CentER

Discussion Paper

No. 2011-120

ADAPTATION EFFECTIVENESS AND FREE-RIDING INCENTIVES IN INTERNATIONAL ENVIRONMENTAL AGREEMENTS

By Hassan Benchekroun, Walid Marrouch,
Amrita Ray Chaudhuri

November, 2011

ISSN 0924-7815

TILBURG UNIVERSITY

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Hassan Benchekroun

Department of Economics, CIREQ, McGill University, 855 Sherbrooke Ouest, Montreal, QC, Canada, H3A-2T7. E-mail: hassan.benchekroun@mcgill.ca

Walid Marrouch*,‡

*Lebanese American University, School of Business, Department of Economics and Finance, Beirut, Lebanon, P.O. Box 13-5053 / F-15, New York Office 475 Riverside Drive, Suite 1846 New York, NY 10115-0065-USA, Email: walid.marrouch@lau.edu.lb

‡CIRANO (Center for Interuniversity Research and Analysis on Organizations), 2020, University St., 25th Floor, Montreal, QC, Canada, H3A 2A5

Amrita Ray Chaudhuri**,†

**Department of Economics, The University of Winnipeg, 515 Portage Avenue, Winnipeg, MB, Canada R3B 2E9; E-mail: a.raychaudhuri@uwinnipeg.ca

†CentER, TILEC, Tilburg University, Warandelaan 2, P.O. Box 90153, 5000 LE Tilburg, The Netherlands

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Abstract

While an international agreement over the reduction of greenhouse gases (GHGs) emissions proves to be elusive, there is a large and growing support for investment in developing more effective technologies to adapt to climate change. We show that an increase in effectiveness of adaptation will diminish the incentive of individual countries to free-ride on a global agreement over emissions. Moreover, we show that this positive effect of an increase in adaptation's effectiveness can also be accompanied by an increase in the gains from global cooperation over GHGs emissions.

JEL Classifications: Q54, Q59

Keywords: adaptation, climate change, international environmental agreements, trans-boundary pollution.

1 Introduction

Countries around the world are currently actively pursuing different means of tackling climate change. First, countries are attempting to mitigate emissions of greenhouse gases (GHGs) through international negotiations. Second, countries are undertaking adaptive measures to reduce the negative effects of climate change. The purpose of this paper is to investigate how the success of the first, in fact, depends on the latter. That is, how does adaptation affect individual countries' incentives to participate in international environmental agreements (IEAs) that limit GHGs emissions?

An individual country's emission of GHGs causes a negative externality on other countries by exacerbating climate change. A country choosing its emission level non-cooperatively (i.e. maximizing its individual welfare) would, therefore, over-pollute relative to the cooperative outcome (where each country maximizes joint welfare of all countries when choosing its emission level). Such behavior is referred to in the literature as "free-riding". International cooperation to reduce emissions has, thus, been a natural approach to alleviating climate change. However, some have argued that mitigation of greenhouse gas emissions cannot be the only policy response to climate change because due to the inertia of the climate system, even drastic emission reduction targets today would not be sufficient to slow down global climate change. This has resulted, in recent years, in countries increasingly undertaking adaptive measures to reduce the potential damage caused by climate change induced catastrophes such as floods. A recent article in The Economist, entitled "How to live with climate change: It won't be stopped, but its effects can be made less bad", captures the ongoing developments as follows: "... in the wake of the Copenhagen summit, there is a growing acceptance that the effort to avert serious climate change has run out of steam... Acceptance, however, does not mean inaction. Since the beginning of time, creatures have adapted to changes in their environment..."[1]

The term "adaptation", within this context, refers to adjustments in ecological, social or

[1] See The Economist print edition, November 27, 2010.

economic systems for reducing potential damage from climate change (Parry et al, 2007). It is loosely defined to cover a wide range of measures including the building of dykes or levees, which protects a coastal region repeatedly from an increasing onset of floods caused by climate change, the changing of crop types, facilitating early storm warning or disaster response and recovery cost.[2] Although each country has a private incentive to invest in the deployment of adaptive measures, there are a number of international and concerted initiatives aimed at improving the effectiveness of adaptation. The increased effectiveness may be in the form of improved disaster response measures: e.g., more efficient flood evacuation schemes.[3] It can also be in the form of more efficient proactive disaster management measures, including prevention measures such as early warning measures and developing methods for accurate risk assessments,[4] education campaigns, improvement of irrigation facilities in rural areas, more efficient flood prevention mechanisms ranging from shore protection (building levees) and terracing in rural areas[5] to adaptation of production, and sound urban planning.[6] Given the wide range of adaptation activities undertaken by countries, how can

[2] See http://www.ifrc.org/Global/Publications/disasters/defusing-disaster-en.pdf

[3] The World Bank has implemented post-disaster reconstruction projects in Argentina (e.g. The Argentina Flood Rehabilitation Project), Brazil (e.g. The Rio Flood Reconstruction Prevention Project), Mexico and India (e.g. Maharashtra Emergency Earthquake Rehabilitation Program). See Ranghieri (2010) for further details.

[4] Example of early warning programs include The Early Warning System for Hydrogeological Risk Monitoring and Forecast of Calabria Region (Italy) and the National Forecast Center (Cuba). The United Nations International Strategy for Disaster Reduction includes The Hyogo Framework for Action (HFA) monitoring tools for disaster risk reduction in the Europe region (http://www.preventionweb.net/english/hyogo/hfamonitoring/).

The EU has its own program MOVE: Methods for the Improvement of Vulnerability Assessment in Europe. The UFZ – CapHaz-Net, RiskMap & ConHaz: Natural Hazards Management Projects in Germany has similar objectives. There also exists the Capacity Building Program through DIANE-CM (Decentralised Integrated Analysis and Enhancement of Awareness through Collaborative Modelling and Management of Flood Risk) which aims to Integrate, Consolidate and Disseminate European Flood Risk Management Research.

[5] Examples include proactive projects such as Coastal environmental preservation - mangrove planting: Vietnam Red Cross, Focus on response preparedness: Bangladesh Red Crescent Society and FREEMAN: Flood REsilience Enhancement and MANagement: a pilot study in Flanders, Germany and Italy.

[6] At the Mayors' Summit in Copenhagen (December 2009), the Mayors' Task Force on Urban Poverty and Climate Change was formed and is actively helping cities like Dar es Salaam, Jakarta, Mexico City and Sao Paulo (see Ranghieri, 2010). National and regional governments also have set up several institutes to prevent disasters such as the All India Disaster Mitigation Institute, and the ENSURE Program of the EU for enhancing resilience of communities and territories facing natural hazards.

the "effectiveness" of adaptation be measured? The World Resources Institute has proposed the "Bellagio framework for adaptation assessment and prioritization" for this purpose.[7] It is a standardized and comprehensive measure of adaptation effectiveness that takes into account planning, management and services delivery functions of the system of adaptation of a country. These criteria include how broadly the system is applicable, how flexible it is to accommodate national circumstances, how straightforward it is to implement, its user-friendliness and compatibility with other tools, frameworks, and decision criteria. Based on these criteria, countries may be ranked on the effectiveness of their adaptation efforts.

This paper asks whether an increase in the effectiveness of such adaptive measures reduces countries' free-riding incentives and increases the likelihood of sustaining a self-enforcing international environmental agreement over emissions.

This question gains importance in light of the persistent failure of countries to reach binding commitments on emission targets, as embodied at the UN Climate Conferences held in Kyoto in 1997 and Copenhagen in 2009, and the billions of dollars that governments are setting aside for developing more effective adaptive measures to safeguard against imminent damage from climate change. Since 1980, the World Bank has approved more than 500 operations related to disaster management, amounting to more than US$40 billion. Estimates provided by international organizations of financial resources needed in developing countries for adaptation include: $10 to $40 billion annually (World Bank, 2007), $50 billion annually (Oxfam International, 2007), $86 billion annually by 2015 (UNDP, 2007), $46 to $171 billion annually by 2030 (UNFCCC, 2007). Moreover, there exist several adaptation funds run by the UNFCCC, World Bank and European Commission that have already contributed in the millions towards adaptation.[8]

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[7] This document is available at http://pdf.wri.org/working_papers/bellagio_framework_for_adaptation.pdf

[8] According to Le Goulven (2008), existing adaptation funds inlcude the following. The UNFCCC pledged $50 million through the SPA (Strategic Priority "Piloting an Operational Approach to Adaptation") in 2001 of which $28 million had been committed and $14.8 million disbursed by 2008. The UNFCCC pledged $165 million through the LDCF (Least Developed Countries Fund) in 2001 of which $59 million had been committed and $9.8 million spent by 2008. The UNFCCC pledged $65 million through the SCCF (Special Climate Change Fund) in 2001 of which $9 million had been committed and $1.4 million spent by 2008.

The existing literature on adaptation can be broadly categorized into two streams. The first provides a description of the trade-off facing countries when deciding how to allocate resources between mitigating GHG emissions and adapting to climate change (see for example, Auerswald, Konrad and Thum, 2011; Buob and Stephan, 2011; Ingham, Ma, and Ulph, 2005; Tol, 2005). The second stream explicitly incorporates adaptation in integrated assessment models to analyze the interaction between mitigation and adaptation (see for example Bosello, Carraro and de Cian, 2011; De Bruin, Dellink, and Tol, 2009). Other integrated assessment models such as RICE (Nordhaus and Yang, 1996) implicitly capture adaptation by incorporating the costs of adaptation in the regional damage function. For a recent survey of the literature on the economics of adaptation, please refer to Agrawala et al (2011). But none of these papers allow for coalition formation amongst the countries and therefore, do not analyze the impact of adaptation on the incentives to participate in international environmental agreements.

This paper sets up a game theoretic framework, which incorporates both adaptation and participation in a global agreement on emission reduction as strategies available to individual countries dealing with climate change. We assume that the effect of adaptation is local whereas the damage caused by emissions is global, in line with real examples of adaptive measures currently being undertaken by different countries.

We show that more effective adaptation reduces the incentive of a coalition member to free-ride and leave the grand coalition, i.e., the coalition that includes all countries. This result is shown to hold for all coalition sizes except for a coalition of size two.[9] Moreover, we show that this positive impact of increased effectiveness of adaptation can be accompanied by an increase in the gains from cooperation over the control of emissions. The incentive of a coalition member to leave a coalition corresponds to the criterion of internal stability of a

Also in 2001, the Kyoto Protocol set up an Adaptation Fund which pledged $160-950 million by 2012. In 2008, the World Bank's Pilot Program for Climate Resilience under the Strategic Climate Fund pledged $500 million. In 2007, the European Commission pledged EUR 50 million under the Global Climate Change Alliance and the German Ministry of the Environment pledged EUR 60 million.

[9] In the case of a coalition of two members, the impact of a more effective adaptation on free riding incentives of an individual country to abandon the coalition is ambiguous.

coalition, used in D'Aspremont et al. (1983) in a cartel formation game and extensively used in the IEA literature (for a comprehensive analytical treatment of the IEA formation game see for example, Barrett, 1994; Diamantoudi and Sartzetakis, 2006; Rubio and Ulph, 2006).[10] This literature examines stable coalition sizes that are internally and externally stable, that is, coalitions where no insider has an incentive to leave a coalition and no outsider wishes to join the coalition. In general, it is shown that stable coalitions are small and that large coalitions are stable only when the gains from a large coalition are small. Our work is motivated by the question of whether a more effective adaptation can help achieve large coalitions. This is why our primary focus is on the analysis of the grand coalition and its internal stability. An important result that we obtain is that a more effective adaptation can simultaneously reduce incentives of a coalition member to leave the grand coalition *and* increase the gains from cooperation over the control of emissions. This is a rather optimistic result about the impact of having more effective adaptation, especially when compared to the existing literature, which concludes that incentives to free-ride are small (or non-existent) only when the gains from cooperation are negligible (see for example, Barrett, 1994; de Zeeuw, 2008). Thus, adaptation, rather than merely being a substitute for the failed attempts at negotiating an IEA, as suggested currently in The Economist (November 2010) and other media outlets, may actually foster international cooperation on mitigating emissions of GHGs.[11]

A recent strand of the IEA literature has analyzed the role that breakthrough technologies can play in dealing with climate change. Barrett (2006) has shown that unless technology

[10]A recent strand of the literature examines the 'farsighted' stability criterion that allows for a more sophisticated behavior of players. In deciding whether to join or leave a coalition a player considers the implication of her decision on other players's decision to leave or stay in a coalition. (see e.g. Diamantoudi and Sartzetakis, 2002; de Zeeuw, 2008; Osmani and Tol, 2009). Another approach to model the dynamic aspect of coalition formation has been to allow for an evolutionary process to determine which countries join and/or leave the coaliton over time (see e.g. Breton, Sbragia and Zaccour, 2010).

[11]Indeed, it seems that countries are realizing the importance of including adaptation in international negotiations, given the new "Cancun Adaptation Fund" that has been established at the COP16 Meetings held at Cancun in December 2010. (UNFCCC Press Release, 11 December 2011, http://unfccc.int/files/press/news_room/press_releases_and_advisories/application/pdf/pr_20101211_cop16_closing.pdf)

adoption involves increasing returns, a treaty on the development and adoption of breakthrough technologies will suffer from the same strong free-riding incentives that prevail in a treaty over the abatement of emissions. This pessimistic result can be reversed if, for example, the cost of adoption of a breakthrough technology can be decreasing with the level of R&D (see Hoel and de Zeeuw, 2010) or if global investment in R&D is not a perfect public good, and there are imperfect and asymmetric degrees of R&D spillovers between coalition members and non-members (see El-Sayed and Rubio, 2011). These papers focus on international cooperation on R&D and/or development and adoption of 'breakthrough technologies'. In this paper, we abstract from the development and the adoption phase of the technology and our focus is on international cooperation on emissions. We consider an exogenous technological innovation that is available and adopted by all countries (whether signatories of an IEA or not) and that reduce the cost to adapt to climate change, i.e., improves the effectiveness of the adaptation efforts to reduce the harm caused by climate change[12]. In our model, each country chooses a level of emissions and a level of adaptation effort. We assess how such increase in adaptation effectiveness impacts the incentive of a country to participate in an IEA over emissions. As in Tulkens and van Steenberghe (2009) we explicitly include adaptation costs in the total environmental cost function and characterize the cost-minimizing balance between 'mitigation, adaptation and suffering'. However, they do not consider the issue of the incentive to participate in an IEA.

We proceed as follows. Section 2 presents the model. Section 3 characterizes the equilibrium of the model. Section 4 presents the effects of adaptation on the free-riding incentives. Section 5 provides a robustness check of the main results under alternative formulations. Section 6 concludes.

[12] The increase in 'effectiveness' may include an 'incremental' improvement of an existing adaptation technique or measure.

2 The Model

Let $N = \{1, ..., n\}$ denote the set of all countries, with $n \geq 3$. A by-product of the consumption and production activities of each country is the emission of a global pollutant. Country i emits $e_i \geq 0$ units of the pollutant with the aggregate emissions denoted by $E = \sum_{i=1}^{n} e_i$. Each country is also allowed to spend resources on adapting to the damage from pollution. The level of adaptation chosen by country i is given by a_i, and, in line with reality, is assumed to reduce the effects of pollution for country i only.

Let $B(e_i)$ represent the benefit to country i from its own emissions as follows:

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

with $\alpha > 0$ and $\beta > 0$. We have $B'(e_i) > 0$ and $B''(e_i) < 0$ for all $e_i < \bar{e} \equiv \frac{\alpha}{\beta}$.

Let $D(E, a_i)$ represent the damage to country i from pollution as follows:

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

with $\omega > 0$ and $\theta \geq 0$.[13] The damage function, as given by (2), captures two features pertaining to climate change. First, the damage is convex in global emissions. Second, the marginal damage from emissions is decreasing in the level of adaptation. From (2), the marginal damage from emissions is given by $\frac{\partial D(E,a_i)}{\partial E} = \omega E - \theta a_i$, which is decreasing in θ and positive for $a_i < \bar{a} \equiv \frac{\omega E}{\theta}$. We also have that $\frac{\partial D(E,a_i)}{\partial a_i} = -\theta E < 0$, that is, pollution damage faced by country i is decreasing in the level of country i's adaptation. From (2), it also follows that $\frac{\partial^2 D(E,a_i)}{\partial E \partial a_i} = \frac{\partial^2 D(E,a_i)}{\partial a_i \partial E} = -\theta$.[14]

[13]The tradeoff, in our damage function, between the levels of emission, E, and adaptation, a_i, is similar to that in the literature on multiple pollutants in the context of climate change, where some pollutants such as CO_2 increase global warming and others such as SO_2 have a cooling effect (see, for example, Legras and Zaccour, 2011).

[14]In our model, the net cost of adaptation is given by the cost function, $C(a_i)$, less the benefit from adaptation in terms of reduced damage, $\theta a_i E$. Thus, our net cost of adaptation is decreasing in the global emission level, E, for all $\theta > 0$. This is analogous to the way in which cost of R&D has been modeled by Hoel and de Zeeuw (2010) within the context of international cooperation on the development of clean

Henceforth in the paper, we distinguish between the "level" of adaptation, as denoted by a_i, and the "effectiveness" of adaptation, as denoted by θ. Here a high (low) θ refers to those adaptive measures that lead to a large (small) reduction in the marginal damage of emissions. Examples of more effective adaptation measures being implemented include the following. Consider fishing villages in Pondicherry (India). A few years ago a computer linked to the internet has been set up in these villages. This provides villagers access to the latest weather reports, tailored to match the villages' own stretch of coast. This is then broadcast to the village over a loudspeaker system. Because of this system villagers have reported that the average number of fishermen lost at sea annually has dropped from about six to zero.[15] Another example of increased effectiveness of adaptive measure are the levees in New Orleans. According to the US Department of Homeland Security, the U.S. Army Corps of Engineers (Corps) repaired and restored 220 miles of floodwalls and levees since September 2005, such that the New Orleans hurricane protection system is more effective than it was when Katrina hit. Levees and flood walls have been armored to protect against erosion from possible overtopping in several areas, and pumping stations are being storm proofed. Floodgates have been added at the outfall canals to protect against storm surge and a tree cutting program on existing levees for protection is ongoing. The Corps continues to construct stronger protection for New Orleans by engineering, constructing and improving storm and flood protection infrastructure to a 100-year protection level. This work includes higher levees, stronger floodwalls and greater interior drainage capacity.[16]

Let $C(a_i)$ represent the cost of adaptation of country i as follows:

$$C(a_i) \equiv \frac{c}{2} {a_i}^2 \tag{3}$$

where $c > 0$. That is, the cost of adaptation is strictly convex and increasing in a_i.

Our modeling of adaptation in (2) and (3) is in line with Tulkens and van Steenberghe

technologies, where the cost of R&D is decreasing in the level of R&D.

[15] For further details, see http://news.bbc.co.uk/2/hi/programmes/from_our_own_correspondent/2932758.stm

[16] See http://www.dhs.gov/xfoia/archives/gc_1157649340100.shtm for further details.

(2009) who consider the full cost minimization problem faced by countries in the presence of both mitigation and adaptation.

Social welfare of each country is assumed to be given by the following:

$$w(E, a_i) \equiv B(e_i) - D(E, a_i) - C(a_i) \tag{4}$$

where $B(e_i)$, $D(E, a_i)$ and $C(a_i)$ are given by (1), (2), and (3) respectively.

In the non-cooperative case, the objective of each country's government is to simultaneously choose e_i and a_i that maximize its own welfare taking as given the emissions and adaptation strategies of the other countries. That is,

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

where $w(E, a_i)$ is given by (4).

In the fully cooperative case, the countries simultaneously choose e_i and a_i that maximize joint welfare. That is,

$$\max_{e_i, a_i} \sum_{i=1}^{n} w(E, a_i) \tag{6}$$

Assumption 1: *We have that* $\omega > \underline{\omega} \equiv \frac{\theta^2}{c}$.

Assumption 1 ensures that, in the non-cooperative equilibrium and the fully cooperative equilibrium, the marginal benefit to each country from emissions is non-negative, that is, $e_i < \bar{e}$ such that $B'(e_i) \geq 0$, and that $a_i < \bar{a}$ such that $\frac{\partial D(E, a_i)}{\partial E} > 0$.

3 The equilibrium

Consider the scenario where the countries decide to form an international environmental agreement. More specifically, let $S \subset N$ countries sign an agreement while $N \backslash S$ do not.

We denote the size of coalition S by s and the total emission generated by the coalition by $E_s = se_s$, where e_s is the emission of a representative signatory. Similarly, $E_{ns} = (n-s)e_{ns}$ is the total emissions generated by the complement of the coalition with e_{ns} being the emissions generated by a representative non-signatory. The sum of the emissions of the signatory and non-signatory countries, that is global emissions, is given by $E = E_s + E_{ns}$.

We assume that the non-signatories and signatories simultaneously choose their best response functions. The coalition acts as a single player in the game once a coalition has been formed.

The non-signatories' maximization problem is given by (5) which results in the following best response function:

$$e_i = \frac{\alpha - \left(\omega - \frac{\theta^2}{c}\right)\left(\sum_{j \neq i}^{n-s} e_j + \sum_{k}^{s} e_k\right)}{\beta + \omega - \frac{\theta^2}{c}}, \quad i \in N \backslash S, k \in S \tag{7}$$

The signatories' maximization problem is given by:

$$\max_{e_i, a_i} \sum\nolimits_{i \in S} w\left(E, a_i\right) \tag{8}$$

which results in the following best response function:

$$e_i = \frac{\alpha - s\left(\omega - \frac{\theta^2}{c}\right)\left(\sum_{j}^{n-s} e_j + \sum_{k \neq i}^{s} e_k\right)}{\beta + s\left(\omega - \frac{\theta^2}{c}\right)}, \quad i \in S \text{ and } k \in S \tag{9}$$

For all countries, non-signatories and signatories, the adaptation strategies are given by

$$a_i = \frac{\theta E}{c} \tag{10}$$

which implies that each country's adaptation level increases in total emissions.

By symmetry, the best response functions can be written as:

$$e_{ns}\left(e_s\right)=\frac{\alpha-\left(\omega-\frac{\theta^2}{c}\right)se_s}{\beta+(n-s)\left(\omega-\frac{\theta^2}{c}\right)} \tag{11}$$

$$e_s\left(e_{ns}\right)=\frac{\alpha-s\left(\omega-\frac{\theta^2}{c}\right)(n-s)\,e_{ns}}{\beta+s^2\left(\omega-\frac{\theta^2}{c}\right)} \tag{12}$$

The equilibrium emission levels are given by:

$$e_{ns}^*=\frac{\beta+s\,(s-1)\left(\omega-\frac{\theta^2}{c}\right)}{\beta+(n+s\,(s-1))\left(\omega-\frac{\theta^2}{c}\right)}\frac{\alpha}{\beta}<\bar{e} \tag{13}$$

$$e_s^*=\frac{\beta-(n-s)\,(s-1)\left(\omega-\frac{\theta^2}{c}\right)}{\beta+(n+s\,(s-1))\left(\omega-\frac{\theta^2}{c}\right)}\frac{\alpha}{\beta}<\bar{e} \tag{14}$$

We note that $e_{ns}^*>0$ for all $\theta\geq 0$.

Assumption 2: *We have that* $\omega<\bar{\omega}\equiv\underline{\omega}+\frac{\beta}{(n-s)(s-1)}$.

Assumption 2 ensures that $e_s^*>0$, as shown by (14).

The global emission level is given by:

$$E^*=\frac{n\alpha}{\beta+(n+s\,(s-1))\left(\omega-\frac{\theta^2}{c}\right)} \tag{15}$$

We note that, under Assumption 1, E^* is always positive.

The equilibrium adaptation levels are given by:

$$a_s^*=a_{ns}^*=\frac{\theta}{c}E^* \tag{16}$$

where E^* is given by (15). Notice that in equilibrium, the non-signatory and signatory countries each choose the same level of adaptation, which is less than $\bar{a}$ under Assumption 1. This is consistent with the fact that the effect of adaptation is purely local. Thus, the equilibrium level is the same for each country, regardless of whether the country is maximizing its individual welfare or the joint welfare of all signatories.

The equilibrium welfare levels of each signatory and non-signatory are reported in the Appendix A.

4 Free-riding and more effective adaptation

Within our context, the incentive of a country to participate in a coalition of size s is given by:

$$\begin{aligned}\Phi(s) &= w_s^*(s) - w_{ns}^*(s-1) \qquad (17)\\ &= \frac{n^2\alpha^2\left(\omega-\frac{\theta^2}{c}\right)^2(s-1)\Psi}{2\beta\left(\left(\beta+(n-s+s^2)\left(\omega-\frac{\theta^2}{c}\right)\right)\left(\beta+\left(\omega-\frac{\theta^2}{c}\right)(-3s+n+s^2+2)\right)\right)^2}\end{aligned}$$

where

$$\begin{aligned}\Psi \equiv\; & -\left(n-3s+s^2\right)\left(n+s+ns-2s^2+s^3\right)\left(\omega-\frac{\theta^2}{c}\right)^2 \\ & -\beta^2(s-3)-2\beta\left(\omega-\frac{\theta^2}{c}\right)\left(-n+3s+ns-4s^2+s^3-2\right)\end{aligned}$$

Alternatively, Φ can be interpreted as the incentive of an individual country, member of a coalition of size s, to free-ride and leave that coalition. In this section, we focus on the incentive of an individual country to free-ride and leave the grand coalition (i.e. $s = n$) and determine how the presence of adaptation affects this free-riding incentive. Note that Assumption 2 is always satisfied when $s = n$. We postpone the analysis of cases where $s < n$, to the following section.

We now study the impact of a change in θ on $\Phi(n)$, for a given ω. We note that the larger is Φ, the smaller the incentive of a coalition member to free-ride and leave the coalition. In the following analysis, it is useful to let $X \equiv \left(\omega - \frac{\theta^2}{c}\right)$. Note that from Assumption 1 we have $X > 0$.

Proposition 1: *The incentive of a coalition member to free-ride and leave the grand coalition, i.e., the IEA that includes all countries, decreases when adaptation effectiveness (i.e., θ) increases.*

Proof: We have

$$\frac{\partial (\Phi (n))}{\partial X} = \frac{(z_3 X^3 + z_2 X^2 + z_1 X + z_0)(1-n) X n^2 \alpha^2}{(\beta + Xn^2)^3 (2X + Xn + \beta + Xn(n-3))^3}$$

where z_1, z_2 and z_3, after algebraic manipulation, can be written as follows:

$$z_1 = 3(n(n-1)(n-2)-2)\beta^2 \tag{18}$$

$$z_2 = (n(n-2)(3n(n(n-1)+2)-4)-4)\beta \tag{19}$$

$$z_3 = n^2(n(n(n(n(n-3)+6)-10)+8)-4). \tag{20}$$

From $(18)-(20)$, it can be shown that z_1, z_2 and z_3 are all positive for $n \geq 3$ and therefore

$$\frac{\partial (\Phi (n))}{\partial X} < 0.$$

This, together with the fact that X is decreasing in θ, yields Proposition 1.■

Why does more effective adaptation reduce free-riding incentives? From (7) and (9), it follows that the more effective is adaptation at reducing marginal damage from emissions, the flatter the best response function of each country in terms of emissions. This reduces the level of global emissions in the non-cooperative equilibrium, making it less costly to cooperate on emission strategies. The best response functions are flatter because, when other countries increase emissions, each individual country may, instead of reducing its own emissions, decrease its own damage by increasing adaptation. This explains why the higher the effectiveness of adaptation the lower the free-riding incentives of individual countries in this transboundary pollution game.

Next, we study how the aggregate gains from cooperation change with θ. Let G denote the gains from forming a coalition of size s as compared to the non-cooperative equilibrium. That is,

$$\begin{aligned} G &\equiv sw_s^* + (n-s)\,w_{ns}^* - n\,(w_{ns}^*|_{s=0}) \\ &= \frac{\Gamma\,(s-1)\,X^2 n^2 s\alpha^2}{2\,(\beta + (n-s+s^2)\,X)^2\,(\beta+nX)^2\,\beta} \end{aligned} \tag{21}$$

with $\Gamma = n\,(s-1)\,(s-n)\,X^2 + \beta n\,(2n-3s+s^2)\,X - \beta^2\,(s-2n+1)$.

In the case of the grand coalition $s = n$ we have the following.

Proposition 2: *There exists $\bar{n}$ such that for $n > \bar{n}$, we have that a marginal increase of adaptation effectiveness results in an increase of the welfare gains from forming the grand coalition (i.e., of size $s = n$) as compared to the non-cooperative equilibrium.*

Proof: See Appendix B.

The value of $\bar{n}$ depends on β, ω and c and may well be smaller than 3. This happens for example when β is small enough. More precisely, we have the following corollary.

Corollary: *Assume $\beta \in \left(0, \bar{\beta}\right)$ where $\bar{\beta} \equiv \frac{6\left(\omega - \frac{\theta^2}{c}\right)}{\left(\sqrt{\frac{11}{3}}+1\right)}$, then for all $n \geq 3$, a marginal increase in adaptation effectiveness results in an increase in the gains from the formation of the grand coalition.*

Proof: See Appendix C.

Propositions 1 and 2 give a rather optimistic message. An increase in adaptation effectiveness can result in a decrease of individual countries' incentive to free-ride on a global agreement *and* an increase of the gains from a global agreement. In the existing literature on IEA formation, it has been shown that incentives to free-ride are small (or non-existent) only when the gains from cooperation are negligible.[17]

Why do the gains from cooperation increase with the effectiveness of adaptation? Since

[17] See for example Barrett (1994) who highlights the trade-off between having large stable IEAs with little aggregate welfare improvements upon the non-cooperative outcome versus having small stable IEAs with large improvements upon the non-cooperative outcome.

the cost of adaptation is convex in the level of adaptation, failing to reach a cooperative equilibrium on emissions increases the cost to each individual country through this channel. This explains why the gains from cooperation increase as more adaptation is undertaken. This, together with the fact that more adaptation is undertaken in equilibrium the more effective is adaptation, explains Proposition 2.

5 Discussion

The main results of this paper, as given by Propositions 1 and 2, were shown for the grand coalition. In this section, we examine the case of a coalition of countries of size $s < n$. It is possible to show that Proposition 1 extends to the case $s > 2$. That is,

$$\frac{\partial \left(\Phi \left(s\right)\right)}{\partial \theta} > 0$$

for all $n \geq 3$ and $s \in \{3, .., n\}$. The approach to prove this result is similar to the case where $s = n$. To economize on space, we omit the details of the proof. The case where $s = 2$ needs a special treatment which is provided later. For now, we proceed with analyzing the gains from cooperation for $n \geq 3$ and $s \in \{3, .., n\}$.

The algebraic expressions for the impact of a change in adaptation effectiveness on the gains from cooperation are too cumbersome to derive analytical results. We, therefore, proceed by fixing the number of countries n to 10 and consider coalitions of size $s \in \{3, .., 9\}$.

For $n = 10$, it can be shown that the sign of $\frac{\partial G}{\partial \theta}$ is the same as the sign of the expression P where

$$\begin{aligned} P\left(s, X\right) &= -\frac{X^3}{\beta^3}\left(80s^4 - 160s^3 + 2480s^2 - 400s + 16\,000\right) \\ &\quad + \frac{X^2}{\beta^2}\left(10s^4 - 20s^3 + 70s^2 - 660s + 600\right) \\ &\quad + \frac{X}{\beta}\left(30s^2 - 90s + 600\right) + 38 - 2s \end{aligned}$$

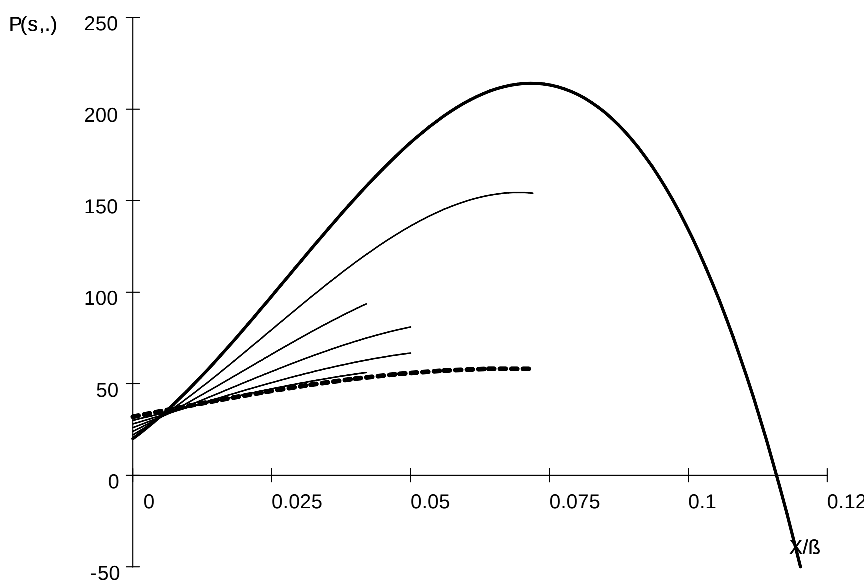
Moreover, for Assumption 2 to hold, we must have $X < \bar{X} \equiv \frac{\beta}{(n-s)(s-1)}$ which in the case of $n = 10$ becomes $X < \frac{\beta}{(10-s)(s-1)}$. Table 1 provides the value of the upper bound of $\frac{X}{\beta}$, $\frac{\bar{X}}{\beta}$, for different values of s between 3 and 9.

Table 1: Upper bound of X as s varies

s	3	4	5	6	7	8	9
$\frac{\bar{X}}{\beta}$	$\frac{1}{14}$	$\frac{1}{24}$	$\frac{1}{20}$	$\frac{1}{20}$	$\frac{1}{24}$	$\frac{1}{14}$	$\frac{1}{8}$

In Figure 1, we plot $P(s,.)$ for $s \in \{3,..9\}$ with $X < \bar{X}$.

Figure 1: $P(s,.)$ as a function of $\dfrac{X}{\beta}$



The curve with the highest maximum corresponds to the plot of $P(9,X)$ over its domain $\left[0, \frac{1}{8}\right]$. The dashed curve corresponds to the plot of $P(3,X)$ over its domain $\left[0, \frac{1}{14}\right]$. The other curves correspond to the cases of $s = 4,..,8$.

We can observe that for all $s \in \{3,..,8\}$ we have $P(s,X) > 0$ for all X in the domain $\left[0, \bar{X}\right]$ and therefore, $\frac{\partial G}{\partial \theta} > 0$ that is an increase in adaptation effectiveness increases the gains from the formation of a coalition. This is also true for $s = 9$ when X does not exceed a certain threshold. A similar conclusion can be reached if we use other values of n instead of 10.

For completeness, we provide the results for a coalition member to leave a coalition of size $s = 2$.

Proposition 3: *For $s = 2$, there exists $\hat{\theta}$ such that*

(i) *for $\theta < \hat{\theta}$, the incentive to free-ride decreases as θ increases, that is,* $\frac{\partial \Phi(2)}{\partial \theta} > 0$.

(ii) *for $\theta > \hat{\theta}$, there exists $\hat{n} > 2$ such that $\frac{\partial \Phi(2)}{\partial \theta} < (>) 0$ for all $n < (>) \hat{n}$.*

Proof: See Appendix D.

For $s = 2$, the effect of increasing the effectiveness of adaptation depends on the initial level of θ. A marginal increase in the effectiveness of adaptive measures reduces the incentive to free-ride when adaptive measures are relatively ineffective ($\theta < \hat{\theta}$) or when the number of countries is large enough ($n > \hat{n}$).

The approach to determine the sign of $\frac{\partial G}{\partial \theta}$ for the case $s \in \{3, .., 9\}$ can be repeated for $s = 2$ and it yields $\frac{\partial G}{\partial \theta} > 0$ for $s = 2$.

6 Concluding Remarks

According to The Economist (27 November 2010), "the green pressure groups and politicians who have driven the debate on climate change have often been loth to see attention paid to adaptation, on the ground that the more people thought about it, the less motivated they would be to push ahead with emissions reduction." We show that an increase in the effectiveness of adaptation may result in a reduction of individual countries' incentives to free-ride on an IEA and an increase in the gains from forming the IEA. Therefore, the concern of environmentalists with adaptation is partially mitigated.

The incentives to free-ride on an IEA may decrease in the presence of adaptation because we show that the more effective is adaptation at reducing marginal damage from emissions, the flatter the best response functions of each country in terms of emissions. This reduces the levels of global emissions in the non-cooperative equilibrium, making it less costly to cooperate on emission strategies. This is because, when other countries increase emissions, each individual country may, instead of reducing its own emissions, decrease its own damage by increasing adaptation. However, since the cost of adaptation is convex in the level of adaptation, failing to reach a cooperative equilibrium on emissions increases the cost to each individual country through this channel. This explains why the gains from cooperation increase as more adaptation is undertaken.

In the current paper, we have analyzed the case of identical countries. In reality different regions are vulnerable to different degrees to the effects of climate change and will therefore undertake different amounts/types of adaptation, for example, Southern Europe is expected to be affected more than Northern Europe by climate change. Therefore, allowing for asymmetries across countries would be a relevant extension.

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Appendices

Appendix A

The welfare of each signatory country, at the equilibrium, is given by:

$$\begin{aligned} w_s^* &\equiv e_s^*\left(\alpha-\beta\frac{e_s^*}{2}\right)-\left(\frac{\omega}{2}\left(E^*\right)^2-\theta a_s^* E^*\right)-\frac{c}{2}a_s^{*2} \\ &= \frac{\alpha^2}{2}\frac{\left(\omega-\frac{\theta^2}{c}\right)^2(s-1)(n-s)(s(1-s-n)-n)+\beta^2-\beta(n(n-2)-2s(s-1))\left(\omega-\frac{\theta^2}{c}\right)}{\beta\left(\beta+(n-s+s^2)\left(\omega-\frac{\theta^2}{c}\right)\right)^2} \end{aligned} \tag{22}$$

The welfare of each non-signatory country, at the equilibrium, is given by:

$$\begin{aligned} w_{ns}^* &\equiv e_{ns}^*\left(\alpha-\beta\frac{e_{ns}^*}{2}\right)-\left(\frac{\omega}{2}\left(E^*\right)^2-\theta a_{ns}^* E^*\right)-\frac{c}{2}a_{ns}^{*2} \\ &= \frac{\alpha^2}{2}\frac{\left(\omega-\frac{\theta^2}{c}\right)^2 s(s-1)(2n-s+s^2)+\beta^2-\beta(n(n-2)-2s(s-1))\left(\omega-\frac{\theta^2}{c}\right)}{\beta\left(\beta+(n-s+s^2)\left(\omega-\frac{\theta^2}{c}\right)\right)^2} \end{aligned} \tag{23}$$

Appendix B: proof of Proposition 2

For $s=n$, we have:

$$G=\frac{(n-1)^2 n^3\alpha^2X^2}{2(\beta+n^2X)(\beta+nX)^2}$$

We have that

$$\frac{\partial G}{\partial X}=\frac{1}{2}\frac{Xn^3\alpha^2(n-1)^2n^3}{(Xn^2+\beta)^2(\beta+Xn)^3}(X-X_1)(X_2-X)$$

where $X_1=-\frac{1}{2n}\beta\left(\sqrt{\frac{n+8}{n}}-1\right)<0$ and $X_2=\frac{1}{2n}\beta\left(\sqrt{\frac{n+8}{n}}+1\right)>0.$ Therefore, we have the following:

$$\frac{\partial G}{\partial X}>0 \text{ iff } X<X_2$$

Since $X\equiv\left(\omega-\frac{\theta^2}{c}\right)$ we have:

(i) $X<X_2$ iff $\omega-\frac{\theta^2}{c}<\frac{1}{2n}\beta\left(\sqrt{\frac{n+8}{n}}+1\right)$

(ii) $\frac{\partial G}{\partial\theta}=\frac{\partial G}{\partial X}\frac{\partial X}{\partial\theta}=-2\frac{\theta}{c}\frac{\partial G}{\partial X}$

From (i) and (ii), it follows that:

$$\frac{\partial G}{\partial \theta} > 0 \text{ iff } \frac{\omega - \frac{\theta^2}{c}}{\beta} > \frac{1}{2n}\left(\sqrt{\frac{n+8}{n}} + 1\right)$$

This, along with the fact that, $\frac{1}{2n}\left(\sqrt{\frac{n+8}{n}} + 1\right)$ is monotonically decreasing in n and asymptotically converges to zero as n tends to infinity, completes the proof. ■

Appendix C: Proof of Corollary

This follows from the fact that $\frac{1}{2n}\left(\sqrt{\frac{n+8}{n}} + 1\right)$ is monotonically decreasing in n and therefore if $\frac{\left(\omega - \frac{\theta^2}{c}\right)}{\beta} > \frac{1}{6}\left(\sqrt{\frac{11}{3}} + 1\right)$ (or $\beta < \bar{\beta}$) we necessarily have $\frac{\left(\omega - \frac{\theta^2}{c}\right)}{\beta} > \frac{1}{2n}\left(\sqrt{\frac{n+8}{n}} + 1\right)$. This, along with conditions (i) and (ii) in the proof of Proposition 2, gives $\frac{\partial G}{\partial \theta} > 0$ for all $n \geq 3$.■

Appendix D: Proof of Proposition 3

We have

$$\frac{\partial \Phi\left(2\right)}{\partial X} = \frac{\Omega X n^2 \alpha^2}{\left(2X + Xn + \beta\right)^3 \left(Xn + \beta\right)^3}$$

where

$$\Omega \equiv X^3\left(-5n^3 + 8n + 8\right) + X^2\beta\left(-9n^2 + 12n + 16\right) + X\beta^2\left(12 - 3n\right) + \beta^3$$

The sign of $\frac{\partial \Phi(2)}{\partial X}$ is the same as that of Ω. For convenience we use the notation $\Omega\left(n\right)$ to specifically analyze Ω as a function of n. We first note that

$$\Omega'\left(n\right) = X\left(12X\beta - 18Xn\beta + 8X^2 - 3\beta^2 - 15X^2n^2\right)$$

is strictly decreasing in n, implying the following:

$$\Omega'\left(n\right) < \Omega'\left(2\right) = -\left(24X\beta + 52X^2 + 3\beta^2\right)X < 0$$

Therefore, the function $\Omega(n)$ is a strictly decreasing function of n. The evaluation of $\Omega(2)$ gives the following:

$$\Omega(2) = (4X + \beta)\left(2X\beta - 4X^2 + \beta^2\right)$$

It can be shown that there exists a unique $\hat{X} > 0$ such that $\Omega(2) < 0$ for $X > \hat{X}$. Since $\Omega'(n) < 0$, we can state that there exists $\hat{X} > 0$ such that $\Omega(n) < 0$ for $X > \hat{X}$ or $\frac{\partial \Phi(2)}{\partial X} < 0$ for $X > \hat{X}$. This, along with the fact that $\frac{dX}{d\theta} < 0$, completes the proof of (i). When $0 < X < \hat{X}$ we have $\Omega(2) > 0$. Moreover, from Assumption 2 we have $X < \frac{\beta}{n-2}$ or $n < \frac{\beta}{X} + 2$ with $\Omega\left(\frac{\beta}{X} + 2\right) = -16(X + \beta)^3 < 0$. This combined with $\Omega'(n) < 0$ proves (ii). ■