ | | |

Table B.2: Emissions and welfare change from non-cooperative to coalition equilibrium

Member countries can be categorized into three types based on their vulnerability. Type I has very low vulnerability (e.g. low adaptation cost and/or high effectiveness in adaptation), and have to reduce their emissions. The welfare will fall after joining the coalition for those members: they need reduce significant amount of emissions but benefit little from global emissions reduction. Type II countries are moderately vulnerable. They still have to reduce their emissions, but the welfare rises as the coalition formed. The reduced climate change cost is enough to compensate the loss from emission cut. Members with high vulnerability composite Type III. These countries afford higher emissions after joining the coalition, and suffer less damage. Thus the grand coalition is definitely profitable for Type III countries, as stated in Lemma 9. Thus a stable coalition can only have Type II and Type III countries. Type I countries cannot exist in a stable coalition since the coalition is not profitable for them.

If the coalition is the grand coalition, the three categories in Table B.2 can be applied to all countries. When countries are symmetric, they are all Type II countries. However, as heterogeneity increases, Type I and Type III countries will emerge. Thus the grand coalition is not likely to be formed in heterogeneous world.

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

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

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

From Lemma 6, 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 main context 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, large gaps in adaptation cost and effectiveness may prevent pivotal countries' participation in an IEA. 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 IEA on mitigation of climate change: reduce gaps in adaptation, especially among pivotal countries, may foster cooperation on mitigation of climate change.

*Appendix B.1. Profitability of the Grand Coalition*

In a homogeneous world where all countries are symmetric, the grand coalition without transfer is a Pareto improvement compared to the non-cooperative equilibrium. Moreover, Benchekroun et al. (2014) show that if number of countries is large enough, the welfare gain by forming the grand coalition increases in adaptation efficiency. As shown in the appendix, this is also true in our model: in a homogenous world, the grand coalition is profitable for every member. Profitability increases as net vulnerability falls (natural vulnerability falls and/or adaptation efficiency improves). The underlying reason is also given by Benchekroun et al. (2014). The key is that the cost of adaptation is convex in adaptation level. The profitability increases as the cost of adaptation saved by full cooperation increases.

If countries are asymmetric, the grand coalition is not profitable for all countries.

The aggregate welfare change is given by,

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

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

*Proof.*

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

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

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

For mean preserving $\Phi_i$ for n countries, the higher the variance of $\Phi_i$ the higher the $\Delta W$ is. Thus heterogeneity in adaptation increases the total 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 extreme they are( e.g. low $\phi_i$ with high $\beta_i$, high $\phi_i$ with low $\beta_i$), the more welfare gain after a grand coalition formed.