ADAPTING TO CLIMATE CHANGE: EQUILIBRIUM WELFARE IMPLICATIONS FOR LARGE AND SMALL ECONOMIES

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ABSTRACT

We show that the availability of adaptation can be welfare-reducing in the non-cooperative equilibrium in a setting with multiple countries. Adaptation is a private good while abatement is a public good. This means that substitution out of abatement and into adaptation by any one country imposes a negative externality on all other countries. The potentially deleterious impact of adaptation is asymmetric: small economies are most likely to be hurt by the availability of adaptation because they control a small fraction of global emissions relative to the biggest emitters.

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1. INTRODUCTION

The international debate on climate policy to date has focused primarily on the goal of reducing global emissions. Yet adaptation will also play an increasingly important role in policy responses to climate change, especially if a cooperative agreement to reduce emissions cannot be reached. There is growing concern within the international community that an increased emphasis on adaptation could reduce the abatement efforts of the largest emitters, to the detriment of smaller countries who have little power to affect global emissions on their own [UNDP (2007)]. The purpose of our paper is to examine the basis for this concern, and to assess the relative welfare impacts of adaptation on large and small economies in a non-cooperative setting.

There is a fundamental difference between abatement and adaptation: adaptation is primarily a private good while abatement is a public good. The availability of adaptation therefore changes the nature of the strategic interaction between countries in the abatement game, with a potentially profound effect on equilibrium actions and welfare. In particular, we show that the availability of adaptation can be *welfare-reducing* – especially for small countries – because global emissions are higher when large emitters substitute into adaptation and out of abatement. Small countries are relatively disadvantaged even when all countries face the same cost of adaptation.

Our theoretical model focuses on the *asymmetric scope of control* that is a defining feature of the climate change game in practice. In particular, the vast majority of countries are effectively powerless to influence unilaterally the global emissions that cause their climates to change, because they are such small contributors to those emissions in the first place. The data we present in Section 2 highlights the extreme nature of this asymmetry. For example, the median economy currently accounts for less than 0.008% of global emissions. This country could eliminate its emissions entirely and still see no meaningful difference in the climate change it faces. In stark contrast, bold abatement action by China, the US or the EU – who together currently account for around 57% of global emissions – would have a major impact on long run climate change.

The lack of meaningful control that small countries have over their own climatic destinies is precisely why they are so concerned by the prospect of the largest emitters choosing to emphasize adaptation over abatement. Accordingly, variation across countries in their scope of control over global emissions is a key feature of our model, and a driving force behind our results on the welfare effects of adaptation.

Our paper adds to a growing body of theoretical work on the relationship between abatement and adaptation. Agrawala *et. al.* (2011) provide a review of this work. One key issue of interest in this literature is whether abatement and adaptation are substitutes or complements. Lecocq and Shalizi (2007) argue that they are best viewed as substitutes, and consequently, they should be determined jointly in any international climate change treaty. Barrett (2008a) makes a similar argument. Ingham *et. al.* (2013) also make the case for viewing the two actions as substitutes. In contrast, Yohe and Strzepeck (2007) argue that if the climate damage function is not smooth and monotonic, then abatement and adaptation should be treated as complements in many circumstances. In our model, they are substitutes, and this is important for our results.

The optimal mix of abatement and adaptation is also a key concern in the literature, and a number of papers have examined this issue in the context of a central planning problem. Kane and Shogren (2000) examine the impact of climate change risk on the optimal mix, and argue that it depends crucially on whether the two actions are substitutes or complements. Tulkens and van Steenberghe (2009) study a similar problem. Ingham *et. al.* (2007) also examine a setting with uncertainty, and argue that the availability of adaptation makes it more likely that the prospect of further learning calls for less abatement now. Bréchet *et. al.* (2010) introduce economic growth into the planning problem, and argue that the optimal mix for a country depends on its stage of economic development. While clearly important in practice, we abstract from these considerations, and study a setting with neither uncertainty nor growth but with strategic interaction among countries.

Buob and Stephan (2011) also consider the abatement-adaptation mix problem in a setting with strategic interaction. They show that non-cooperative equilibria with adaptation-only or abatement-only can arise when the two actions are perfect substitutes but equilibria with a mix of actions arise when they are complements. They also examine the importance of intertemporal cost-effectiveness in the equilibrium mix. Ebert and Welsch (2011 and 2012) also study a non-cooperative game between countries, and we describe their work in more detail below.

The importance of strategic interaction between countries has also motivated work on the role of adaptation in shaping *cooperative* action on climate change. Barrett (2008a) – discussed in more detail below – shows that the availability of adaptation can improve the prospects for cooperation. Buob and Stephan (2013) argue that adaptation-funding assistance from developed countries to developing countries could actually reduce developing-country welfare – because it shifts the burden of abatement away from developed countries – and might therefore be unacceptable as part of a climate change treaty.

Our paper is closest in spirit to Barrett (2008a) and Ebert and Welsch (2012). Barrett (2008a) examines a model in which abatement and adaptation are both binary actions, and where a subset of countries are powerless to abate or adapt. He shows that the availability of adaptation to the empowered countries does not necessarily make the powerless countries worse off, despite the incentives it creates for the empowered countries not to abate. The result reflects the fact that adaptation improves the prospects for a cooperative treaty via its impact on the non-cooperative payoffs when abatement and adaptation are substitutes.

Our paper is complementary to Barrett's in some respects but very different in its perspective. The crucial source of asymmetry between countries in our model is economic size. In the non-cooperative equilibrium, small economies choose to undertake very little abatement because they are simply too small to be able to affect global emissions in a meaningful way. However, these countries are not powerless to adapt. On the contrary, these countries undertake relatively *more* adaptation than larger ones because that is the only effective option open to them. The availability of adaptation in general can nonetheless make these countries worse off because non-cooperative emissions are higher as a consequence.

Barrett instead focuses on the difference between rich and poor countries. Poor countries in his model are *unable* to adapt precisely because they are poor. This element of heterogeneity across countries is undoubtedly just as important as economic size for the climate change problem in practice, and it is in this sense that our work is complementary to that of Barrett.

Our perspective on the problem is nonetheless quite different. A key result from the treaty formation literature is that cooperation is most difficult to achieve when the potential gains from cooperation are greatest, or equivalently, when damage from climate change is high. [Barrett (2003)]. The simulation results in Barrett (2008a) are fully consistent with this. While his results show that the availability of adaptation makes cooperation easier, the actual difference between the cooperative and non-cooperative outcomes is minimal when damages are high, regardless of whether or not adaptation is available. In particular, in his high-damage scenario, a treaty comprises only 4 out of 50 countries when adaptation is feasible, and 2 out of 50 when it is not. The realized gains to cooperative action are almost negligible either way.

One can think of Barrett's results and ours as relating in the following way. Adaptation may make cooperative action more likely, but when cooperation matters most – when damage is high – there is very little difference between the cooperative and non-cooperative outcomes anyway. Our results show that the non-cooperative outcome is potentially made worse by the availability of adaptation – especially for small economies – and crucially, that this deleterious effect is *most likely* when damage is high. Thus, even if the availability of adaptation leads to more cooperation, small countries may still be worse off overall.

Ebert and Welsch (2012) also examine the impact of adaptation on non-cooperative equilibria. Our model has some elements similar to theirs, and we see our results as complementary to those that they obtain. Specifically, in a model with two countries, Ebert and Welsch show that the substitutability of adaptation and abatement in the policy mix of each country changes the strategic interaction between those countries, creating the possibility that emissions become strategic complements in the game. [See also Ebert and Welsch (2011)]. They then examine how a change in the effectiveness of adaptation in *one* country affects equilibrium emissions and welfare, when the two countries differ according to their vulnerability to climate change.

Our model and analysis differ from Ebert and Welsch (2012) in two key ways. First, the critical characteristic across which countries differ in our model is economic size. This allows us to capture the asymmetry in the scope of control between large and small economies, and this in turn drives differences among these economies in terms of their equilibrium abatement-adaptation mixes. It also underlies the key welfare results of the paper. Ebert and Welsch (2012) instead focus on differences in vulnerability to damage. While these differences are no doubt real and important, it seems clear that differences in economic size are of at least equal importance in practice.

Second, we examine the welfare implications of the availability of adaptation *per se*. In contrast, Ebert and Welsch study how differential adaptation costs across countries can affect welfare and equilibrium actions. Again, we see these as complementary investigations. Our primary purpose is to assess the legitimacy of concerns raised by small economies – even those with low adaptation costs – that adaptation could be a damaging distraction from abatement efforts among the largest emitters.

The rest of our paper is organized as follows. Section 2 presents some data on emissions and GDP across countries. Our purpose in that section is simply to highlight the dramatic skewness evident in the data which in turn motivates our modeling approach. Section 3 describes the theoretical model. Section 4 derives the first-best solution, and examines the properties of the optimal mix of adaptation and abatement from a global perspective. Section 5 characterizes the non-cooperative equilibrium. Section 6 then presents necessary and sufficient conditions under which the availability of adaptation is welfare-reducing for an individual country, and for the global community as a whole. Section 7 provides some concluding remarks. An Appendix contains all proofs.

2. ASYMMETRIC SCOPE OF CONTROL

The inability of small economies to effectively control the emissions that damage them is a defining feature of the climate change problem. Here we provide a picture of just how skewed the distribution of global emissions – and the underlying distribution of global GDP – actually is. Our data for both emissions and GDP is from 2010, the most recent year for which comprehensive and reasonably reliable country-level emissions data is available.[1]

Figure 1 plots global GDP and carbon dioxide (CO_2) emissions shares for the ten largest economies in the world, together with the totals for the rest of the world (ROW). The 27 countries of the EU (in 2010) are treated as comprising a single economy in view of their coordinated climate change policies.

The figure conveys two key messages. First, a handful of big economies account for the bulk of global output. The biggest three economies – the EU, the US and China – together account for 60% of global GDP. The top ten economies as a group account for around 83% of the total. In comparison, the GDP share of the median economy is 0.026%.

Second, the distribution of emissions is also highly skewed. The biggest three economies together account for around 57% of global emissions. The top ten economies as a group account for 79% of the total. The emissions share of the median economy is 0.008%.

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[1] All data are from the World Bank's *World Development Indicators 2013*. GDP is calculated in current US dollars.

This dramatic skewness in output and emissions creates an enormous asymmetry between large and small economies in terms of their scope of control over global emissions and their own climatic destinies: most small economies are effectively powerless to influence the global emissions that affect their climate. This aspect of the climate change problem is central to our model, and underlies many of our results.

3. THE MODEL

Let $y_i > 0$ denote the economic output of country *i* (as measured by its GDP). We take this as fixed, and focus on the costs and benefits of technology-based abatement and adaptation, *given* that level of output. In practice, countries also have the option of reducing output itself as a way to reduce emissions, but modeling this option requires the incorporation of consumer preferences over different types of goods, and the endogenous determination of output based on country-specific characteristics. We take a simpler approach in which output is fixed so as to focus on the most-easily identified way in which countries differ: the size of their GDP.

Emissions from country *i* are denoted e_i. These emissions are a function of y_i and the abatement technology used in country *i*, denoted $x_i \in [0,1]$:

(1) $$e_i = (1 - x_i) y_i$$

Abatement cost is increasing and strictly convex in x_i but linear in output:

(2) $$c_x(y_i, x_i) = x_i^2 y_i$$

Global emissions are denoted $E = \sum_{i=1}^{N} e_i$ where *N* is the number of countries. Damage from climate change is proportional to *E*. In particular, in the absence of adaptation, climate change destroys some fraction δE of the output in any given country, where δ is the *damage parameter*. Agricultural crop losses are the most obvious example of climate-related damage but most sectors will likely suffer losses due to adverse impacts like rising sea levels, storm-related power outages, and extreme weather events. In general, we treat climate change as a destructive public factor in production.

In reality, δ will vary across countries, depending on economic composition (especially with respect to dependence on agriculture), and geographic characteristics. We abstract from this source of heterogeneity so as to focus on the impact of economic size. This would be problematic if size and vulnerability to climate change are correlated but there is no obvious reason to think that they are. There is almost surely some correlation between vulnerability and income *per capita* – since the poorest countries are typically the most dependent on agriculture, and tend to be located at low latitudes where temperatures are already high – but large economies are not necessarily rich and small economies are not necessarily poor. It therefore seems reasonable to focus on economic size independently of specific vulnerability. Moreover, the dramatic variation and skewness in GDP data that we have highlighted in Section 2 suggests that this source of heterogeneity will swamp any (uncorrelated) differences across countries with respect to specific vulnerability.

We model adaptation as defensive actions taken by country *i* to protect some fraction $a_i \in [0,1]$ of its economy from the damaging impact of climate change. The "undefended" residual fraction of the economy remains subject to damage.[2] Thus, damage in country *i* is

$$d_i = \delta E(1 - a_i)y_i \tag{3}$$

The cost of adaptation for country *i* is strictly convex in its coverage, and proportional to the magnitude of economic activity that must be defended. In particular,

$$c_a(a_i, y_i) = \theta a_i^2 y_i \tag{4}$$

where $\theta > 0$ is a parameter reflecting the cost of adaptation relative to the cost of abatement.

In reality, θ will differ across countries, depending on the composition of their economies and their specific geography. Moreover, there may exist some economies of scale in adaptation (such as in the development of new seed varieties) that give larger economies an advantage over smaller economies. We deliberately abstract from this potential heterogeneity across countries so as to capture the availability of adaptation – and its implications for welfare – with a single parameter.

It should also be noted that our specified cost functions exclude the possibility that the marginal costs of abatement and adaptation are interdependent. In practice, undertaking more adaptation could drive up the cost of abatement if the two activities compete for the same resources, or conversely, could reduce the cost of abatement if there are technological spillovers. We abstract from this possible interdependence again for the sake of simplicity; it allows us to capture the availability and relative cost of adaptation with a single parameter.

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[2] Some defensive measures (such as geoengineering) may have significant spillover effects on other countries, possibly negative; see Barrett (2008b). Here we restrict attention to purely private defensive measures.

Aggregate output is $Y = \sum_i^N y_i$. The mean and variance of the global GDP distribution are denoted μ and σ^2 respectively. It will also prove useful to define

$$S \equiv \sum_{i=1}^{N} y_i^2 = N(\mu^2 + \sigma^2) \tag{5}$$

Note that $S < Y^2$ for any $N > 1$.

4. ABATEMENT VS. ADAPTATION: THE FIRST-BEST SOLUTION

The first-best solution solves a planning problem in which total global cost (equal to the sum of abatement cost, adaptation cost, and damage for each country, aggregated across countries) is minimized via the choice of abatement technologies and adaptation actions:

$$\min_{\{a\},\{x\}} \sum_{i=1}^{N} \left(x_i^2 y_i + \theta a_i^2 y_i + \delta \left(\sum_{j=1}^{N} y_j (1 - x_j) \right) (1 - a_i) y_i \right) \tag{6}$$

The solution to this problem is summarized in Proposition 1.

PROPOSITION 1. Let $\{a_i^{**}, x_i^{**}\}$ denote the first-best policy for country *i*. The properties of that policy vary across three key regions of the parameter space, as follows.

(a) If $\delta \leq \frac{2}{Y}$ and $\theta \geq \frac{\delta Y}{2}$, then

$$x_i^{**} = x^{**} = \frac{\delta(2\theta - \delta Y)Y}{4\theta - \delta^2 Y^2} \quad \forall i \tag{7}$$

and

$$a_i^{**} = a^{**} = \frac{\delta(2 - \delta Y)Y}{4\theta - \delta^2 Y^2} \quad \forall i \tag{8}$$

(b) If $\delta \geq \frac{2}{Y}$ and $\theta > 1$, then $x_i^{**} = 1 \ \forall i$ and $a_i^{**} = 0 \ \forall i$; and

(c) If $\theta \leq \frac{\delta Y}{2}$ and $\theta < 1$, then $x_i^{**} = 0 \ \forall i$ and $a_i^{**} = 1 \ \forall i$.

This first-best solution is summarized in Figure 2. The figure partitions the (δ, θ) space into critical regions corresponding to the three scenarios in Proposition 1. Regions A1 and A2 (both shaded) correspond to scenario (a) in the proposition: the solution is interior. Regions B and

C (both unshaded) correspond to scenarios (b) and (c) respectively. In these regions, the solution involves a corner. Note that in all cases, the solution is identical across countries.

The dividing line between regions A1 and C on one hand, and regions A2 and B on the other, is where $\theta = 1$: the marginal cost of adaptation (MCA) is just equal to the marginal cost of abatement via cleaner technology adoption (MCT). The characteristics of the first-best solution are very different either side of $\theta = 1$, and we briefly describe each case in turn.

(i) $\theta < 1$: Regions A1 and C

In these regions, MCA is lower than MCT. The first-best policy mix therefore places more emphasis on adaptation than on abatement. Figure 3 illustrates the profiles of a^{**} and x^{**} against δ in region A1, for a given value of $\theta < 1$. The most notable feature of these profiles is that the first-best technology is not monotonic in δ. The technology initially rises with δ but eventually begins to fall for δ sufficiently large, and drops to zero at the boundary with region C. Conversely, adaptation rises monotonically with δ until the boundary with region C is reached, at which point all economies are fully defended against climate change.

These properties of the first-best solution reflect the low cost of adaptation in this region of the parameter space. A higher damage parameter means that economic activity is more subject to damage from climate change, and this makes adaptation more worthwhile. It also initially makes cleaner technology adoption more worthwhile – since damage is proportional to emissions – and so both actions initially rise as δ rises. However, as adaptation becomes increasingly complete, the benefits of fighting climate change via abatement eventually begin to fall, and so the optimal technology begins to decline as well. At the boundary of regions A1 and C – and throughout all of region C – adaptation is complete ($a^{**} = 1$), and hence there is no point at all to abatement; thus, $x^{**} = 0$ in region C.

(ii) $\theta > 1$: Regions A2 and B

In these regions, MCA is greater than MCT. The first-best policy mix therefore favors cleaner technology adoption over adaptation. Figure 4 illustrates the profiles of a^{**} and x^{**} against δ in region A2, for a given value of $\theta > 1$. These profiles are the opposite of those in region A1: the technology becomes monotonically cleaner as δ rises, while adaptation initially rises with δ before eventually falling to zero (at the boundary with region B).

The intuition behind these profiles is simply the reverse of that underlying the policy in region A1. A larger damage parameter calls for greater protection from climate change via adaptation, and greater effort to reduce emissions, whose damaging effects are proportional to δ. Thus, both actions initially rise with δ. However, since adaptation is more costly than cleaner technology adoption ($\theta > 1$), the policy mix favors abatement. As technology becomes cleaner – and emissions fall – the value of adaptation eventually declines, and optimal adaptation declines with it. As the boundary with region B is reached, abatement becomes complete ($x^{**} = 1$) and adaptation has no value at all; thus, $a^{**} = 0$ in region B.

(iii) The $\theta = 1$ Boundary

Cleaner technology adoption and adaptation are equally costly in the knife-edge case where $\theta = 1$. Thus, $a^{**} = x^{**}$ at any $\delta < 2/Y$ when $\theta = 1$. Moreover, a^{**} and x^{**} are both continuous in θ for any $\delta < 2/Y$. However, the optimal policy is discontinuous in θ at $\theta = 1$ for any $\delta > 2/Y$ because the global cost function is not convex in this range. Thus, when $\delta \geq 2/Y$, the optimal policy jumps discontinuously at $\theta = 1$ from one corner solution to the other. At $\theta = 1$, both corner solutions yield the same total social cost, and a global planner would be indifferent between them.

The corner solutions identified in Proposition 1 are of some theoretical interest but an optimal policy in practice is likely to involve a policy mix. Accordingly, we henceforth restrict attention to that part of the parameter space in which both a^{**} and x^{**} are interior. Thus, we assume that $\delta < 2/Y$ and $\theta \geq \delta Y/2$ (henceforth identified as Assumption 1).

5. EQUILIBRIUM ADAPTATION

We now turn to the non-cooperative equilibrium. The policy problem for country *i* is to set a_i and x_i to minimize its total domestic cost (equal to the sum of domestic abatement cost, domestic adaptation cost, and domestic damage):

$$(9) \qquad \min_{a_i, x_i} \; x_i^2 y_i + \theta a_i^2 y_i + \delta[(1 - x_i) y_i + E_{-i}](1 - a_i) y_i$$

The solution to this problem yields best-response functions for the technology choice and adaptation in terms of E_{-i}; these are reported as (A10) and (A11) respectively in the Appendix.

The parameter restrictions that ensure an interior first-best solution (Assumption 1 above) also guarantee that these best-response functions solve for an interior and stable equilibrium. The key properties of that equilibrium are described in Proposition 2.

PROPOSITION 2. The interior equilibrium technology and adaptation choices for country *i* are

$$\hat{x}_i = \frac{\delta(2\theta - \delta Y)y_i}{4\theta - \delta^2 S} \tag{10}$$

and

$$\hat{a}_i = \frac{\delta(2Y - \delta S)}{4\theta - \delta^2 S} \tag{11}$$

respectively, and the corresponding level of emissions for country *i* is

$$\hat{e}_i = y_i - \phi y_i^2 \tag{12}$$

where

$$\phi \equiv \frac{2\delta\theta - \delta^2 Y}{4\theta - \delta^2 S} > 0 \tag{13}$$

These equilibrium policies have four noteworthy properties. First, $\hat{x}_i$ is increasing in θ (when the first-best solution is interior). Thus, lower-cost adaptation leads all countries to use dirtier technologies. The reason for this is straightforward: adaptation reduces the damage done by emissions, and thereby reduces the marginal benefit of reducing those emissions. To put this differently, abatement and adaptation are substitutes in the protection of economic activity.

Second, the response to an increase in θ is largest for the highest-GDP countries: $\partial\hat{x}_i / \partial\theta$ is increasing in y_i. This is a direct consequence of the scope-of-control effect: abatement is a relatively poor substitute for adaptation for small economies because their own individual abatement efforts have such little impact on global emissions. In contrast, a policy-driven cleaner technology choice by a large economy produces a large reduction in global emissions, and this makes abatement a much more effective policy for large economies.

Third, the equilibrium technology choice for any country depends on the mean and variance of the GDP distribution (captured by *S*). This reflects an element of strategic interaction introduced by the availability of adaptation that would not otherwise arise in this setting. In particular, the linear relationship that we have specified between global emissions and damage means that the marginal damage of own-country emissions for any one country is independent of other-country emissions. However, the availability of adaptation means that the domestically-optimal *mix* of abatement and adaptation for any country does depend on other-country emissions. If other-country emissions rise then adaptation becomes a relatively more attractive measure for any given country because those other-country emissions are beyond its control in terms of abatement. In contrast, it has complete control over adaptation. Thus, the availability of adaptation means that emissions become strategic complements.[3]

Fourth, while the scope-of-control effect means that higher-GDP countries choose cleaner technologies, equilibrium adaptation is *independent* of GDP; all countries protect the same fraction of economic activity. This reflects our assumptions that adaptation cost and damage are both linear in GDP, but more importantly, that adaptation is a private good. The scope-of-control effect that links abatement to GDP arises because each country is able to control only a fraction of the global emissions that damage its climate, and that fraction rises with GDP. In contrast, each country has complete control over its adaptation, regardless of GDP. This asymmetry means that the relative importance of adaptation in the equilibrium policy mix (as measured by the ratio $\hat{m}_i \equiv \hat{a}_i / \hat{x}_i$) is higher for lower-GDP countries. In short, a small economy has little control over global emissions, so its best policy is to defend itself against the damaging impact of those emissions via adaptation.

Finally, the equilibrium policy mix between abatement and adaptation is distorted for *all* countries relative to the first-best solution. Using (7) and (8) to construct the ratio $m^{**} \equiv a^{**} / x^{**}$, we can then construct

$$r_i \equiv \frac{m^*}{\hat{m}_i} = y_i \left(\frac{2 - \delta Y}{2Y - \delta S} \right) \tag{14}$$

as a measure of the policy-mix distortion for country *i*. It is straightforward to show that $r_i < 1$ for any $y_i < Y$ (because $S < Y^2$, and $Y \leq 2/\delta$ by Assumption 1). Thus, all countries choose a policy

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[3] Ebert and Welsch (2011 and 2012) derive a more a general result. They assume that damage is strictly convex in global emissions, and this means that emissions are strategic substitutes when adaptation is not available; the best-response functions are negatively-sloped. The introduction of adaptation then creates the *possibility* that emissions become strategic complements but the slopes of the best-response functions depend on the convexity of the damage function relative to the effectiveness of adaptation. We have assumed a linear damage function here because it allows us to derive closed-form solutions for the equilibrium while still highlighting the impact of adaptation on the nature of the strategic interaction between countries.

mix in equilibrium that is skewed excessively towards adaptation. This reflects the fundamental distinction between abatement as a public good and adaptation as a private good.

6. CAN ADAPTATION BE WELFARE-REDUCING?

We now turn to the central question posed in our introduction: can the availability of adaptation be welfare-reducing for some countries? We answer this question in two parts. We first derive necessary and sufficient conditions under which a country is made better-off by a *marginal* increase in the cost of adaptation. We then derive necessary and sufficient conditions under which a country would be better-off if adaptation was *universally unavailable*.

PROPOSITION 3

(a) A marginal increase in θ is welfare-improving for country *i* if and only if

$$(15) \qquad y_i^2 < S - \frac{2Y - \delta S}{4\phi}$$

(b) Country *i* would be better off if adaptation was universally unavailable if and only if

$$(16) \qquad y_i^2 < S - \frac{2Y - \delta S}{2\phi + \delta}$$

Condition (15) is sufficient for condition (16) but the converse is not true.

These results are best understood in the context of a diagram. Figure 5 plots total cost for country *i* as a function of θ for $\theta > \delta Y / 2$ (where the equilibrium is interior). As illustrated, there is a turning point in this cost function at $\tilde{\theta}_i$. Why does this turning point arise? Recall from the discussion following Proposition 2 that $\hat{\partial} x_i / \partial \theta > 0$: a *lower* cost of adaptation causes all countries to substitute out of abatement and into adaptation. In doing so, each country imposes an externality on every other country because abatement is a public good. If θ is initially high then this externality is large enough to cause the overall cost for country *i* to rise as θ falls because much of its economy is undefended and hence exposed to damage from the higher emissions. Conversely, if θ is already small then the externality associated with higher emissions as θ falls is of little consequence because a large fraction of the economy is already defended against damage. Thus, there exists some threshold value of θ at which any further reduction in θ must be welfare-improving for country *i*; this threshold is the turning point at $\tilde{\theta}_i$ in Figure 5.

Figure 5 also illustrates the cost for country *i* as $\theta \to \infty$, labeled C_{0i}. This scenario corresponds to one in which adaptation is universally unavailable. If the cost function has a turning point in θ then there must also exist a critical threshold value of θ, denoted $\bar{\theta}_i$ in the figure, such that total cost *with* adaptation exceeds C_{0i} at any finite $\theta > \bar{\theta}_i$. Thus, total cost for country *i* would be lower when adaptation is universally unavailable if and only if $\theta > \bar{\theta}_i$. Note that if $\theta > \tilde{\theta}_i$ then $\theta > \bar{\theta}_i$ but the converse is not true.

Now consider why a change in θ has different impacts for different countries. Recall that $\hat{\partial} x_i / \partial\theta$ is increasing in y_i due to the scope-of-control effect. This means that the biggest contributions to the increase in global emissions when θ falls come from the largest economies. Thus, the externality associated with substituting out of abatement and into adaptation is not symmetric across countries, and smaller economies suffer disproportionately as a consequence. In the context of Figure 5, both $\bar{\theta}_i$ and $\tilde{\theta}_i$ are increasing in y_i so any *given* value of θ (such as θ^* in the figure) must lie *above* both of these critical values for sufficiently small countries, and *below* both of these critical values for sufficiently large countries. (Picture the cost function in Figure 5 shifting to the right as GDP rises while holding θ^* fixed). This underlies the key conditions on y_i^2 in Proposition 3.

It is important to stress that all countries could be so large that conditions (15) and (16) are not met for *any* country. In particular, if

$$\theta < \frac{\delta^3 S^2}{2(2Y - 3\delta S)} \tag{17}$$

then the RHS of (16) is negative. However, note also that this threshold value of θ is decreasing in δ: a higher damage parameter exacerbates the externality associated with substitution out of abatement. Thus, the availability of adaptation is most likely to be welfare-reducing for at least some countries when damage is high.[4]

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[4] Of course, welfare cannot be higher when adaptation is unavailable if there is only one country. In that special case, $S = y_i^2$ and neither condition (15) nor condition (16) can ever hold.

It is important to note that high damage also means that the non-cooperative equilibrium may not be very different from a *cooperative* outcome, since cooperation is most difficult to achieve when the potential gains from cooperation are greatest [Barrett (2003)]. Thus, even if the availability of adaptation raises the prospects for cooperation – is in Barrett (2008a) – small countries could nonetheless be better off overall if adaptation was not available at all.

Proposition 3 tells us that at an increase in θ can potentially make some small countries better-off while making other countries worse-off. The impact of θ on *global cost* – the sum of domestic costs across countries – could therefore go either way, depending on the properties of the GDP distribution. The next result pins down that relationship in terms of the skewness of the distribution.

PROPOSITION 4

(a) Total global cost is decreasing in θ if and only if

$$Q < YS - \frac{(2Y - \delta S)Y}{4\phi} \tag{18}$$

where

$$Q = \sum_{i=1}^{N} y_i^3 \tag{19}$$

(b) Total global cost is lower when adaptation is universally unavailable if and only if

$$Q < YS - \frac{(2Y - \delta S)Y}{2\phi + \delta} \tag{20}$$

Condition (18) is sufficient for condition (20) but the converse is not true.

The relationship between parts (a) and (b) of Proposition 4 is analogous to the relationship between the two parts of Proposition 3. In particular, simply reinterpret the country-level cost function depicted in Figure 5 as the global cost function. The turning point of the global cost function must occur at a value of θ greater than the threshold value at which global cost is just equal to its limiting value as $\theta \to \infty$. Thus, condition (18) is sufficient but not necessary for condition (20).

Now consider the key role played by Q in both parts of Proposition 4. For any given mean and variance of the GDP distribution, Q is increasing in the skewness of that distribution, denoted γ. In particular,

(21) $$Q = N(\gamma\sigma^3 + \mu^3 + 3\mu\sigma^2)$$

If the distribution has a large positive skewness – as the true GDP distribution does – then global GDP is dominated by a relatively small number of large economies. The impact of adaptation on global cost is therefore governed mostly by its impact on the costs of the largest economies, and we know from Proposition 3 that the largest economies tend to benefit more from the availability of adaptation than do small economies. Thus, global cost can be decreasing in θ, for any given values of μ and σ^2, only if skewness is not too large.[5]

7. CONCLUSION

Our paper has addressed the question of whether the availability of adaptation can be welfare-reducing in the non-cooperative equilibrium. Our results show that it can be. The root cause of this perverse outcome is that adaptation is a private good while abatement is a public good. This means that substitution out of abatement and into adaptation by any one country imposes a negative externality on all other countries. The potentially deleterious impact of adaptation is asymmetric: small economies are most likely to be hurt be the availability of adaptation because they control such a small fraction of global emissions relative to the biggest emitters. Ironically, this same scope-of-control effect means that the smallest economies rely most heavily on adaptation in their equilibrium policy mixes.

Our results will provide little comfort to small economies concerned by any increased emphasis on adaptation over abatement by large emitters. These concerns could be well-justified, and there may be very little that small countries can do about it. Restricting the use of adaptation universally – even if doing so would be welfare-improving – is hardly a viable policy response globally, and is clearly beyond the powers of any one country. In the absence of a cooperative agreement to reduce emissions, the message here for small economies is that adaptation could be the only effective option open to them, and that abatement may not be an appropriate priority for them.

Our results also have some sobering implications for how small economies may need to approach negotiations on an international treaty to reduce emissions. Failure to reach a substantial agreement could have more drastic consequences for small countries than large ones,

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[5] Note that $Q = YS$ if there is only one country, so conditions (18) and (20) can never hold in that case.

given the availability of adaptation, and this may limit the demands that small economies can realistically make as part of such an agreement. Even if the availability of adaptation enhances the prospects for cooperation – as in Barrett (2008a) – adaptation may further diminish the bargaining power that small economies have over allowance allocations and transfers within the treaty. This might be inequitable but it may nonetheless be the reality that small countries face.

Our simple model has obviously abstracted from a variety of factors that are relevant to these issues in practice. Some of them we have noted already. In particular, there is neither growth nor uncertainty in the model. The absence of uncertainty is especially limiting because it obscures the potential importance of *timing* in terms of abatement and adaptation actions.[6] As Ingham *et. al*. (2007) note, the availability of adaptation can strengthen the case for waiting for more information about damage before undertaking abatement: there is a partial escape hatch if it turns out that we chose too little abatement. However, irreversible adaptation actions – such as the construction of sea walls – might also serve as a *commitment* not to abate in the future, and this has important repercussions in a non-cooperative setting. This is an issue worth pursuing.

We have also abstracted from the asymmetry across countries with respect to GDP *per capita*. As discussed earlier, this axis of heterogeneity is central to the analysis in Barrett (2008a). The small economies in our model are not necessarily poor and the large economies are not necessarily rich. A natural way to incorporate some of the insights from both Barrett (2008a) and Ebert and Welsch (2012) into our model, while preserving the central scope-of-control effect, is to allow our adaptation cost parameter to vary according to GDP *per capita*. This too may be an extension worth pursuing.

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[6] We are grateful to an anonymous referee for drawing our attention to this point and its implications.

APPENDIX

Proof of Proposition 1

The first-order conditions for x_i and a_i are, respectively,

(A1) $$2x_i y_i = y_i \delta \sum_{j=1}^{n} y_j (1-a_j) \quad \forall i$$

and

(A2) $$2\theta a_i y_i = y_i \delta \sum_{j=1}^{n} y_j (1-x_j) \quad \forall i$$

From (A2) we obtain

(A3) $$a_i = \frac{\delta}{2\theta} \sum_{j=1}^{n} y_j (1-x_j) \equiv a \quad \forall i$$

Thus, adaptation is identical across countries. Substituting *a* from (A3) for a_j in (A1), and rearranging, we obtain

(A4) $$x_i = \frac{\delta(1-a)Y}{2} \equiv x \quad \forall i$$

Thus, technologies are identical across countries. Substituting x from (A4) for x_j in (A3), and rearranging, we obtain

(A5) $$a^{**} = \frac{\delta}{2\theta}\left(1 - \frac{\delta(1-a^{**})Y}{2}\right)Y$$

Solving for a^{**} yields

(A6) $$a^{**} = \frac{\delta(2-\delta Y)Y}{4\theta - \delta^2 Y^2}$$

Finally, substituting a^{**} for *a* in (A4) yields

(A7) $$x^{**} = \frac{\delta(2\theta - \delta Y)Y}{4\theta - \delta^2 Y^2}$$

Solving for the conditions under which $a^{**} \in [0,1]$ and $x^{**} \in [0,1]$ yields the three parts of Proposition 1. It is straightforward to show that second-order conditions are satisfied.♣

Proof of Proposition 2

The first-order conditions for x_i and a_i are, respectively,

(A8) $$2x_i y_i = \delta y_i^2(1-a_i)$$

and

(A9) $$2\theta a_i y_i = \delta(y_i(1-x_i)+E_{-i})y_i$$

Solving (A8) and (A9) yields best-response functions for x_i and a_i. These are, respectively,

(A10) $$x_i(E_{-i}) = \frac{\delta(2\theta-\delta y_i-\delta E_{-i})y_i}{4\theta-\delta^2 y_i^2}$$

and

(A11) $$a_i(E_{-i}) = \frac{\delta(2y_i+2E_{-i}-\delta y_i^2)}{4\theta-\delta^2 y_i^2}$$

From (A10) we can obtain the best-response function in terms of emissions:

(A12) $$e_i = [1-x_i(E_{-i})]y_i = \frac{(4\theta-2\theta\delta y_i+\delta^2 y_i E_{-i})y_i}{4\theta-\delta^2 y_i^2}$$

Setting $E_{-i} = E - e_i$ in (A12) and rearranging to make e_i the subject, we have

(A13) $$e_i = y_i - \frac{(2\theta-\delta E)\delta y_i^2}{4\theta}$$

Summing across *i* allows us to solve for the equilibrium *E*:

(A14) $$\hat{E} = \frac{2\theta(2Y-\delta S)}{4\theta-\delta^2 S}$$

Setting $E = \hat{E}$ in (A13), we can then solve for the equilibrium $\hat{e}_i$:

(A15) $$\hat{e}_i = \frac{[4\theta-\delta^2 S - y_i\delta(2\theta-\delta Y)]y_i}{4\theta-\delta^2 S}$$

From (A15) we can then obtain

(A16) $$\hat{x}_i = 1-\frac{\hat{e}_i}{y_i} = \frac{\delta(2\theta-\delta Y)y_i}{4\theta-\delta^2 S}$$

Substituting $\hat{x}_i$ for x_i in (A8) then allows us to solve for a_i:

(A17) $$\hat{a}_i = \frac{\delta(2Y-\delta S)}{4\theta-\delta^2 S} \quad \forall i$$

Assumption 1 (from Section 4) ensures that these solutions are interior, that second-order conditions hold, and that the equilibrium is stable. We can then express $\hat{e}_i = (1-\hat{x}_i)y_i$ as $\hat{e}_i = y_i - \phi y_i^2$, where

(A18) $$\phi = \frac{2\delta\theta - \delta^2 Y}{4\theta - \delta^2 S} > 0$$

as reported in the text.♣

Proof of Proposition 3

(a) Equilibrium domestic cost for country *i* is

(A19) $$C(y_i,\theta) = x_i^2 y_i + \theta a_i^2 y_i + \delta E y_i (1-a_i)$$

In an interior equilibrium, x_i, a_i and E are evaluated at their equilibrium values given by (A16), (A17) and (A14) respectively. It will prove useful to express this cost function in terms of ϕ:

(A20) $$C(y_i,\theta) = \phi^2 y_i^3 + S\left(\phi + \frac{\delta}{2}\right)\left(\frac{Y}{S} - \phi\right)y_i$$

where ϕ is given by (A18). The second bracketed term can be expressed as

(A21) $$\frac{Y}{S} - \phi = \left(\frac{2\theta}{\delta S}\right)\hat{a}$$

so it must be positive if the equilibrium is interior.

Differentiating $C(y_i,\theta)$ with respect to θ yields

(A22) $$\frac{\partial C(y_i,\theta)}{\partial \theta} = 2\phi y_i (y_i^2 - \tilde{s})\frac{\partial \phi}{\partial \theta}$$

where

(A23) $$\tilde{s} = S - \frac{2Y - \delta S}{4\phi}$$

and

(A24) $$\frac{\partial \phi}{\partial \theta} = \frac{2\delta^2(2Y - \delta S)}{(4\theta - \delta^2 S)^2} > 0$$

at an interior equilibrium. Thus, $\partial C / \partial \theta > 0$ for $y_i^2 > \tilde{s}$ and $\partial C / \partial \theta < 0$ for $y_i^2 < \tilde{s}$.

(b) Making adaptation universally unavailable is equivalent to taking the limit

(A25) $$\lim_{\theta \to \infty} (\phi) = \frac{\delta}{2}$$

Making this substitution for ϕ in (A20) yields cost for country *i* when adaptation is universally unavailable :

(A26) $$C_0(y_i) = \left(\frac{\delta^2}{4}\right) y_i^3 + \delta\left(\frac{2Y - \delta S}{2}\right) y_i$$

where the second bracketed term must be positive in an interior equilibrium. Setting $C(y_i, \theta) = C_0(y_i)$ and solving for y_i^2 yields a critical threshold denoted

(A27) $$\bar{s} \equiv S - \frac{2Y - \delta S}{2\phi + \delta}$$

Taking the difference $\tilde{s} - \bar{s}$ yields

(A28) $$\tilde{s} - \bar{s} = \left(\phi - \frac{\delta}{2}\right)\left(\frac{2Y - \delta S}{4\phi^2 + 2\phi\delta}\right)$$

This is strictly positive at an interior equilibrium for any finite θ since $\partial\phi / \partial\theta > 0$. Thus, $\bar{s} < \tilde{s}$. Since $\partial C / \partial\theta < 0$ for $y_i^2 < \tilde{s}$ (by part (a) above), it follows that $\partial C / \partial\theta < 0$ at $y_i^2 = \bar{s}$. That is, $C(y_i, \theta)$ crosses $C_0(y_i)$ at $y_i^2 = \bar{s}$ from above. Thus, $C_0(y_i) < C(y_i, \theta)$ for $y_i^2 < \bar{s}$ and $C_0(y_i) > C(y_i, \theta)$ for $y_i^2 > \bar{s}$.♣

Proof of Proposition 4

(a) Total cost for country *i* is given by (A20). Summing across *i* yields total global cost:

(A29) $$G(Y, \theta) = \phi^2 Q + S\left(\phi + \frac{\delta}{2}\right)\left(\frac{Y}{S} - \phi\right) Y$$

where $Q = \sum_{i=1}^{N} y_i^3$. Differentiating $G(Y, \theta)$ with respect to θ yields

(A30) $$\frac{\partial G(Y, \theta)}{\partial\theta} = 2\phi(Q - \tilde{Q})\frac{\partial\phi}{\partial\theta}$$

where

(A31) $$\tilde{Q} = YS - \frac{(2Y - \delta S)Y}{4\phi}$$

and $\partial\phi / \partial\theta > 0$ is given by (A24). Thus, $\partial G / \partial\theta > 0$ for $Q > \tilde{Q}$ and $\partial G / \partial\theta < 0$ for $Q < \tilde{Q}$.

(b) Taking the limit of $G(Y,\theta)$ as $\theta \rightarrow \infty$ yields total global cost when adaptation is universally unavailable:

(A32) $$G_0(Y) = \left(\frac{\delta^2}{4}\right)Q + \delta\left(\frac{2Y - \delta S}{2}\right)Y$$

Setting $G(Y,\theta) = G_0(Y)$ and solving for Q yields a critical threshold denoted

(A33) $$\overline{Q} = YS - \frac{(2Y - \delta S)Y}{2\phi + \delta}$$

Taking the difference $\tilde{Q} - \overline{Q}$ yields

(A34) $$\tilde{Q} - \overline{Q} = Y\left(\phi - \frac{\delta}{2}\right)\left(\frac{2Y - \delta S}{4\phi^2 + 2\phi\delta}\right)$$

This is strictly positive at an interior equilibrium for any finite θ since $\partial\phi / \partial\theta > 0$. Thus, $\overline{Q} < \tilde{Q}$. Since $\partial G / \partial\theta < 0$ for $Q < \tilde{Q}$ (by part (a) above), it follows that $\partial G / \partial\theta < 0$ at $Q = \overline{Q}$. That is, $G(Y,\theta)$ crosses $G_0(Y)$ at $Q = \overline{Q}$ from above. Thus, $G_0(Y) < G(Y,\theta)$ for $Q < \overline{Q}$ and $G_0(Y) > G(Y,\theta)$ for $Q > \overline{Q}$.♣

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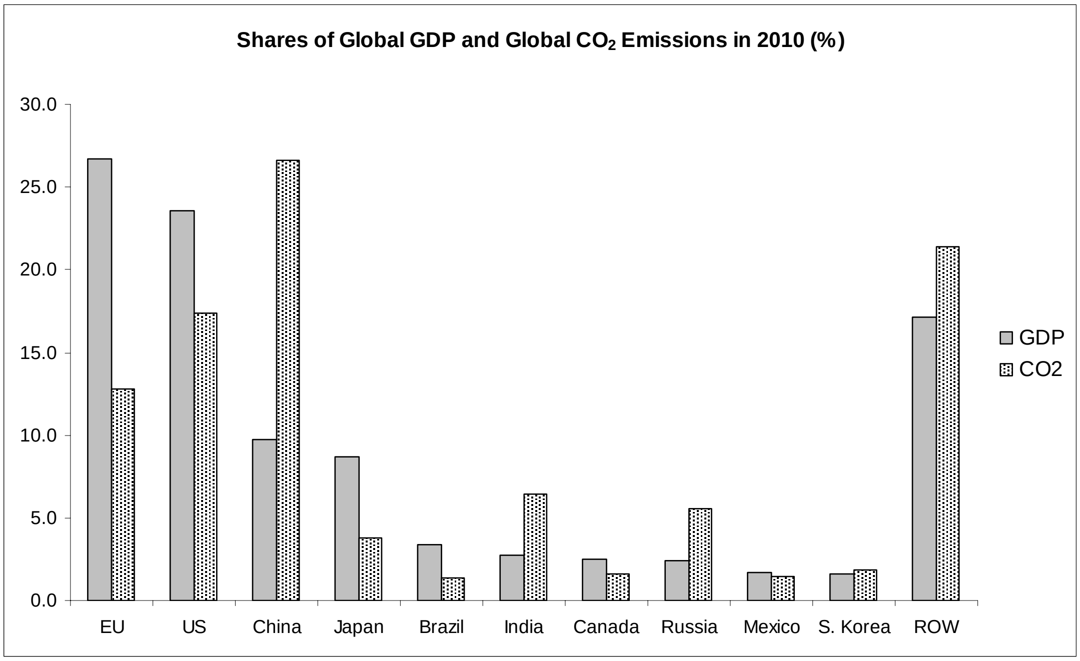

FIGURE 1: INCOME AND EMISSIONS SHARES

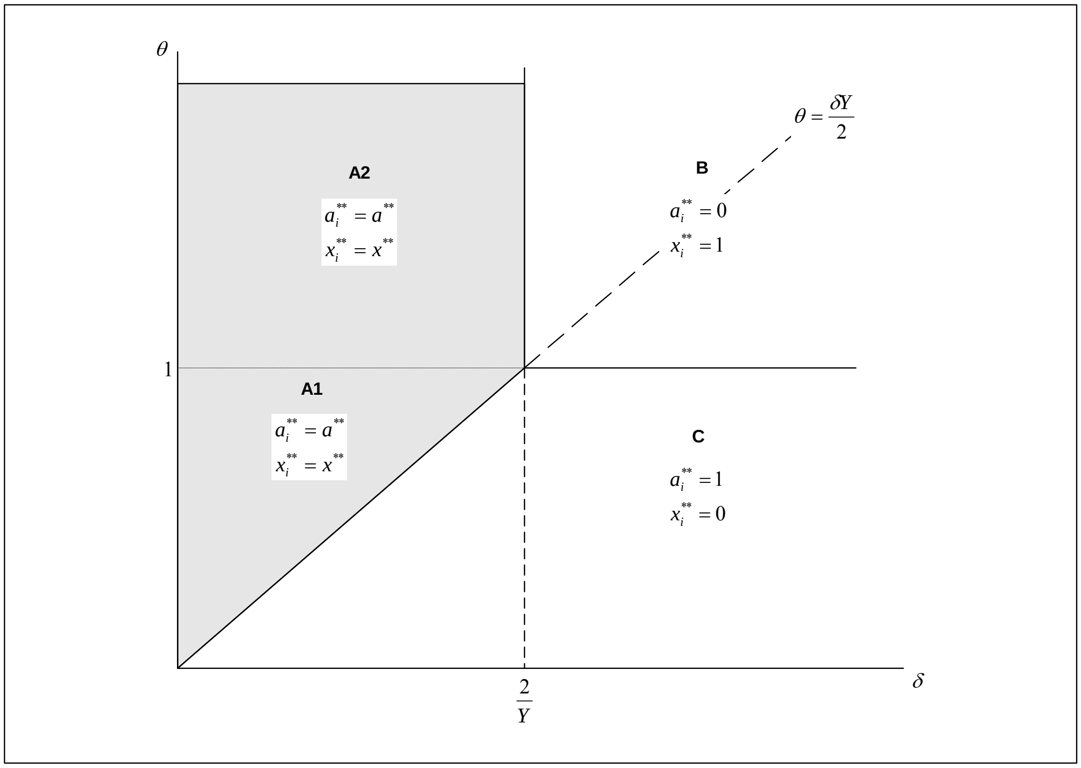

FIGURE 2: THE FIRST-BEST SOLUTION

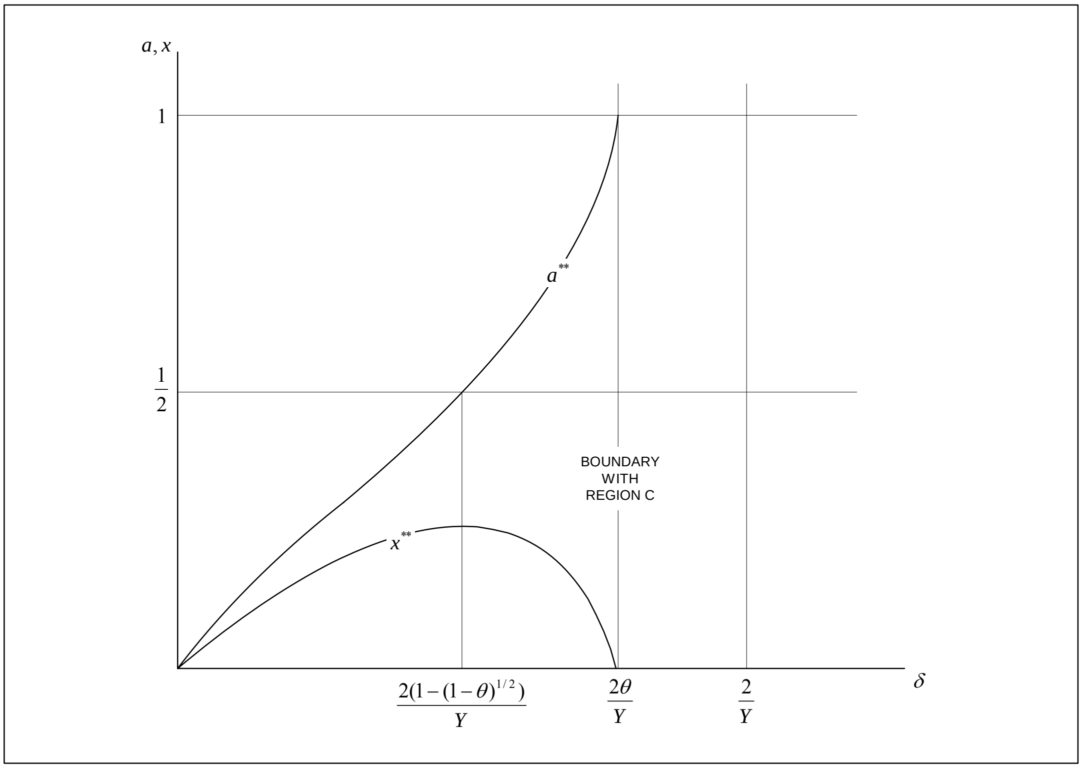

FIGURE 3: THE FIRST-BEST SOLUTION IN REGION A1

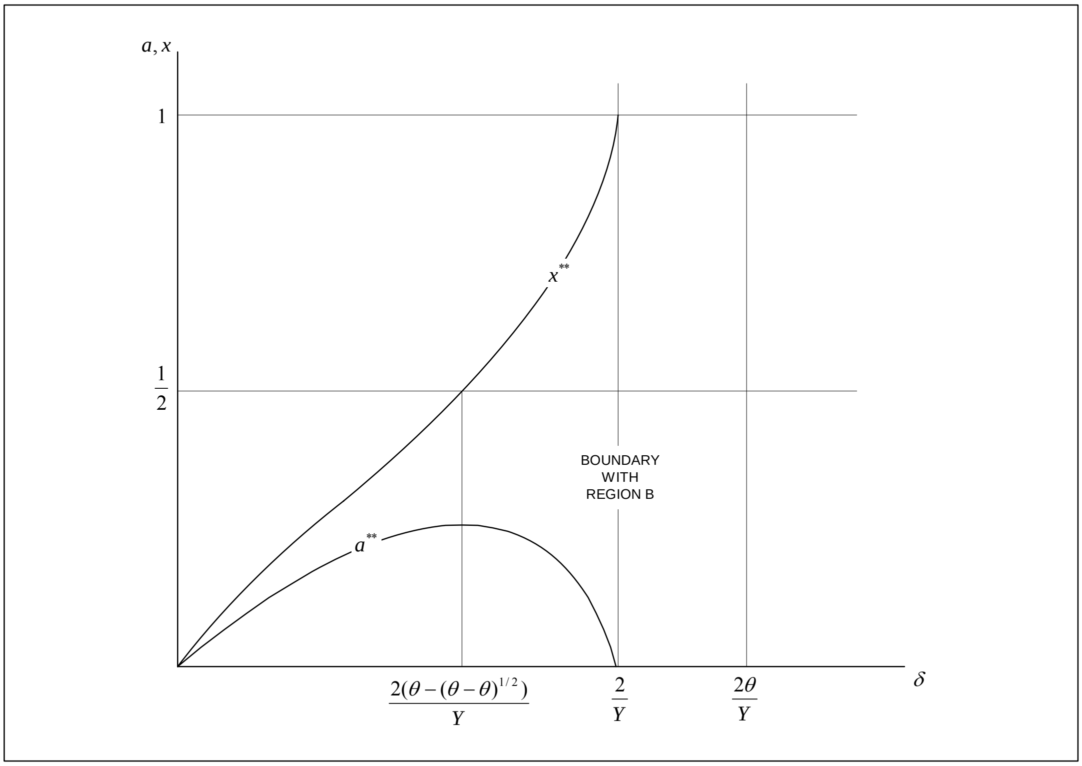

FIGURE 4: THE FIRST-BEST SOLUTION IN REGION A2

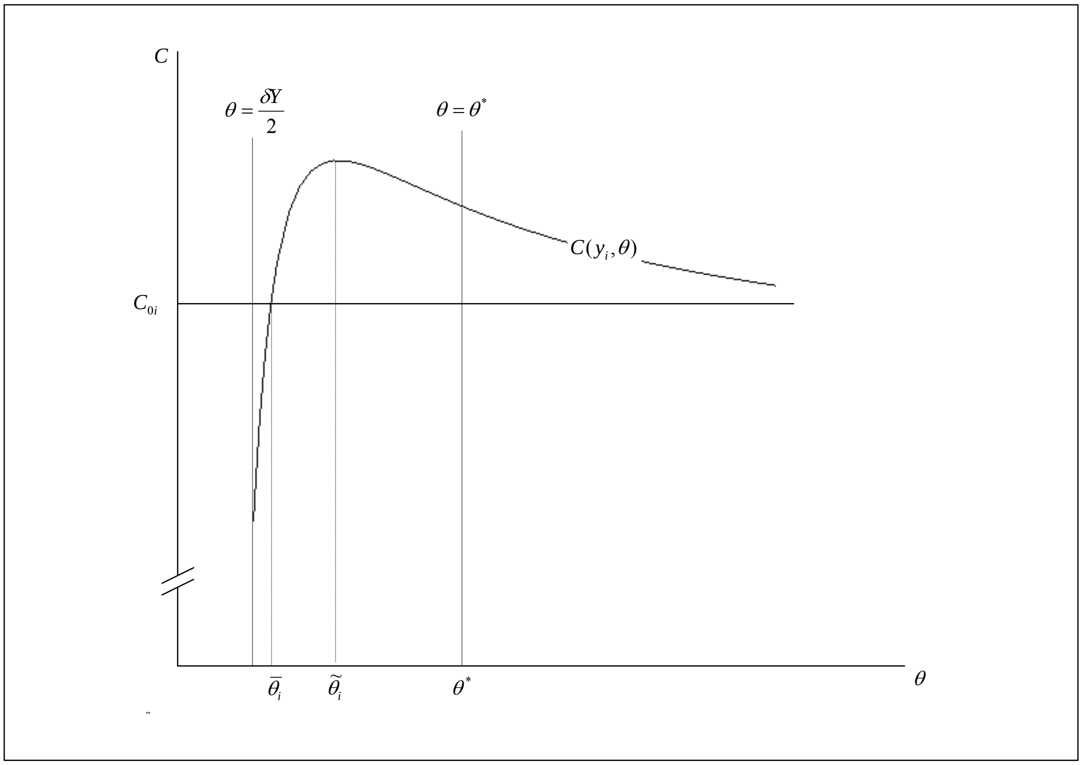

FIGURE 5: THE EQUILIBRIUM COST FUNCTION FOR COUNTRY *i*