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Adaptation for Mitigation

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Abstract: This paper develops a dynamic model consisting of two regions (North and South), in which the accumulation of human capital is negatively influenced by the global stock of pollution. By characterizing the equilibrium strategy of each region, we show that the regions' best responses can be strategic complements through a dynamic complementarity effect. The model is used to analyze the impact of adaptation assistance from North to South. It is shown that North's unilateral assistance to South (thus enhancing South's adaptation capacity) can facilitate pollution mitigation in both regions, especially when the assistance is targeted at human capital protection.

JEL Classification: D91, Q54, Q58

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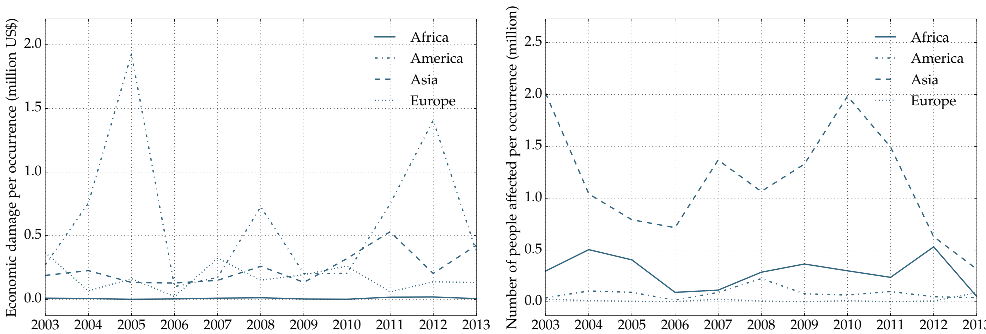
1 Introduction

Global climate change causes damage and this damage can differ greatly between regions, not only in terms of magnitude, but also in terms of its destructive nature (IPCC, 2014). The economic damage caused by climate-related disasters is relatively large in developed regions, but if we are concerned with human capital then climate change has more impact in less-developed regions.



(a) Economic damage

(b) People affected

Figure 1: Impacts of weather- and climate-related natural disasters through 2003–2013. *Source*: EM-DAT, the OFDA/CRED International Disaster Database, Université Catholique de Louvain, Brussels, Belgium.

In Figure 1 we show the economic and human-related damage per occurrence of climatic disasters over the past eleven years. While the economic damage in Asia and Africa is smaller than or comparable to the economic damage in Europe and America (Panel (a)), the number of people affected in Asia and Africa is much larger (Panel (b)). Since human capital cannot be easily restored once it is lost, more frequent and more powerful disasters are likely to have a negative and long-lasting impact on human capital accumulation in less-developed regions.

This simple observation is intriguing because it provides a link between climate damage, economic growth, and mitigation capacity. Since human capital is an essential driver of sustainable economic growth, the expected loss of human capital is a serious obstacle for the economic and social development in climate-sensitive regions. The resulting sluggish development, together with a chronic shortage of human capital, makes it difficult for these regions to allocate sufficient financial and human resources to badly-needed mitigation activities. As Yohe (2001) and Winkler et al. (2007) point out, a country's ability to implement emission mitigation depends on its level of development, including a sufficient stock of human capital. Put differently, if the damage from climate change can be weakened, mitigation capacity will be enhanced in otherwise ill-equipped regions, thus providing a basis for long-term mitigation efforts at a global level. Averting climate damage today will help to avert damage in the future as well.

The most-often discussed policy for averting climate damage is the reduction of carbon dioxide emission. However, weakening climate damage through mitigation takes time, while global climate is changing already and the expectation is that this trend will continue due to the inertia of the climate system, even if the amount of carbon emission were significantly reduced today (IPCC, 2014). Hence, if current and future climate damage is to be reduced, then adaptation should play an important role, especially in climate-sensitive regions. The problem, though, is that for developing countries, many of which are located in climate-sensitive regions, capital for and knowledge of effective adaptation are typically unavailable. To make things worse, even modest additional warming in these countries requires large adjustments to the way people live, while possible adaptation options are limited by resources and inadequate infrastructure (World Bank, 2010a). Developing countries, particularly the poorest and most exposed, therefore require assistance in adapting to the changing climate.

Unfortunately, financial and technological assistance available for developing countries is small compared to the projected needs. Indeed, World Bank (2010a) estimates that current financing for adaptation and mitigation is less than five percent of what may be needed annually by the year 2030. This small percentage is due, at least in part, to the fact that adaptation assistance is primarily thought of as humanitarian aid, without taking economic aspects into consideration. In the realm of international politics, where no country can be forced to cooperate, this lack of perceived economic incentives makes financing the required assistance more difficult. After all, it does not seem a fair deal for developed countries to unilaterally make a financial commitment without any promise of mitigation efforts by developing countries. As we show in this paper, however, financial aid to enhance adaptation capacity of vulnerable countries makes good sense, both in terms of efficiency and incentive compatibility. Adaptation assistance, when appropriately designed, makes developing countries more capable of engaging in mitigation activities in the future. In this sense, the climate policy discussion can be viewed as 'adaptation for mitigation', not as 'adaptation or mitigation'.

To formalize this argument, the present paper develops a dynamic model of a North-South economy where the accumulation process of human capital is negatively influenced by the global stock of pollution. While South is more vulnerable to the damage from pollution, North can make a commitment to provide assistance so that South can protect itself against the expected damage. Given the absence of an effective international treaty, both regions are assumed to behave in a non-cooperative manner. We show the existence of a Nash equilibrium and characterize the equilibrium strategy of each region. The short-term and long-term impacts of adaptation assistance are examined in detail.

To the best of our knowledge, this paper is the first to examine the consequences of human-capital degradation caused by pollution in a dynamic and strategic environment. In the endogenous growth literature, Ikefuji and Horii (2012) consider the possible destruction of physical and human capital due to pollution, but their analysis is based on a single-region model. In a similar context, a North-South framework is introduced by Bretschger and Suphaphiphat (2014). Although they examine the impact of international financial assistance, the strategic interaction is absent in their model because their focus is on the comparison of different policy scenarios. As we shall see shortly, the interaction between human capital and global pollution has strategic significance in dynamic settings. Through a channel of dynamic influence from one region to another, the regions' best responses can be strategic complements. This finding is particularly relevant from the perspective of global environmental protection. If the regions' actions were strategic substitutes rather than complements, then additional future mitigation efforts by South would discourage North from remaining active in pollution reduction, making the net impact ambiguous.

The adaptation literature is primarily concerned with the optimal level of adaptation or the optimal mix with mitigation. Kane and Shogren (2000), for example, consider a static model where the risk of climate change is endogenous and investigate the optimal portfolio of mitigation and adaptation. They show that the optimal level of adaptation, quite intuitively, depends on whether the two types of policies are complements or substitutes. Ingham et al. (2013) examine a variety of economic models with mitigation-adaptation interplay and conclude that these policies are most likely to be substitutes in the sense that strengthening one type of policy will weaken the other. This result is mostly consistent with the numerical analysis based on integrated assessment models by de Bruin et al. (2009) and others. A theoretical analysis in a dynamic context is conducted by Bréchet et al. (2013), who consider a social planner problem in a Solow-Swan one-sector growth model, in which adaptation and mitigation are separate decision variables. Their results suggest that the optimal level of adaptation depends on the stage of development of the country. While the characterization of optimal adaptation policy has great policy relevance in itself, these studies do not incorporate the interaction between heterogeneous regions, which is inherent to the problem of global climate change.

Recently, the strategic aspect in the presence of mitigation-adaptation interplay has received some attention. Buob and Stephan (2011) analyze a non-cooperative two-stage game in which multiple regions simultaneously choose the level of mitigation in the first stage and the level of adaptation in the second. They show that, at equilibrium, a positive mixture of mitigation and adaptation can only emerge when the marginal cost of adaptation depends inversely on the global level of mitigation. Closer to the present paper are Onuma and Arino (2011) and Ebert and Welsch (2012). Based on a static North-South model, Onuma and Arino (2011) assume that adaptation is only possible for one region and investigate the consequences of improving the adaptation capacity. Using a similar two-region static mitigation-adaptation model, Ebert and Welsch (2012) study the roles of various aspects of the economy, including productivity, adaptation capacity, and sensitivity to pollution damage. Perhaps the main message of both papers is that an enhancement of adaptation capacity in one region can cause an increase of regional emission. This is a direct consequence of the fact that mitigation and adaptation are substitutes. Accordingly, unilateral improvements of adaptation capacity will negatively affect the welfare of the other region. This result, however, crucially depends on the static nature of the analysis. In a dynamic setting, where human capital accumulation is taken into account, adaptation can be a complement to mitigation in the sense that the former stimulates the latter in the long run.

The main contribution of our paper is twofold. First, we develop a multi-region dynamic model where human capital accumulation is influenced by global pollution. The model is simple enough for theoretical analysis, yet captures the essential aspects of the dynamics between economy and the environment, both within a region and across regions. This provides a general framework in which strategic interactions can emerge through the channel of human capital accumulation. Second, in the specific context of adaptation, we analyze the impact of assistance from one region to another. We show in particular that, although enhancing adaptation capacity in one region may cause a temporary increase of pollution in the short run, the long-term level of pollution stock is likely to decline. Making a commitment to adaptation assistance can therefore be incentive compatible and Pareto improving. This finding contrasts sharply to the existing literature, which either considers a non-strategic setting or a static model. Policy implications are discussed and robustness checks performed.

The remainder of the paper is organized as follows. Section 2 develops the benchmark North-South model without adaptation. The equilibrium of the model is derived and characterized in Section 3. Section 4 introduces adaptation of South together with a transfer from North, followed by a detailed analysis of the impacts of adaptation in Section 5. Section 6 investigates the welfare implications of adaptation assistance and examines the incentive compatibility of such assistance. The results are numerically illustrated in Section 7 based on a more general specification of the model. Section 8 concludes. All proofs are in the appendix.

2 Model without transfers

Our stylized economy consists of two regions: North (*n*) and South (*s*). We consider an infinite-horizon model where periods are equally spaced in time. Periods are indexed by $t = 0, 1, \dots$, where period t denotes the time interval between point t and point $t + 1$. Each region contains two sectors: production $Y_{i,t}$ and abatement $A_{i,t}$, where i denotes the region and t the time period.

Total 'effective' labor available in region i during period t is given by $L_{i,t}$, the stock of human capital, and the process of human capital accumulation is described by

$$L_{i,t+1} = \eta_i e^{-\zeta_{i,t} M_t} L_{i,t}, \tag{1}$$

which depends explicitly on the pollution stock M_t. Notice that pollution is a global, not a regional, phenomenon, so that each region faces the same amount of pollution. The parameter $\eta_i - 1$ denotes the baseline growth rate of human capital in the absence of pollution. We assume $\zeta_{i,t} > 0$, so that the growth rate of human capital is negatively affected by pollution. The effective labor force is divided between the production sector ($L^y_{i,t}$) and the abatement sector ($L^a_{i,t}$):

$$L_{i,t} = L^y_{i,t} + L^a_{i,t}, \tag{2}$$

and we write

$$L^y_{i,t} = (1 - b_{i,t})L_{i,t}, \qquad L^a_{i,t} = b_{i,t}L_{i,t}, \tag{3}$$

so that $b_{i,t}$ denotes the share of effective labor used in the abatement sector.

The production function of region i at period t takes the form

$$Y_{i,t} = \Omega_{i,t}e^{-\xi_{i,t}M_t}(L^y_{i,t})^{\alpha}P^{1-\alpha}_{i,t} \qquad (0 < \alpha < 1), \tag{4}$$

where $P_{i,t}$ denotes the amount of a polluting input and $\Omega_{i,t}e^{-\xi_{i,t}M_t}$ captures the total factor productivity of region i. We assume $\xi_{i,t} > 0$, so that the pollution stock negatively affects productivity.

Abatement activities require labor input $L^a_{i,t}$, and we specify

$$A_{i,t} = \mu(L^a_{i,t})^{\gamma} \qquad (\mu > 0, \;\; 0 < \gamma < 1). \tag{5}$$

The net emission $E_{i,t}$ of pollutants in period t is determined by the polluting input and the amount of emission abated during that period:

$$E_{i,t} = P_{i,t} - A_{i,t} \geq 0. \tag{6}$$

Locally emitted pollutants are accumulated at a global level, and the dynamics is governed by

$$M_{t+1} = (1 - \delta_m)M_t + E_{n,t} + E_{s,t} \qquad (0 < \delta_m < 1), \tag{7}$$

where δ_m denotes the depreciation rate of the pollution stock.

In our model, North and South are allowed to differ from each other in several respects: vulnerability to pollution ($\xi_{i,t}$ and $\zeta_{i,t}$), productivity ($\Omega_{i,t}$), baseline growth rate of human capital (η_i), and initial amount of human capital ($L_{i,0}$). By assuming $\xi_{s,t} \geq \xi_{n,t}$ and $\zeta_{s,t} \geq \zeta_{n,t}$, we characterize South as being more vulnerable to pollution than North due to a lack of adaptation capability. This gap can be narrowed if North provides assistance to South, but for the moment we assume that no such assistance takes place. We shall relax this assumption later.

We let consumption equal output,

$$C_{i,t} = Y_{i,t} \tag{8}$$

and define the welfare function as

$$W_i = U(C_{i,0}) + \beta U(C_{i,1}) + \beta^2 U(C_{i,2}) + \cdots \qquad (0 < \beta < 1), \tag{9}$$

where β denotes the discount factor. To simplify the analysis, we introduce the value function $V_{i,2}(L_{i,2}, M_2)$ at the beginning of period $t = 2$, so that we can write

$$W_i = U(C_{i,0}) + \beta U(C_{i,1}) + \beta^2 V_{i,2}(L_{i,2}, M_2). \tag{10}$$

We interpret period 1 as the short-run future and period 2 as the long run. This three-period framework (containing periods 0, 1, and 2) captures the dynamic interaction of interest and hence is sufficient for our purpose. For the moment we assume that $U(C) = \log(C)$, and we employ a linear approximation to the value function, so that

$$V_{i,2}(L_{i,2}, M_2) = \phi_{i,L} L_{i,2} - \phi_{i,M} M_2 \qquad (\phi_{i,L} > 0, \;\; \phi_{i,M} > 0). \tag{11}$$

These assumptions are relaxed in Section 7, where we discuss the robustness of our results.

North and South are assumed to behave in a non-cooperative manner, and choose P and b simultaneously. Formally, we consider the open-loop Nash equilibrium, which is defined by a list $\{P_{n,t}, P_{s,t}, b_{n,t}, b_{s,t}\}_{t=0,1}$ such that for each $i \in \{n, s\}$

$$\{P_{i,t}, b_{i,t}\}_{t=0,1} \in \operatorname{argmax} W_i \qquad \text{subject to (1)–(10)}, \tag{12}$$

with $L_{i,0} > 0$, $M_0 > 0$, and given the control variables of region $j \neq i$.

3 Equilibrium analysis without transfers

The model's equilibrium is characterized by the following proposition.

Proposition 1. *Our model has an equilibrium with an interior solution if μ, α, and $\zeta_{i,t}$ are all sufficiently small and the two regions are sufficiently homogeneous. The equilibrium is then characterized by*

$$MC_{i,t}(b_{i,t}) = MB_{i,t}(b_{n,t}, b_{s,t}) \tag{13}$$

and

$$P_{i,t} = (1-\alpha)\left(MC_{i,t}(b_{i,t})\right)^{-1} \tag{14}$$

for $t = 0, 1$, where $MC_{i,t}$ and $MB_{i,t}$ are defined by

$$MC_{i,t}(b_{i,t}) = \alpha \left(\gamma \frac{1-b_{i,t}}{b_{i,t}} \mu (b_{i,t} L_{i,t})^{\gamma} \right)^{-1} \tag{15}$$

and

$$MB_{i,t}(b_{n,t}, b_{s,t}) = \begin{cases} \beta\xi_{i,1} + \beta^2\phi_{i,L}\zeta_{i,1}L_{i,2} + \beta^2(1-\delta)\phi_{i,M} & (t=0), \\ \beta\phi_{i,M} & (t=1). \end{cases} \tag{16}$$

What we mean by 'sufficiently small' and 'sufficiently homogeneous' is explained in the appendix. There we obtain upper bounds for μ, α, and ζ. Also, as Lemma 2 in the appendix shows, North and South can be heterogeneous, but we have not been able to show theoretically how heterogeneous the two regions may be. Our simulations suggest, however, that the regions may be quite heterogeneous and still qualify as 'sufficiently homogeneous'. Our theoretical results have therefore practical relevance, and this is confirmed by the numerical examples in Section 7, which show that the equilibrium can be computed within a reasonable range of numerical specifications.

In Proposition 1, $MC_{i,t}$ and $MB_{i,t}$ are the current-value cost and benefit at period t for region i of marginally decreasing M_{t+1}. Notice that $L_{i,1}$ in (15) is determined by (1) given M_0 and $L_{i,0}$. This is why we write $MC_{i,t}$ as a function of $b_{i,t}$ for $t = 0$ and 1. Similarly, given M_0 and $L_{i,0}$, $L_{i,2}$ in (16) is determined by $(b_{n,t}, b_{s,t})$ for $t = 0$ and 1, through (1), (6), (7), and (15). This is why we write $MB_{i,t}(b_{n,t}, b_{s,t})$. It follows from (13) and (14) that the equilibrium level of emission is given by

$$E_{i,t} = \left(\gamma \cdot \frac{1-\alpha}{\alpha} \cdot \frac{1-b_{i,t}}{b_{i,t}} - 1\right) \mu (b_{i,t} L_{i,t})^{\gamma} \tag{17}$$

for $t = 0, 1$.

Condition (13) requires that the cost and benefit of marginally decreasing M_{t+1} should be equalized on current-value basis, which determines the equilibrium values of b's. Condition (14), on the other hand, suggests that the marginal cost of reducing M_{t+1} must be equalized between the two control variables ($b_{i,t}$ and $P_{i,t}$) by which the values of P's are pinned down. Notice that in (16) the first term of $MB_{i,0}$ reflects the impact of M_1 on $Y_{i,1}$ while its impact on $L_{i,2}$ is incorporated in the second term. The last term in $MB_{i,0}$ and the (only) term in $MB_{i,1}$ approximately capture both effects from period $t = 2$ onwards.

The first-order conditions already reveal how the novel features of our model affect the nature of equilibrium. One of the unique aspects of our model is that the pollution stock negatively affects not only production, but also human capital. To clarify the role of this additional channel of externality, suppose for the moment that $\zeta_{i,t} = 0$ so that the pollution externality only exists in the production sector. In this case, $b_{i,t}$ is determined by

$$\alpha \left(\gamma \frac{1-b_{i,t}}{b_{i,t}} \mu (b_{i,t} L_{i,t})^{\gamma}\right)^{-1} = \begin{cases} \beta \xi_{i,1} + \beta^2 (1-\delta) \phi_{i,M} & (t=0), \\ \beta \phi_{i,M} & (t=1), \end{cases} \tag{18}$$

for $i = n, s$. This equation is independent of $b_{j,t}$, meaning that the best response of each region is not affected by the action of the other region. This somewhat counter-intuitive result is due to the combination of a logarithmic utility function and an exponential damage function. An increase of emission in one region decreases the utility of the other region, but only through a constant term. As a result, the equilibrium levels of regional emissions are independent of each other. This result holds exactly only for this particular combination of utility and damage functions. The logarithmic-exponential combination greatly simplifies the analysis without however losing the essence of the problem; see Golosov et al. (2014) for a detailed discussion in the context of climate change. We show in Section 7 that our main results are not sensitive to this assumption.

Now suppose that $\zeta_{i,t} > 0$ so that human capital is affected by the pollution stock. As is clear from (16), $MB_{i,1}$ is still independent of $b_{j,1}$ and therefore $b_{n,1}$ and $b_{s,1}$ are chosen independently. On the other hand, $MB_{i,0}$ is a decreasing function of M_1. This, together with (18) and (7), shows that $MB_{i,0}$ is an increasing function of $b_{j,0}$. Therefore, once region j decreases its emission, the marginal benefit curve of region $i \neq j$ shifts upward, providing region i with an incentive to decrease its own emission as well. In other words, $b_{n,0}$ and $b_{s,0}$ are strategic complements. This leads to our next proposition.

Proposition 2. *At equilibrium, emissions in period* 0 *(*$E_{i,0}$*) are strategic complements while emissions in period* 1 *(*$E_{i,1}$*) are not affected by each other.*

The second part of the proposition is an artifact of the functional specification as explained above. To see why the first part holds, notice that any decrease in $E_{i,0}$ increases the amount of human capital that survives the damage from pollution in the future. In other words, under the pollution externality in human capital accumulation, pollution abatement can be regarded as 'investment' in human capital. What matters for the choice of abatement level is the shadow value of human capital. When the pollution stock is expected to be large in the future, the corresponding damage to human capital is relatively large. In such a case, the shadow value of human capital is relatively small because a large fraction of investment in human capital will be lost. If one region reduces its emission, however, then the global stock of pollution in the future declines and, as a consequence, a larger portion of human capital in both regions will survive the damage from pollution. This means that emission reduction in one region increases the shadow value of human capital in both regions. The larger shadow value of human capital then leads to a stronger incentive to 'invest' in human capital by engaging more actively in emission abatement.

The mechanism discussed above is more general than it may appear. For example, the result holds even when the abatement sector is absent from the model. This can be seen by setting $\mu = 0$ so that $b_{i,t} = 0$ at equilibrium. Then a similar argument as above shows that $P_{n,0}$ and $P_{s,0}$ (and hence $E_{n,0}$ and $E_{s,0}$) are strategic complements. Moreover, adaptation does not play any role for this result; it follows solely from the fact that emission abatement by one region at one point in time influences the shadow value of other regions' capital at another point in time. We call this the *dynamic complementarity effect*. While consideration of this dynamic effect is largely absent in the literature, it can have important policy implications as will be exemplified below in the context of adaptation assistance.

4 Introducing transfers

We noticed in Section 2 that North and South can be different from each other in four respects: vulnerability to pollution, productivity, baseline growth rate of human capital, and initial amount of human capital; and that the assumptions $\xi_{s,t} \geq \xi_{n,t}$ and $\zeta_{s,t} \geq \zeta_{n,t}$ characterize South as being more vulnerable to pollution than North. This vulnerability gap can be narrowed if North provides assistance to South, and this assistance is now introduced in the model. We shall assume that only North has the knowledge and technology to effectively enhance the adaptation capability of South.

To capture the idea of adaptation, let R_t denote 'adaptation-related capital', by which we mean the durable good in South which can be used to reduce damage from pollution. Typical examples of adaptation-related capital are flood-control dikes, improved hospitals and schools, and grain storage facilities (World Bank, 2010b).

We then specify

$$\xi_{s,t} = \xi_s(R_t), \qquad \zeta_{s,t} = \zeta_s(R_t) \tag{19}$$

for some decreasing and continuously differentiable functions ξ_s and ζ_s. We assume that

$$\xi_s'(0) > -\infty, \qquad \lim_{R \to \infty} \xi_s(R) \geq \xi_{n,t}, \tag{20}$$

and

$$\zeta_s'(0) > -\infty, \qquad \lim_{R \to \infty} \zeta_s(R) \geq \zeta_{n,t}. \tag{21}$$

North can invest in R_t so that South can better protect itself against pollution. The value of R_t in the absence of adaptation assistance is normalized to 0 without loss of generality.

We focus on the case where the investment decision by North is made only once. To be more precise, North chooses τ ($0 \leq \tau \leq 1$) and invests a fraction $\tau Y_{n,0}$ of output in R_0. By measuring R_t in the unit of the produced good, we may write

$$R_0 = \tau Y_{n,0}. \tag{22}$$

The adaptation-related stock depreciates over time, and we specify

$$R_1 = \delta_r R_0, \qquad R_2 = 0, \tag{23}$$

so that only a fraction $0 < \delta_r < 1$ of the newly invested stock remains in the short run and it fully depreciates in the long run.

Without transfers, we assumed in (8) that consumption equals output. With transfers, the consumption function is adjusted to

$$C_{i,t} = \begin{cases} (1-\tau)Y_{n,0} & \text{for } (i,t) = (n,0), \\ Y_{i,t} & \text{otherwise}. \end{cases} \tag{24}$$

North and South are again assumed to behave in a non-cooperative manner and the game proceeds in two stages. In the first stage, North chooses τ, anticipating the non-cooperative game with South in the stage that follows. This means that North can make a commitment to the adaptation assistance in the first period, but not to the level of mitigation. In the second stage, North and South simultaneously choose P and b, taking τ as given.

5 Adaptation

We solve the problem backwards. We note first that the level of τ chosen in the first stage does not directly affect North's strategy in the second stage. To see this we write

$$U(C_{n,0}) = \log((1-\tau)Y_{n,0}) = \log(1-\tau) + \log(Y_{n,0}), \tag{25}$$

which means that τ does not affect the marginal rate of substitution. Hence, North's behavior is not affected by τ as long as South does not change its strategy. The behavior of South, however, is affected by τ through the changes in $\xi_{s,t}$ and $\zeta_{s,t}$. In response to an enhanced adaptation capability, South will adjust its resource allocation and emission level. This in turn influences the behavior of North through the negative externality of pollution.

We know from Proposition 2 that the equilibrium level of regional emission in period 1 is determined independently of what the other region does. In period 0, on the other hand, emissions of North and South are strategic complements due to the dynamic complementarity effect we identified in Section 3. This result, together with the observation above, suggests that if a higher adaptation capability implies a greater willingness of South to abate emission, it is likely that adaptation at the local level induces mitigation at the global level. In what follows, we clarify the conditions under which such a scenario may arise.

5.1 Long-run emission

Let us first focus on the long-run effect, more precisely the long-run impact of enhanced adaptation capability on South's emission. In period $t = 1$ the equilibrium condition (13) implies that

$$\alpha \left(\gamma \frac{1 - b_{s,1}}{b_{s,1}} \mu (b_{s,1} L_{s,1})^{\gamma} \right)^{-1} = (1 - \alpha) P_{s,1}^{-1} = \beta \phi_{s,M}, \tag{26}$$

where

$$L_{s,1} = \eta_s e^{-\zeta(R_0) M_0} L_{s,0}. \tag{27}$$

Taking the total derivative of (26) with respect to R_0, we obtain

$$\frac{dP_{s,1}}{dR_0} = 0, \quad \frac{db_{s,1}}{dR_0} \frac{1}{b_{s,1}} = -\frac{1 - b_{s,1}}{b_{s,1}} \left(\frac{\gamma b_{s,1}}{1 - \gamma + \gamma b_{s,1}} \right) M_0 \zeta_s'(R_0) > 0. \tag{28}$$

Since $E_{s,1} = P_{s,1} - \mu(b_{s,1} L_{s,1})^{\gamma}$, we then have

$$\begin{aligned} \frac{dE_{s,1}}{dR_0} &= \frac{dP_{s,1}}{dR_0} - \gamma \mu (b_{s,1} L_{s,1})^{\gamma} \frac{db_{s,1}}{dR_0} \frac{1}{b_{s,1}} \\ &= \gamma \frac{1 - b_{s,1}}{b_{s,1}} \mu (b_{s,1} L_{s,1})^{\gamma} \left(\frac{\gamma b_{s,1}}{1 - \gamma + \gamma b_{s,1}} \right) M_0 \zeta_s'(R_0) < 0. \end{aligned} \tag{29}$$

This means that the long-run emission in South unambiguously declines as a result of enhanced adaptation capability. We have thus proved the following result.

Proposition 3. *When the initial adaptation stock in South is marginally increased, the long-run emission from South decreases while the long-run emis-*

sion from North does not change. Accordingly, at least in the long run, enhanced adaptation capability in South helps decrease pollution at a global level.

The mechanism behind this result is quite simple. Thanks to the enhanced adaptation capability in South, human capital $L_{s,1}$ increases, and this enlarges productivity in the abatement sector. Put differently, the long-run cost of mitigation declines as a result of short-run adaptation. We call this the *cost-reduction effect* of adaptation. When human capital is protected against pollution today, a larger portion of effective labor becomes available in the future, not only for production, but also for mitigation activities.

5.2 Short-run emission

Once the adaptation capability of South is enhanced, long-run emission declines unambiguously because of the cost-reduction effect. The short-run impact is, however, not straightforward. To see why, consider the equality $MC_{i,0}(b_{i,0}) = MB_{i,0}(b_{n,0}, b_{s,0})$, which determines $b_{i,0}$. By taking the total derivative of this equation with respect to R_0, we obtain

$$\frac{db_{s,0}}{dR_0} = \Gamma_s \frac{\partial MB_{s,0}}{\partial R_0}, \quad \frac{db_{n,0}}{dR_0} = \Gamma_n \frac{\partial MB_{s,0}}{\partial R_0}. \tag{30}$$

Our framework allows us to determine the signs of Γ_s and Γ_n.

Proposition 4. *Γ_s and Γ_n are both strictly positive.*

On the other hand, it follows from (17) that

$$\frac{dE_{i,0}}{dR_0} = -\left(\frac{b_{i,0}}{1 - b_{i,0}} + (1-\alpha)(1-\gamma) \right) \frac{P_{i,0}}{1-\alpha} \frac{db_{i,0}}{dR_0} \frac{1}{b_{i,0}}. \tag{31}$$

Hence,

$$\frac{dE_{i,0}}{dR_0} < 0 \iff \frac{db_{i,0}}{dR_0} > 0 \iff \frac{\partial MB_{s,0}}{\partial R_0} > 0 \tag{32}$$

for $i = n, s$. Therefore, a higher adaptation capability in South results in a short-run emission reduction if and only if the marginal benefit curve $MB_{s,0}$ of South shifts upward when its adaptation capability is enhanced.

To decompose the impact of adaptation on the marginal benefit curve, we write

$$\frac{\partial MB_{s,0}}{\partial R_0} = \beta\xi_s'(\delta_r R_0)\delta_r + \beta^2\phi_{s,L}\zeta_s'(\delta_r R_0)\delta_r L_{s,2} \\ - \beta^2\phi_{s,L}\zeta_s(\delta_r R_0)\left(\zeta_s'(\delta_r R_0)\delta_r M_1 + \zeta_s'(R_0)M_0\right)L_{s,2}. \qquad (33)$$

The first and the second terms on the right-hand side are both negative, making marginal benefit smaller. We call this the *substitution effect* of adaptation because, under this effect, adaptation becomes a substitute for mitigation. The enhanced adaptation capability reduces the marginal damage from M_1 both in the production sector and in human capital accumulation. As a result, the substitution effect weakens the case for mitigation efforts in South. From the perspective of North, this poses a dilemma in integrating adaptation assistance into mitigation policy.

The third term in (33) is strictly positive, acting against the substitution effect. We call this the *complementarity effect* of adaptation because adaptation can become a complement to mitigation when this effect is sufficiently strong. The complementarity effect follows from a similar, but distinct, mechanism as pointed out in Section 5.1. An increase in R_0 boosts the growth rate of human capital, which increases the baseline human capital stock in the absence of pollution damage. This change is exogenous to South. Given the increased baseline of human capital, South then finds it more important to keep the growth rate from falling due to pollution. The larger is the stock of human capital, the greater is the importance of its growth rate. This implies a larger marginal benefit of pollution abatement since the expected decline in human capital growth can be partially avoided by abatement activities.

Compared with the substitution effect, the complementarity effect has two noteworthy features. First, the effect does not vanish even after the adaptation-related stock depreciates. Second, unlike the substitution effect, the magnitude of the complementarity effect is proportional to the level of pollution damage. These features are due to the fact that the complementarity effect follows from the changes in the stock of human capital in the future. Since human capital is a stock variable, any change in its current value affects its values in subsequent periods. This makes the complementary effect long-lasting. Also, because the enhanced adaptation capability boosts the growth rate of human capital, how much it benefits depends on the level of human capital, which is inversely proportional to the damage from the pollution stock. This is why the term $\zeta_s M_t$ appears in the complementarity effect, but not in the substitution effect.

It is not clear from (33) whether the complementarity effect outweighs the substitution effect. The net impact of adaptation on short-run emissions is, in general, ambiguous. Nevertheless, the sign of the net impact can be determined based on the following simple conditions.

Proposition 5. *There exists a constant $\bar{\delta_r} \in (0, 1]$ such that*

$$\left.\frac{dE_{i,0}}{dR_0}\right|_{R_0=0} < 0 \quad \textit{if} \quad \delta_r < \bar{\delta}_r. \tag{34}$$

Moreover, if $M_0 \geq 1/((1-\delta)\zeta_s(0))$, then there exists a constant $\bar{\zeta}'_s < 0$ such that

$$\left.\frac{dE_{i,0}}{dR_0}\right|_{R_0=0} < 0 \quad \textit{if and only if} \quad \zeta'_s(0) < \bar{\zeta}'_s. \tag{35}$$

The proposition first states that if the stock of adaptation-related capital augmented by North's assistance depreciates at a sufficiently fast rate, then adaptation assistance is always followed by a short-term decline in global pollution. To understand why this happens, set $\delta_r = 0$. In this extreme case the direct impact of adaptation assistance only exists in the initial period. Those damages that are already occurring in South are then partially alleviated, but the damages expected in the future are not affected by this assistance. Since the current damage is irrelevant for the substitution effect, the substitution effect vanishes. In fact, the first two terms in (33) disappear when $\delta_r = 0$. The complementarity effect, on the other hand, is still valid; see Equation (86) in the Appendix. The enhanced adaptation capability today increases the stock $L_{s,1}$ of human capital in the next period. This makes it more important to avoid the damage to the growth rate of $L_{s,1}$ because a decline in the growth rate then causes a significant decrease in $L_{s,2}$. As a result, the marginal benefit of reducing M_1 unambiguously shifts upward. This remains true as long as δ_r is sufficiently small.

The second part of the proposition is particularly interesting. Short-run emission declines if and only if adaptation assistance is sufficiently effective in preventing damage to human capital. As long as the initial pollution stock is large, this result holds even when δ_r is far away from zero. As (33) suggests, the effectiveness of adaptation in the production sector, which is captured by the absolute value of ξ'_s, always works in favor of the substitution effect. On the other hand, the effectiveness of adaptation in human capital accumulation, which is captured by the absolute value of $\zeta_s'(0)$, increases both the substitution effect and the complementarity effect. While the overall role of $\zeta_s'(0)$ is unclear in general, its contribution to the complementarity effect is always greater than its contribution to the substitution effect when M_0 is sufficiently large. This is because, as mentioned above, the complementarity effect is proportional to the level of damage, which is a monotonic transformation of the level of the pollution stock. Given that a higher value of $|\zeta_s'(0)|$ always works in favor of the complementarity effect, what matters is whether $|\zeta_s'(0)|$ is sufficiently large relative to $|\xi_s'|$. If this is the case, then the complementarity effect dominates and short-run emissions decline in both regions.

5.3 Pollution stock

For society as a whole, what matters most is whether the level of global pollution stock can be well-managed. The discussion so far suggests that the long-run emission always decreases thanks to the cost-reduction effect. Moreover, the short-run emission also decreases when the complementarity effect outweighs the substitution effect. This happens in particular when the adaptation in South is sufficiently effective for human capital protection, in which case it is quite obvious that both short-run and long-run pollution stocks decline. When the substitution effect is larger than the complementarity effect, however, the overall impact on the pollution stock is less obvious.

The long-run impact on the pollution stock is given by

$$\frac{dM_2}{dR_0} = (1-\delta)\frac{dM_1}{dR_0} + \frac{dE_{n,1}}{dR_0} + \frac{dE_{s,1}}{dR_0}, \tag{36}$$

where

$$\frac{dM_1}{dR_0} = \frac{dE_{n,0}}{dR_0} + \frac{dE_{s,0}}{dR_0}. \tag{37}$$

Suppose the initial stock of pollution is sufficiently large. Then Proposition 5 shows that

$$\left.\frac{dM_1}{dR_0}\right|_{R_0=0} < 0 \quad \text{if and only if} \quad |\zeta_s'(0)| > |\bar{\zeta}_s'|. \tag{38}$$

If $|\zeta_s'(0)| < |\bar{\zeta}_s'|$, then the substitution effect outweighs the complementarity effect and the short-run level of global pollution stock increases as a result of adaptation assistance. Even in this case, however, the stock of pollution can be smaller in the long run and this is where the cost-reduction effect comes into play. If the long-run cost-reduction effect is sufficiently large, it can compensate for the short-run substitution effect.

In order to see how this works, we recall from (29) that the cost-reduction effect is an increasing function of $|\zeta_s'(0)|$, just as the complementarity effect. This suggests that even if $|\zeta_s'(0)|$ is smaller than the threshold $|\bar{\zeta}_s'|$, the net impact of adaptation assistance to the long-run pollution stock can be negative as long as $|\zeta_s'(0)|$ is sufficiently close to $|\bar{\zeta}_s'|$. This argument is formalized in the following proposition.

Proposition 6. *Suppose* $M_0 \geq 1/((1-\delta)\zeta_s(0))$. *Then there exists a constant* $\tilde{\zeta}_s'$ *such that* $\bar{\zeta}_s' < \tilde{\zeta}_s' < 0$ *and*

$$\left.\frac{dM_2}{dR_0}\right|_{R_0=0} < 0 \quad \textit{if and only if} \quad \zeta_s'(0) < \tilde{\zeta}_s'. \tag{39}$$

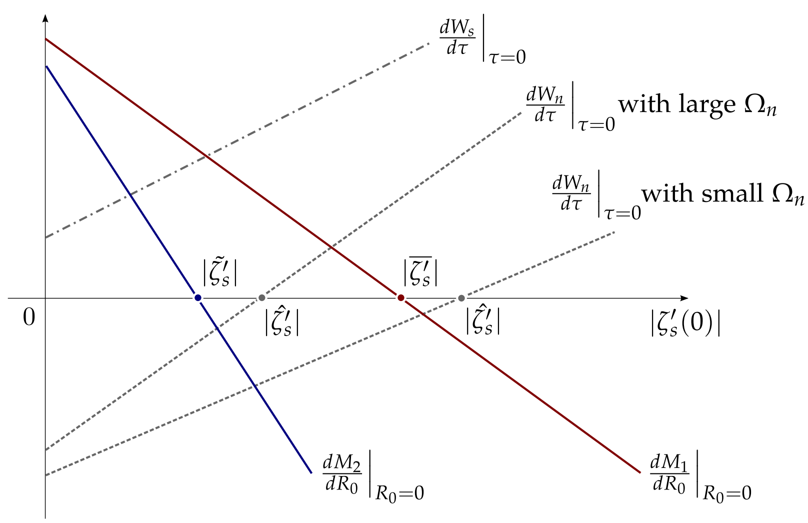


Figure 2: Impact of adaptation assistance

Figure 2 illustrates this result. When $|\zeta_s'(0)|$ is smaller than $|\tilde{\zeta}_s'|$, enhanced adaptation capability increases both the short-run and long-run levels of the pollution stock. When $|\zeta_s'(0)|$ is larger than $|\bar{\zeta}_s'|$, on the other hand, the short-term and long-term levels of the pollution stock both decline. When $|\zeta_s'(0)|$ is in-between $|\tilde{\zeta}_s'|$ and $|\bar{\zeta}_s'|$, the level of the pollution stock increases in the short run, but decreases in the long run.

6 Why should North transfer?

We now turn to the first stage in which North makes a commitment about adaptation assistance. The discussion so far suggests that adaptation assistance by North, if sufficiently effective for human capital protection, enables South to better engage in mitigation activity in the future and possibly provides a short-term mitigation incentive as well. This in turn benefits not only South but also North since the pollution stock is reduced at a global level. Of course, North needs to pay the cost of assistance in the form of suppressed consumption. The question then arises whether providing adaptation assistance to South is incentive-compatible for North. If the cost of adaptation assistance, which has to be borne in the initial period, is larger than the benefit of environmental improvement for North in subsequent periods, then North has no incentive to provide assistance in the first stage.

To examine this point further, let $W_i(\tau)$ denote equilibrium welfare of region i in the second stage, where τ is chosen by North in the first stage. North chooses τ in such a way that $W_n(\tau)$ is maximized. For our purpose it is sufficient to check when and under what conditions $dW_n/d\tau > 0$ evaluated at $\tau = 0$. When this is the case, then the equilibrium level of τ is always positive. Now, the marginal welfare with respect to τ is

$$\begin{aligned}\left.\frac{dW_n(\tau)}{d\tau}\right|_{\tau=0} &= -1 - \left(\frac{b_{n,0}}{1-b_{n,0}} + (1-\alpha)(1-\gamma)\right)\frac{db_{n,0}}{dR_0}\frac{1}{b_{n,0}}Y_{n,0} \\ &\quad - \left(\beta\xi_{n,1}\frac{dM_1}{dR_0} + \beta^2\phi_{n,L}\zeta_{n,1}L_{n,2}\frac{dM_1}{dR_0} + \beta^2\phi_{n,M}\frac{dM_2}{dR_0}\right)Y_{n,0}. \end{aligned} \tag{40}$$

The first and second terms in (40) together capture the net cost of adaptation assistance. The first term is the direct cost of reduced consumption measured in units of present value of utility. The second term reflects the fact that any change in τ (and hence in R_0) in the first stage causes an adjustment of South's emission in the second stage and also an adjustment of North's emission in response to the expected change in South's behavior. For example, if $db_{n,0}/dR_0$ is positive then the second term is positive; it represents the indirect cost of assistance in the form of additional abatement in the second stage. If $db_{n,0}/dR_0$ is negative then the second term is negative, implying that the cost of adaptation assistance will be partly compensated by a smaller abatement effort in the second stage. All benefits are captured by the third term.

The expression in (40) is a little complicated. Our next proposition is simpler and contains a necessary and sufficient condition for North to commit a positive amount of adaptation assistance in the first stage.

Proposition 7. *There exists* $\hat{\zeta}_s' < 0$ *such that*

$$\left.\frac{dW_n(\tau)}{d\tau}\right|_{\tau=0} > 0 \quad \textit{if and only if} \quad \zeta_s'(0) < \hat{\zeta}_s'. \tag{41}$$

The threshold $\hat{\zeta}_s'$ *is an increasing function of* $\Omega_{n,0}$. *In particular, if* $\Omega_{n,0}$ *is sufficiently large, then* $\hat{\zeta}_s' > \bar{\zeta}_s'$. *On the other hand, it is always the case that*

$$\left.\frac{dW_s(\tau)}{d\tau}\right|_{\tau=0} > 0. \tag{42}$$

Again, a key issue is the effectiveness of adaptation in protecting human capital. Proposition 7 shows that North always has an incentive to provide a positive level of adaptation assistance to South as long as the adaptation assistance is sufficiently effective for human capital protection. Moreover, even if the adaptation assistance is not very effective (so that the assistance causes a rise of pollution stock in the short run), North can still be better off by making a commitment to assist. This is possible if $\Omega_{n,0}$ is sufficiently large or, in other words, if North is already sufficiently wealthy. This point is illustrated in Figure 2. The wealthier North is, the more incentive it has to engage in adaptation assistance. Once the assistance materializes, South is better off in any case. Hence, providing adaptation assistance achieves a Pareto improvement whenever North has an incentive to do so. It is also worth noting that the welfare impact of adaptation assistance in South is increasing not only in $|\zeta_s'(0)|$ but also in δ_r; see Equation (99) in the appendix. This is good news for South, because South will obviously benefit more from adaptation assistance if it has a long-lasting effect.

The results presented so far have a number of implications, of which we mention two. First, once the damage to human capital is taken into account in a dynamic setting, emissions in different regions are likely to be strategic complements. A relevant question is then how to encourage coordination among regions. The coordination can be facilitated by North's commitment to adaptation assistance to South. Adaptation assistance has three distinct effects: cost-reduction, substitution, and complementarity. While the substitution effect weakens South's incentive to reduce pollution, the other two effects work in favor of a greater abatement incentive for South. In particular, when the adaptation assistance does not have a direct long-lasting effect or when it is sufficiently effective in protecting human capital, then the latter two effects dominate the former. South will then become more capable of reducing emission and will be more willing to do so. This in turn provides an additional incentive for North to engage in emission abatement in the future due to the strategic complementarity.

A second implication of our results is that adaptation assistance may cause a temporary increase in the pollution stock in the short run, while the long-term pollution stock declines. This happens when the effectiveness of adaptation is not sufficiently large. In terms of welfare, however, North can be compensated for the negative impact of such a temporary intensification of pollution as long as the region is sufficiently wealthy. We conclude therefore that wealthy countries should make a commitment to adaptation assistance in favor of poor countries, making sure that the assistance is targeted at those activities that effectively protect human capital in the poor countries against pollution damage. Alternatively, the assistance could be focused on those adaptation activities with only a short-lasting effect. Although such assistance is likely to be consistent with the incentives of the wealthy countries, it will naturally reduce the benefits for the poor countries.

7 Robustness

In what follows, we illustrate our results by presenting some simple numerical examples. In addition, the analysis in this section serves as a robustness check. Clear-cut policy implications in the preceding section are partly due to the simplifications used in the model. One might argue, for example, that our analytic results depend on the assumption that the model has only three periods. Another possible criticism is that our results might be only valid for the logarithmic utility function. We address these two issues below.

Of course, there are more model assumptions that can be challenged. Our model does not have physical capital, which is not entirely realistic for a dynamic model. Also, we do not explicitly model how the baseline accumulation process of human capital is determined. We could use more sophisticated equilibrium concepts instead of the open-loop Nash equilibrium. The one-shot nature we assume for adaptation investment may be too simplistic. Addressing these issues is certainly useful, but they would require significant modifications of the model, and are therefore extensions rather than robustness checks. Hence, we limit ourselves in this paper to the two robustness issues mentioned above.

7.1 Numerical model

For the numerical exercises in this section we specify the utility function as

$$W_i = \sum_{t=0}^{T} \beta^t U(C_{i,t}), \tag{43}$$

where

$$U(C) = \frac{C^{1-\epsilon} - 1}{1 - \epsilon} \quad \epsilon > 0. \tag{44}$$

We take the time horizon sufficiently long, so that the discount factor β^T will become very small. We may therefore ignore the contribution of the value function which we would otherwise need at the last period. Accordingly, the linear approximation we used in the three-period model is no longer necessary. Moreover, the functional form (44) is more general than the one used in the analytic model: the logarithmic function is a limiting case of (44) with $\epsilon \to 1$. This more general specification of the model allows us to demonstrate the robustness of our results. To quantify the damage from pollution, we specify functions ξ_s and ζ_s as

$$\xi_s(R) = \underline{\xi} + (\overline{\xi} - \underline{\xi}) e^{-\frac{\xi'}{\overline{\xi} - \underline{\xi}} R}, \quad \overline{\xi} > \underline{\xi} > 0, \quad \xi' \geq 0, \tag{45}$$

$$\zeta_s(R) = \underline{\zeta} + (\overline{\zeta} - \underline{\zeta}) e^{-\frac{\zeta'}{\overline{\zeta} - \underline{\zeta}} R}, \quad \overline{\zeta} > \underline{\zeta} > 0, \quad \zeta' \geq 0, \tag{46}$$

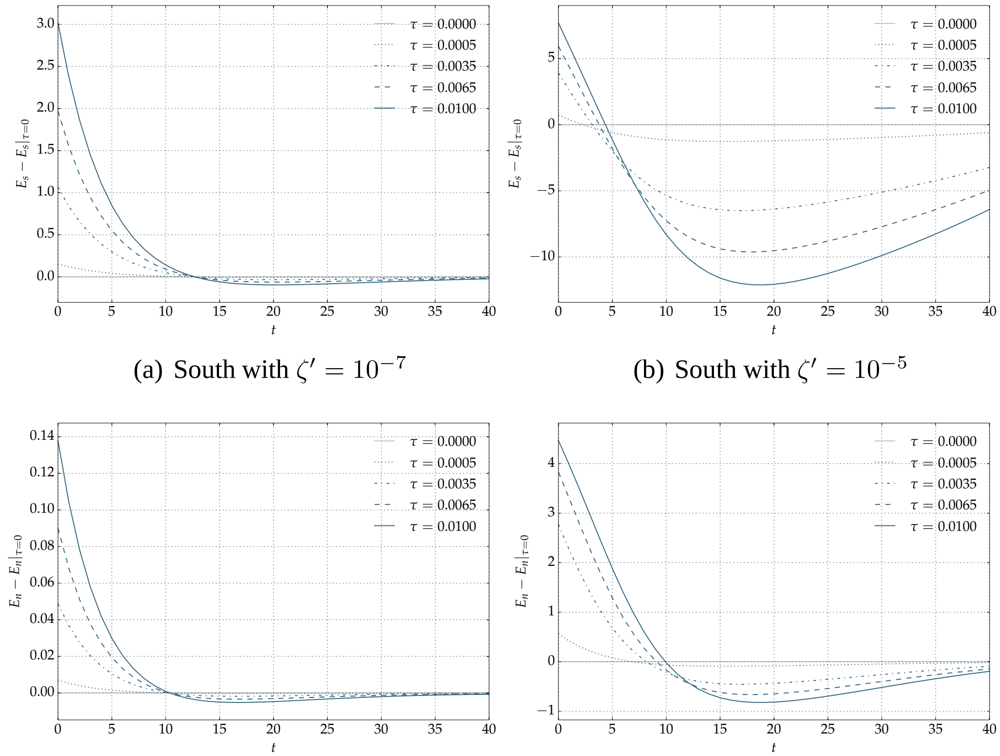
where the parameters are explained in Table 1, which also provides the numerical values chosen for the robustness experiment. With these specifications, we have $|\xi_s'(0)| = \xi'$ and $|\zeta_s'(0)| = \zeta'$ so that the effectiveness of adaptation in the production sector and in human capital accumulation is captured by ξ' and ζ', respectively. The depreciation process of the adaptation-related stock is now governed by $R_t = \delta_r^t R_0$ for $t = 0, 1, \ldots, T$.

Table 1: Parameter values for numerical simulations

Symbol	Value	Description
T	120	Time horizon
α	0.3	Labor elasticity of production
β	0.9	Discount factor
γ	0.8	Parameter in abatement function
ϵ	1.5	Consumption elasticity of marginal utility
μ	5.0	Parameter in abatement function
δ_m	0.025	Depreciation rate of pollution stock
δ_r	0.8	Remaining fraction of adaptation capital
η_i	1.0	Baseline human capital growth
M_0	800	Initial pollution stock
$L_{i,0}$	50	Initial human capital
$\Omega_{i,t}$	10	Baseline total factor productivity (constant)
$\xi_{n,t}$	0.0005	North's damage coefficient in production (constant)
$\overline{\xi}$	0.0010	South's damage coefficient in production for $R = 0$
$\underline{\xi}$	0.0005	South's damage coefficient in production for $R \to \infty$
ξ'	10^{-5}	Effectiveness of adaptation in South's production
$\zeta_{n,t}$	0	North's damage coefficient in human capital (constant)
$\overline{\zeta}$	0.00001	South's damage coefficient in human capital for $R = 0$
$\underline{\zeta}$	0	South's damage coefficient in human capital for $R \to \infty$
ζ'	$[10^{-7}, 10^{-5}]$	Effectiveness of adaptation in South's human capital

7.2 Results

We only report the results for the case $\epsilon = 1.5$, but very similar results are obtained for different values of ϵ, including the case of logarithmic utility. Figure 3 depicts the equilibrium regional emissions for different values of τ and ζ'. As shown in Panel (a) of the figure, when adaptation assistance is not very effective for human capital protection ($\zeta' = 10^{-7}$), North's investment in adaptation capital in South causes a short-term increase of South's emission. This is a consequence of the substitution effect. In the long run, when the adaptation capital depreciates sufficiently (Figure 4(a)), the combined effect of complementarity and cost reduction becomes important, due to the additional human capital protected by the adaptation (Figure 4(b)). As a result, the temporary hike of regional emission is followed by a decrease of emission in subsequent periods. The magnitude of the long-term emission reduction is, however, relatively small.



(a) South with $\zeta' = 10^{-7}$

(b) South with $\zeta' = 10^{-5}$

(c) North with $\zeta' = 10^{-7}$

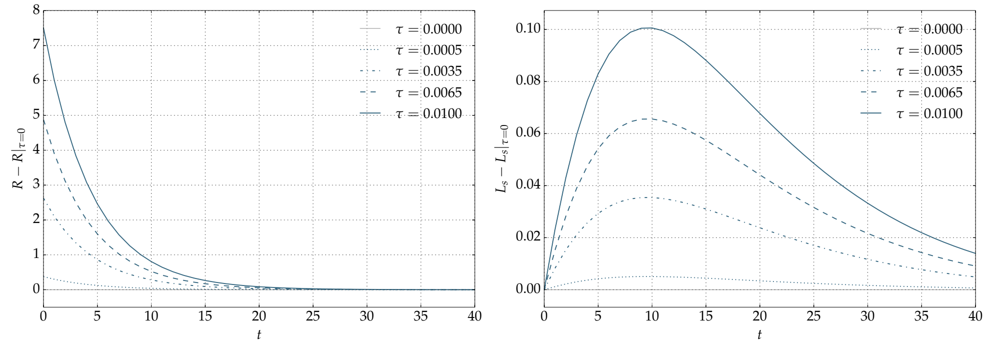
(d) North with $\zeta' = 10^{-5}$

Figure 3: Equilibrium regional emissions relative to the case with $\tau = 0$

The role of complementarity and cost-reduction is much more pronounced when the adaptation assistance can more effectively protect human capital. This can be seen in Figure 3(b), which presents the equilibrium emission of South for a larger value of ζ'. In this case the increase in short-term emission becomes larger, but the period of emission hike ends at an earlier point in time. Moreover, the emission reduction thereafter is significantly larger and remains even after the adaptation capital has depreciated completely. This is consistent with our theoretical findings in the preceding section.

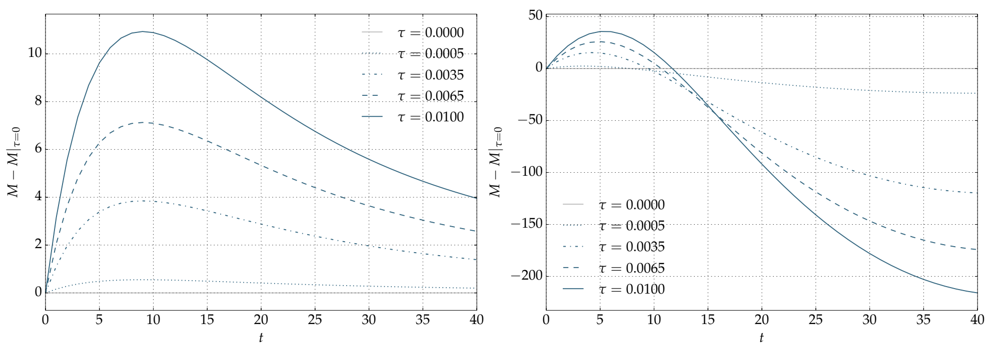
In Figures 3(c) and (d) we depict the equilibrium emission of North. The qualitative characteristics of North's emission are quite similar to those of South. This is an indication that the emissions of these regions are strategic complements, in agreement with the analytic results of the simpler model. Accordingly, the global emission in response to adaptation assistance follows the same pattern: a short-term increase and a long-term decrease.

The equilibrium pollution stock is reported in Figure 5. Again, the quali-



(a) Adaptation capital (b) Human capital in South

Figure 4: Adaptation capital and human capital ($\zeta' = 10^{-7}$)

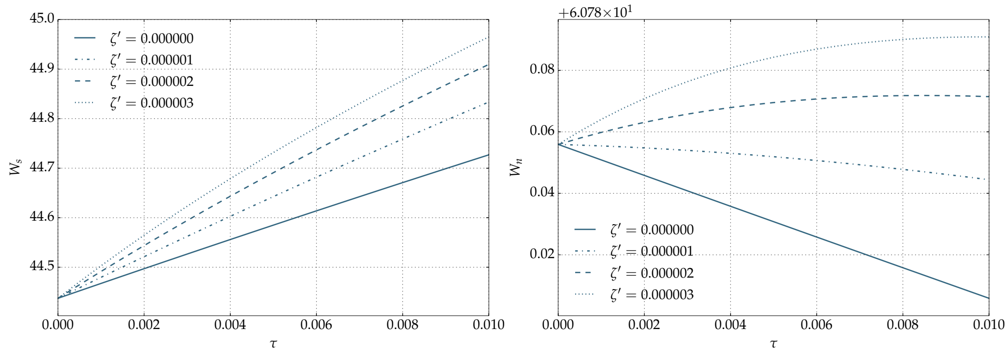


(a) $\zeta' = 10^{-7}$ (b) $\zeta' = 10^{-5}$

Figure 5: Equilibrium global pollution stock relative to the case with $\tau = 0$

tative characteristics we found in the analytic model are replicated. When the adaptation assistance is not effective in terms of human capital protection, both the short-term and long-term levels of pollution stock rise (Panel (a)). If the assistance is targeted to those adaptation activities with more effective human capital protection, the stock of pollution eventually declines although the economy experiences a slight short-term deterioration of the environment (Panel (b)). The more effective the adaptation is in protecting human capital, the shorter is the period of temporary environmental degradation.

Figure 6 shows the equilibrium welfare as a function of τ. Adaptation assistance makes South always better off, regardless of its effectiveness in human capital protection. On the other hand, North can be worse off if the effectiveness is relatively small. Hence, North only makes a commitment to a positive level of adaptation assistance when it can effectively reduce the damage from pollution



(a) South (b) North

Figure 6: Equilibrium regional welfare

to human capital in South, precisely what we would expect from the analytic results obtained earlier.

In summary and with appropriate caution, the numerical exercises in this section suggest that our results are robust. The three-period framework of the preceding section may seem restrictive, but the same qualitative results are obtained for a model with a longer time horizon. Some of the knife-edged results only hold for the logarithmic utility function, but most of the important features of the model survive when we employ a more general utility function. The key message of this paper is therefore more general than it may appear at first.

8 Conclusions

In this paper, we developed a dynamic model of a North-South economy, where the accumulation process of human capital is negatively influenced by the global stock of pollution. By characterizing the equilibrium strategy of each region, we showed that the interaction between human capital and global pollution has strategic significance in dynamic settings. More precisely, the regional best responses will be strategic complements. A key role is played by the dynamic complementarity effect. In the presence of pollution externality in human capital accumulation, emission abatement by one region at one point in time influences the shadow value of the other region's capital at another point in time. This result is particularly important for global environmental protection. Establishing the complementary relationship between regional behaviors opens up the possibility of mutually beneficial cooperation among regions.

Our detailed analysis of adaptation assistance shows that a unilateral commitment by one region to help the other can make both regions better off. In particular, adaptation assistance by a wealthy region will enable a vulnerable region to better engage in emission reduction in the future, although regional emissions might increase in the short run. If appropriately designed, this cooperation scheme will provide both regions with a short-term mitigation incentive as well. In this sense, contrary to common perception, adaptation can be regarded as a complement to mitigation. However, this is only the case if the assistance is provided in such a way that human capital is effectively protected against climate damage. Otherwise, the substitution effect discourages South from reducing emission and, as a result, the cooperation scheme would not be incentive compatible. Our findings, based on a simple model, appear to be fairly robust against extensions of the model.

The results of this paper suggest several areas for further research. It is important to examine the quantitative magnitude of the dynamic complementarity effect which we identified. This could be done by extending existing integrated assessment models, such as the RICE model of Nordhaus and Yang (1996). A key issue would then be how to reestimate the damage function so that the climate-related impact on human capital accumulation can be separated from other damages. Also, for practical applications, the exact impact of adaptation assistance needs to be measured. Although estimating the effectiveness of adaptation is not straightforward, a recent study by Millner and Dietz (2014) could be a good starting point. Another important issue is coalition formation. Clarifying the implications of dynamic complementarity and adaptation assistance in coalition formation would help us design a more promising international framework for climate cooperation.

Appendix: Proofs of the propositions

Proof of Proposition 1

We show that there exists an equilibrium of the model under a reasonable set of assumptions. This is achieved by first establishing the result for symmetric regions and then proving the general result.

Symmetric case

Let

$$\theta = (\alpha, \beta, \gamma, \delta, \mu, M_0, \eta_i, \xi_{i,t}, \zeta_{i,t}, \phi_{i,L}, \phi_{i,M}, L_{i,0})$$

denote the vector of parameters, Θ the set of all possible values of θ, and

$$\chi_i = (\xi_{i,t}, \zeta_{i,t}, \eta_i, \phi_{i,L}, \phi_{i,M}, L_{i,0})$$

denote the subvector of θ containing the region-specific parameters. We first consider the case where the two regions are symmetric, so that

$$\chi_n = \chi_s = (\xi_t, \zeta_t, \eta, \phi_L, \phi_M, L_0).$$

We henceforth drop the subscript i whenever appropriate.

To ensure the existence of equilibrium with an interior solution we need to assume that μ, ζ_t, and α are sufficiently small. To formalize the argument, let $\xi = \max\{\xi_0, \xi_1\}$, $\zeta = \max\{\zeta_0, \zeta_1\}$, and define $\bar{\mu}$, $\bar{\zeta}$, and $\bar{\alpha}$ by

$$\bar{\mu} = \min\left\{ \frac{1-\alpha}{\beta\phi_M(\eta L_0)^\gamma}, \frac{1-\alpha}{[\beta\xi + \beta^2\phi_L\zeta\eta^2 L_0 + \beta^2\phi_M(1-\delta)]L_0^\gamma} \right\}, \tag{47}$$

$$\bar{\zeta} = \min\left\{ \frac{s + \frac{1-\alpha}{\alpha}[2-\gamma(1-b)]}{(s + \frac{1-\alpha}{\alpha}[1-\gamma(1-b)])^2} \frac{(1-\gamma)b^{1-\gamma}}{2\gamma\mu L_0^\gamma} \middle| b \in [\tilde{b}, 1] \right\}, \tag{48}$$

and

$$\bar{\alpha} = \left(\gamma \frac{1-\tilde{\beta}}{\tilde{\beta}} \mu(\tilde{\beta} L_0)^\gamma \right) \beta^2 \phi_M (1-\delta), \tag{49}$$

where

$$\tilde{b} = \frac{(1+\gamma)^{1/2}(1-\gamma)^{1/2} - (1-\gamma)}{(1+\gamma)^{1/2}(1-\gamma)^{1/2} + (1+\gamma)}. \tag{50}$$

Since $\tilde{b} > 0$, $\bar{\zeta}$ is well-defined and strictly positive. Let Θ_0 be a subset of Θ defined by

$$\Theta_0 = \{\theta \in \Theta | \chi_n = \chi_s, \alpha < \bar{\alpha}, \zeta_{i,t} < \bar{\zeta}, \mu < \bar{\mu}\}. \tag{51}$$

Our first lemma establishes the existence of the unique symmetric Nash equilibrium.

Lemma 1. *For any $\theta \in \Theta_0$ there exists a unique symmetric equilibrium with an* *interior solution. The equilibrium is characterized by (13), (14), (15), (16), and*

$$\frac{\partial MC_{i,0}}{\partial b_{i,0}} > 2\frac{\partial MB_{i,0}}{\partial b_{i,0}} \tag{52}$$

for $i \in \{n, s\}$.

Proof. Fix the control variables of region $j \in \{n, s\}$ and consider the problem of region $i \neq j$. We solve the problem backwards. Define the value function at the beginning of period $t = 1$ by

$$V_{i,1}(L_{i,1}, M_1) = \max_{P_{i,1}, b_{i,1}} \log(C_{i,1}) + \beta V_{i,2}(L_{i,2}, M_2) \quad \text{subject to (1)–(9)}. \tag{53}$$

The first-order conditions with respect to $P_{i,1}$ and $b_{i,1}$ immediately imply (13) and (14) for $t = 1$. Notice that (13) has the unique solution $b_{i,1}$ in $(0, 1)$. and (14) implies $P_{i,1} > 0$. Also, since $\mu < \bar{\mu}$ by assumption,

$$E_{i,1} = \frac{1-\alpha}{\beta_i \phi_{i,M}} - \mu(b_{i,1}L_{i,1})^{\gamma} > \frac{1-\alpha}{\beta \phi_{i,M}} - \mu(\eta_i L_{i,0})^{\gamma} > \frac{1-\alpha}{\beta \phi_{i,M}} - \bar{\mu}(\eta_i L_{i,0})^{\gamma} \geq 0, \tag{54}$$

which shows that the solution is in fact interior. Hence,

$$\begin{aligned} V_{i,1}(L_{i,1}, M_1) = \log\left(\frac{\alpha^{\alpha}(1-\alpha)^{1-\alpha}}{\beta \phi_{i,M}\left(\gamma\mu\right)^{\alpha}}\right) - (1-\alpha) - \beta\phi_{i,M}E_{j,1} \\ + \alpha(1-\gamma)\log(b_{i,1}L_{i,1}) + \beta\phi_{i,M}\mu(b_{i,1}L_{i,1})^{\gamma} \\ + \beta\phi_{i,L}\eta_i e^{-\zeta_{i,1}M_1} L_{i,1} - [\xi_{i,1} + \beta\phi_{i,M}(1-\delta)]M_1, \end{aligned} \tag{55}$$

where $b_{i,1}$ is implicitly defined by (13) as a function of $L_{i,1}$.

The problem of region i at the beginning of period $t = 0$ is then given by

$$\max_{P_{i,0}, b_{i,0}} \log(C_{i,0}) + \beta V_{i,1}(L_{i,1}, M_1) \quad \text{subject to (1)–(9) and (55)}. \tag{56}$$

Again, the first-order conditions for $P_{i,1}$ and $b_{i,1}$ imply (13) and (14) for $t = 0$. What remains to be proved is that there exists an interior solution to $MC_{i,0}(b_{i,0}) = MB_{i,0}(b_{n,0}, b_{s,0})$.

Since $b_{n,0} = b_{s,0}$ in any symmetric equilibrium, we suppress the subscript for regions and define

$$MC_*(b_0) = \alpha \left(\gamma \frac{1-b_0}{b_0} \mu (bL_0)^\gamma \right)^{-1} \tag{57}$$

and

$$MB_*(b_0) = \beta\xi_1 + \beta^2 \phi_L \zeta_1 \eta e^{-\zeta_1 M_1} L_1 + \beta^2 (1-\delta)\phi_M, \tag{58}$$

where M_1 is a function of b_0 defined by

$$M_1 = (1-\delta)M_0 + 2\left(\gamma \left(\frac{1-\alpha}{\alpha} \right) \frac{1-b_0}{b_b} - 1 \right) \mu (b_0 L_0)^\gamma. \tag{59}$$

We shall show that there exists a unique $b_0^* \in (0,1)$ such that

$$MC_*(b_0^*) = MB_*(b_0^*). \tag{60}$$

Then, if b_0^* also satisfies

$$E_{i,0} = \left(\gamma \left(\frac{1-\alpha}{\alpha} \right) \frac{1-b_0^*}{b_0^*} - 1 \right) \mu (b_0^* L_{i,0})^\gamma > 0, \tag{61}$$

$b_{n,0} = b_{s,0} = b_0^*$ constitutes the unique symmetric Nash equilibrium.

First notice $\lim_{b_0 \to 0} MC_*(b_0) = 0$ and $\lim_{b_0 \to 1} MC_*(b_0) = \infty$. Also, $\lim_{b_0 \to 0} M_1 = \infty$ and $\lim_{b_0 \to 1} M_1 = (1-\delta)M_0 - 2\mu L_0^\gamma$. Thus,

$$\lim_{b_0 \to 0} MB_*(b_0) = \beta\xi_1 + \beta^2 \phi_M (1-\delta) > \beta^2 \phi_M (1-\delta) > 0, \tag{62}$$

while

$$\begin{aligned} \lim_{b_0 \to 1} MB_*(b_0) &= \beta\xi_1 + \beta^2 \eta^2 \phi_L L_0 \zeta_1 e^{-\zeta_0 M_0 - \zeta_1 (1-\delta) M_0 + \zeta_1 \mu L_0^\gamma} + \beta^2 \phi_M (1-\delta) \\ &< \beta\xi_1 + \beta^2 \eta^2 \phi_L L_0 \zeta_1 + \beta^2 \phi_M (1-\delta) < \infty. \end{aligned} \tag{63}$$

Therefore there exits $b_0^* \in (0,1)$ such that $MC_*(b_0^*) = MB_*(b_0^*)$.

To prove that b_0^* is unique we observe that $MC_*(b_0) > 0$ and

$$\frac{MC_*'(b_0) b_0}{MC_*(b_0)} = \frac{b_0}{1-b_0} + 1 - \gamma > 0 \tag{64}$$

for all $b_0 \in (0,1)$. Moreover,

$$\frac{MC_*''(b_0)b_0}{MC_*'(b_0)} = 2\frac{\left(\frac{b_0}{1-b_0}\right)^2 + (1-\gamma)\left(\frac{b_0}{1-b_0}\right) - \frac{\gamma(1-\gamma)}{2}}{\frac{b_0}{1-b_0} + 1 - \gamma}, \tag{65}$$

implying that

$$MC_*''(b_0) > 0 \iff b_0 > \tilde{b} = \frac{(1+\gamma)^{1/2}(1-\gamma)^{1/2} - (1-\gamma)}{(1+\gamma)^{1/2}(1-\gamma)^{1/2} + (1+\gamma)}. \tag{66}$$

Hence, MC_* is increasing and strictly convex in the open interval $(\tilde{b}, 1)$.

Concerning $MB_*(b_0)$ we have

$$MB_*'(b_0) = -\frac{\partial M_1}{\partial b_0}\beta^2\phi_L\zeta_1^2 L_2 > 0 \tag{67}$$

for all $b \in (0,1)$, where

$$\frac{\partial M_1}{\partial b_0} = -\frac{2}{MC_*(b_0)b_0}\left(\frac{b_0}{1-b_0} + (1-\alpha)(1-\gamma)\right) < 0. \tag{68}$$

Moreover,

$$\frac{MB_*''(b_0)}{MB_*'} = -\frac{\partial M_1}{\partial b_0}\left(\zeta_1 - \Psi(b_0)\right), \tag{69}$$

where

$$\Psi(b_0) = \frac{s + \frac{1-\alpha}{\alpha}[2-\gamma(1-b_0)]}{(s + \frac{1-\alpha}{\alpha}[1-\gamma(1-b_0)])^2}\frac{(1-\gamma)b_0}{2\gamma\mu(b_0 L_0)^\gamma}. \tag{70}$$

Since $\zeta_1 < \bar{\zeta} \leq \Psi(b_0)$ for all $b_0 \in [\tilde{b}, 1]$ by assumption, this implies that $MB_*(b_0)$ is increasing and strictly concave on the interval $[\tilde{b}, 1)$. Therefore, if b_0^* is not in $(0, \tilde{b}]$, the solution must be unique.

Define $\underline{b}$ and $\bar{b}$ implicitly by

$$MC_*(\underline{b}) = \beta^2\phi_M(1-\delta), \tag{71}$$

$$MC_*(\bar{b}) = \beta\xi_1 + \beta^2\eta^2\phi_L L_0\zeta_1 + \beta^2\phi_M(1-\delta), \tag{72}$$

so that (62), (63), and (64) imply $MC_*(b_0) < MB_*(b_0)$ for all $b_0 \in (0, \underline{b}]$ and $MC_*(b_0) > MB_*(b_0)$ for all $b_0 \in [\bar{b}, 1)$. Then, $\underline{b} < b_0^* < \bar{b}$. Since $\alpha < \bar{\alpha}$ by assumption, we have

$$MC_*(\tilde{b}) = \alpha\left(\gamma\frac{1-\tilde{b}}{\tilde{b}}\mu(\tilde{b}L_0)^\gamma\right)^{-1} \leq \bar{\alpha}\left(\gamma\frac{1-\tilde{b}}{\tilde{b}}\mu(\tilde{b}L_0)^\gamma\right)^{-1}$$
$$\leq \beta^2\phi_M(1-\beta) = MC_*(\underline{b}), \tag{73}$$

so that $\tilde{b} \leq \underline{b} < b_0^* < \bar{b}$. We conclude that b_0^* is unique.

The uniqueness of b_0^* implies that

$$MC_*'(b_0)\big|_{b_0=b_0^*} > MB_*'(b_0)\big|_{b_0=b_0^*}. \tag{74}$$

Since $MB_*'(b_0) = 2\partial MB_{i,0}/\partial b_{i,0}$, this yields (52).

Finally, since $b_0^* < \bar{b} < 1$ and $\mu < \bar{\mu}$,

$$\begin{aligned}\gamma\left(\frac{1-\alpha}{\alpha}\right)\frac{1-b_0^*}{b_0^*} - 1 &> \gamma\left(\frac{1-\alpha}{\alpha}\right)\frac{1-\bar{b}}{\bar{b}} - 1\\ &= \frac{1-\alpha}{\beta\mu(\bar{b}L_0)^\gamma}\frac{1}{MC_*(\bar{b})}\\ &> \frac{1}{\bar{\mu}}\frac{1-\alpha}{[\beta\xi_1 + \beta^2\eta^2\phi_L L_0\zeta_1 + \beta^2\phi_M(1-\delta)]L_0^\gamma} > 0,\end{aligned} \tag{75}$$

implying (61). This completes the proof of Lemma 1.

Asymmetric case

Now we are ready to prove the existence of an equilibrium in the more general case. Since we know that the symmetric equilibrium exists for each set of parameters in Θ_0, the model is likely to have equilibria in a neighborhood of each $\theta \in \Theta_0$, which includes the case of asymmetric regions as well. The next lemma formalizes this idea.

Lemma 2. *There exists an open set Θ_* such that (a) $\Theta_* \supset \Theta_0$ and $\Theta_* \neq \Theta_0$; (b) for each $\theta \in \Theta_*$, there exists a Nash equilibrium which is characterized by (13), (14), and (52); and (c) the equilibrium is continuously differentiable with respect to each parameter.*

Proof. Define a function $F : (0,1) \times (0,1) \times \Theta \to \mathbb{R}^2$ such that

$$F(b_{n,0}, b_{s,0}, \theta) = [F_n(b_{n,0}, b_{s,0}, \theta), F_s(b_{n,0}, b_{s,0}, \theta)], \tag{76}$$

where

$$F_i(b_{n,0}, b_{s,0}, \theta) = MC_{i,0}(b_{i,0}) - MB_{i,0}(b_{n,0}, b_{s,0}) \tag{77}$$

for each $i \in \{n, s\}$. We know from Lemma 1 that, for each $\theta \in \Theta_0$, there exists $b_0^* \in (0, 1)$ such that

$$F(b_{n,0}^*, b_{s,0}^*, \theta) = [F_n(b_{n,0}^*, b_{s,0}^*, \theta), F_s(b_{n,0}^*, b_{s,0}^*, \theta)] = (0, 0), \tag{78}$$

where $b_{n,0}^* = b_{s,n}^* = b_0^*$. Fix $\theta \in \Theta_0$ and observe that

$$\left.\frac{\partial F_i(b_{n,0}, b_{s,0}, \theta)}{\partial b_{i,0}}\right|_{b_{n,0}=b_{s,0}=b_0^*} = MC'_*(b_0^*) - \frac{1}{2} MB'_*(b_0^*), \tag{79}$$

and, for $j \neq i$,

$$\left.\frac{\partial F_i(b_{n,0}, b_{s,0}, \theta)}{\partial b_{j,0}}\right|_{b_{n,0}=b_{s,0}=b_0^*} = -\frac{1}{2} MB'(b_0^*). \tag{80}$$

The Jacobian of F at $(b_{n,0}^*, b_{s,0}^*, \theta)$ is then given by

$$\begin{aligned}
&\det \begin{pmatrix} MC'_*(b_{n,0}^*) - \frac{1}{2} MB'_*(b_{n,0}^*) & -\frac{1}{2} MB'_*(b_{n,0}^*) \\ -\frac{1}{2} MB'_*(b_{s,0}^*) & MC'_*(b_{s,0}^*) - \frac{1}{2} MB'_*(b_{s,0}^*) \end{pmatrix} \\
&\quad = \left(MC'_*(b_0^*)\right)^2 - MC'_*(b_0^*) MB'_*(b_0^*) \\
&\quad = MC'_*(b_0^*) \left(MC'_*(b_0^*) - MB'_*(b_0^*)\right) > 0,
\end{aligned} \tag{81}$$

where the inequality follows from (74). Then, by the implicit function theorem, there exists an open set $\Theta_*(\theta)$ such that (a) $\theta \in \Theta_*(\theta)$; (b) for each $\theta' \in \Theta_*(\theta)$, there exists a Nash equilibrium which is characterized by (13), (14), and (52); and (c) the equilibrium is continuously differentiable with respect to each parameter. Putting $\Theta_* = \cup_{\theta \in \Theta_0} \Theta_*(\theta)$ completes the proof of Lemma 2.

Lemma 2 shows that an equilibrium exists not only in the case with symmetric regions, but also in the case with asymmetric regions, as long as the two regions are ‘sufficiently’ homogeneous. The lemma does not state how much regions may differ from each other.

Proof of Proposition 2

See text in Section 3.

Proof of Proposition 3

See text in Section 5.1.

Proof of Proposition 4

By taking the total derivative of $MC_{i,0}(b_{i,0}) = MB_{i,0}(b_{n,0}, b_{s,0})$ with respect to R_0, we obtain

$$\frac{db_{s,0}}{dR_0} = \Gamma_s \frac{\partial MB_{s,0}}{\partial R_0}, \quad \frac{db_{n,0}}{dR_0} = \Gamma_n \frac{\partial MB_{s,0}}{\partial R_0}, \tag{82}$$

where

$$\Gamma_s = \frac{\frac{\partial MC_{n,0}}{\partial b_{n,0}} - \frac{\partial MB_{n,0}}{\partial b_{n,0}}}{\left(\frac{\partial MC_{s,0}}{\partial b_{s,0}} - \frac{\partial MB_{s,0}}{\partial b_{s,0}}\right)\left(\frac{\partial MC_{n,0}}{\partial b_{n,0}} - \frac{\partial MB_{n,0}}{\partial b_{n,0}}\right) - \frac{\partial MB_{s,0}}{\partial b_{n,0}}\frac{\partial MB_{n,0}}{\partial b_{s,0}}} \tag{83}$$

and

$$\Gamma_n = \frac{\frac{\partial MB_{n,0}}{\partial b_{s,0}}}{\frac{\partial MC_{n,0}}{\partial b_{n,0}} - \frac{\partial MB_{n,0}}{\partial b_{n,0}}} \Gamma_s. \tag{84}$$

We need to show that Γ_s and Γ_n are both strictly positive. Lemma 2 shows that, at equilibrium, (52) holds for $i = n, s$. Hence,

$$\begin{aligned}
&\left(\frac{\partial MC_{s,0}}{\partial b_{s,0}} - \frac{\partial MB_{s,0}}{\partial b_{s,0}}\right)\left(\frac{\partial MC_{n,0}}{\partial b_{n,0}} - \frac{\partial MB_{n,0}}{\partial b_{n,0}}\right) - \frac{\partial MB_{s,0}}{\partial b_{n,0}}\frac{\partial MB_{n,0}}{\partial b_{s,0}} \\
&\quad > \left(2\frac{\partial MB_{s,0}}{\partial b_{s,0}} - \frac{\partial MB_{s,0}}{\partial b_{s,0}}\right)\left(2\frac{\partial MB_{n,0}}{\partial b_{n,0}} - \frac{\partial MB_{n,0}}{\partial b_{n,0}}\right) - \frac{\partial MB_{s,0}}{\partial b_{n,0}}\frac{\partial MB_{n,0}}{\partial b_{s,0}} \\
&\quad = 0.
\end{aligned} \tag{85}$$

This, together with (83), proves that $\Gamma_s > 0$. Combining this result with (84) proves that $\Gamma_n > 0$ as well, because $\partial MB_{n,0}/\partial b_{n,0} > 0$.

Proof of Proposition 5

To prove the first part of the proposition, we have

$$\lim_{\delta_r \to 0} \frac{\partial MB_{s,0}}{\partial R_0}\bigg|_{R_0=0} = -\beta^2 \phi_{s,L} \zeta_s(0) \zeta_s'(0) M_0 L_{s,2} > 0. \tag{86}$$

If $\partial MB_{s,0}/\partial R_0 > 0$ for all $\delta_r \in (0,1)$, put $\bar{\delta_r} = 1$ and the result follows. If $\partial MB_{s,0}/\partial R_0 \leq 0$ for some $\delta_r \in (0,1)$, there must exist $\tilde{\delta_r} \in (0,1)$ such that $\partial MB_{s,0}/\partial R_0 = 0$, because $\partial MB_{s,0}/\partial R_0$ is continuous in δ_r. Letting $\bar{\delta_r}$ be the smallest value of such $\tilde{\delta_r}$'s, the result follows.

To prove the second part, we have

$$\frac{\partial MB_{s,0}}{\partial R_0}\bigg|_{R_0=0} = \beta \delta_r \xi_s'(0) - \beta^2 \phi_{s,L} L_{s,2} \left(\delta_r \left[\zeta_s(0) M_1 - 1\right] + \zeta_s(0) M_0\right) \zeta_s'(0). \tag{87}$$

Since $M_1 \geq (1-\delta) M_0 \geq 1/\zeta_s(0)$, the term in square brackets is non-negative. Then, putting

$$\bar{\zeta}_s' = \frac{\delta_r \xi_s'(0)}{\beta \phi_{s,L} L_{s,2} \left(\delta_r \left[\zeta_s(0) M_1 - 1\right] + \zeta_s(0) M_0\right)} < 0, \tag{88}$$

yields the result.

Proof of Proposition 6

By combining (29), (30), (31), (33), and (36), we obtain

$$\frac{dM_2}{dR_0}\bigg|_{R_0=0} = \nu_0[\zeta_s'(0) - \bar{\zeta}_s'] + \nu_1 \zeta_s'(0), \tag{89}$$

where

$$\nu_1 = \gamma \frac{1-b_{s,1}}{b_{s,1}} \mu(b_{s,1} L_{s,1})^\gamma \left(\frac{\gamma b_{s,1}}{1-\gamma+\gamma b_{s,1}}\right) M_0 > 0, \tag{90}$$

$$\nu_0 = (1-\delta)(\lambda_n + \lambda_s)\beta^2 \phi_{s,L} L_{s,2} \left(\delta_r \left[\zeta_s(0) M_1 - 1\right] + \zeta_s(0) M_0\right) > 0, \tag{91}$$

and

$$\lambda_i = \frac{1}{1-b_{i,0}} \left(\frac{b_{i,0}}{1-b_{i,0}} + (1-\alpha)(1-\gamma)\right) \frac{P_{i,0}}{1-\alpha} \frac{1}{b_{i,0}} > 0 \tag{92}$$

for $i = n, s$. Therefore, putting

$$\tilde{\zeta}_s' = \frac{\nu_0}{\nu_0 + \nu_1}\bar{\zeta}_s' > \bar{\zeta}_s', \tag{93}$$

yields the result.

Proof of Proposition 7

The envelope theorem implies that the second-order effects cancel out, so that (40) boils down to

$$\begin{aligned} \left.\frac{dW_n(\tau)}{d\tau}\right|_{\tau=0} &= -1 - MB_{n,0}\frac{dE_{s,0}}{R_0}Y_{n,0} - \beta MB_{n,1}\frac{dE_{s,1}}{R_0}Y_{n,0} \\ &= -1 - \nu_3[\zeta_s'(0) - \bar{\zeta}_s']Y_{n,0} - \nu_4\zeta_s'(0)Y_{n,0}, \end{aligned} \tag{94}$$

where

$$\begin{aligned} \nu_3 = MB_{n,0}\left(\frac{b_{n,0}}{1-b_{n,0}} + (1-\alpha)(1-\gamma)\right)\frac{P_{s,0}}{1-\alpha}\frac{\Gamma_s}{b_{s,0}} \\ \times \beta^2\phi_{s,L}(\delta_r[\zeta_s(0)M_1 - 1] + \zeta_s(0)M_0) > 0 \end{aligned} \tag{95}$$

and

$$\nu_4 = MB_{n,1}\left(\frac{\gamma b_{s,1}}{1-\gamma+\gamma b_{s,1}}\right)\frac{\alpha}{1-\alpha}P_{s,1}M_0 > 0. \tag{96}$$

Hence, defining

$$\hat{\zeta}_s' = -\frac{1}{(\nu_3+\nu_4)Y_{n,0}} + \frac{\nu_3}{\nu_3+\nu_4}\bar{\zeta}_s' \tag{97}$$

yields the first part of the proposition.

For the second part, notice that $\Omega_{n,0}$ only affects $Y_{n,0}$ and that $\lim_{\Omega_n \to \infty} Y_{n,0} = \infty$. Therefore,

$$\lim_{\Omega_{n,0}\to\infty} \hat{\zeta}_s' = \frac{\nu_3}{\nu_3+\nu_4}\bar{\zeta}_s' > \bar{\zeta}_s', \tag{98}$$

which shows $\hat{\zeta}_s' > \bar{\zeta}_s'$ for sufficiently large $\Omega_{n,0}$. As for the welfare effect in South, the envelope theorem shows that

$$\begin{aligned} \left.\frac{dW_s(\tau)}{d\tau}\right|_{\tau=0} &= -\left(\xi_s'(0) + \beta\alpha\zeta_s'(0) + \beta^2\phi_{s,L}L_{s,2}\zeta_s'(0)\right)M_0Y_{n,0} \\ &\quad - \left(\beta\xi_s'(0) + \beta^2\phi_{s,L}L_{s,2}\zeta_s'(0)\right)\delta_r M_1 Y_{n,0} > 0, \end{aligned} \tag{99}$$

completing the proof.

References

Bréchet, T., N. Hritonenko, and Y. Yatsenko (2013). Adaptation and mitigation in long-term climate policy, *Environmental and Resource Economics*, 55, 217–243.

Bretschger, L. and N. Suphaphiphat (2014). Effective climate policies in a dynamic North-South model, *European Economic Review*, 69, 59–77.

Buob, S. and G. Stephan (2011). To mitigate or to adapt: How to confront global climate change, *European Journal of Political Economy*, 27, 1–16.

de Bruin, K.C., R.B. Dellink, and R.S.J. Tol (2009). AD-DICE: An implementation of adaptation in the DICE model, *Climatic Change*, 95, 63–81.

Ebert, U. and H. Welsch (2012). Adaptation and mitigation in global pollution problems: Economic impacts of productivity, sensitivity, and adaptive capacity, *Environmental and Resource Economics*, 52, 49–64.

Golosov, M., J. Hassler, P. Krusell, and A. Tsyvinski (2014). Optimal taxes on fossil fuel in general equilibrium, *Econometrica*, 82, 41–88.

Ikefuji, M. and R. Horii (2012). Natural disasters in a two-sector model of endogenous growth, *Journal of Public Economics*, 96, 784–796.

Ingham, A., J. Ma, and A. Ulph (2013). Can adaptation and mitigation be complements?, *Climatic Change*, 120, 39–53.

IPCC (2014). *Climate Change 2014: Impacts, Adaptation, and Vulnerability*, Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, (C.B. Field, V. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K. L. Ebi, Y.O. Estrada, R.C. Genova, B. Grima, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White, eds), Cambridge University Press, Cambridge, UK, and New York, NY, USA.

Kane, S. and J.F. Shogren (2000). Linking adaptation and mitigation in climate change policy, *Climatic Change*, 45, 75–102.

Millner, A. and S. Dietz (2014). Adaptation to climate change and economic growth in developing countries, *Environment and Development Economics*, forthcoming.

Nordhaus, W.D. and Z. Yang (1996). A regional dynamic general-equilibrium model of alternative climate-change strategies, *American Economic Review*, 86, 741–765.

Onuma, A. and Y. Arino (2011). Greenhouse gas emission, mitigation and innovation of adaptation technology in a North-South economy, *Environment and Development Economics*, 16, 639–656.

Winkler, H., K. Baumert, O. Blanchard, S. Burch, and J. Robinson (2007). What factors influence mitigative capacity?, *Energy Policy*, 35, 692–703.

World Bank (2010a). *World Development Report 2010: Development and Climate Change*, Washington, DC.

World Bank (2010b). *Economics of Adaptation to Climate Change: Synthesis Report*, Washington, DC.

Yohe, G.W. (2001). Mitigative capacity — the mirror image of adaptive capacity on the emissions side, *Climatic Change*, 49, 247–262.