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Adaptation for Mitigation

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Adaptation for mitigation*

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Abstract

This paper develops a two-region (North and South) dynamic model 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 then 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. Pollution might increase in the short run, but in the long run the level of pollution will decline. The adaptation assistance we propose is Pareto improving and incentive compatible.

JEL Codes: D91, Q54, Q58

Keywords: Climate change, Mitigation, Adaptation, Human capital, Strategic complements

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1 Introduction

The economic damage from climate change is often modeled as a flow impact to current output (Stern, 2013). This approach is attractive because of its simplicity, but it ignores the potentially lasting damage of climate change, and hence misses the important link between economy and the environment. In particular, seemingly short-term impacts of climate change can transform into more permanent damages through health and human capital (UNDP, 2007; IPCC, 2014). High temperatures increase mortality (Deschenes, 2014) and, even if they are not fatal, leave long-run damage by reducing learning and productivity (Graff Zivin and Shrader, 2016). There is robust evidence that changes in climatic condition increase the occurrence of conflicts (Hsiang et al., 2013), which cripples the ability of the affected countries to develop human capital (Akresh, 2016). Climate-related disasters destroy educational facilities and force low-income households to resort to child labor in order to cope with the economic shock that follows (Kousky, 2016). Children who experienced weather shocks are more likely to be malnourished and receive significantly lower investments in education and health (Jensen, 2000). This is especially true in developing countries because their primary source of income is agriculture (Hanna and Oliva, 2016).

These simple observations provide a link between climate damage, economic growth, and mitigation capacity. Since human capital is an essential driver of sustainable growth, the expected loss of human capital is a serious obstacle for the long-term development in climate-sensitive regions. Moreover, the 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 efforts to tackle climate change at a global level. Averting climate damage today will help to avert damage in the future as well.

The policy options for averting climate damage can be divided into two broad categories: mitigation and adaptation. Mitigation involves slowing the process of climate change itself, usually by reducing the emission of carbon dioxide. Adaptation, on the other hand, refers to adjustments in human systems that reduce our vulnerability to the potential impact of climate change. Climate policy discussions typically concentrate on mitigation, putting much emphasis on long-term solutions. However, reducing climate damage through mitigation takes time, while global climate is changing already (IPCC, 2014). Hence, if current and future climate damage is to be reduced, adaptation should play an important role as well, especially in climate-sensitive regions. One major problem is that for developing countries, capital for and knowledge of effective adaptation are typically insufficient (World Bank, 2010). The situation is more or less the same in emerging economies like India and China, where the infrastructure is relatively poor and is already stretched beyond capacity under ongoing climate change (WHO, 2010). Therefore, not only poor countries, but also emerging economies need external assistance for adaptation.

Unfortunately, financial and technological assistance available for these countries is small compared to the projected needs. Indeed, World Bank (2010) 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. In the realm of international politics, where no country can be forced to cooperate, the lack of perceived economic incentives makes effective adaptation assistance 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 and more willing to do so 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 Markov-perfect 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.

An early study by Fankhauser and Tol (2005) already recognized that climate change has dynamic consequences through its influences on capital accumulation. But it is only recently that the economic implications of long-lasting climate impacts have been seriously examined. Following a seminal study by Dell et al. (2012), an emerging body of empirical evidence now shows that higher temperatures cause slower growth of the economy, especially in developing countries (Dell et al., 2014). A few recent papers introduced the long-lasting damages (typically, negative growth effect and capital destruction) into the existing integrated assessment models, and found that more stringent climate policies can be justified as a result (Dietz and Stern, 2015; Moore and Diaz, 2015). What we show in this paper is that the capital-destruction nature of climate change does not only change the result quantitatively, but also has qualitatively different implications in a strategic setting.

This paper is also related to the recent developments in the macro climate-economy literature. It has long been thought that fully developed climate-economy models are too complicated for theoretical analysis and hence the primary focus in this literature has been on numerical analysis. Building upon the innovative work by Golosov et al. (2014), however, a growing number of studies now develop a new generation of climate-economy models which work similarly to the traditional integrated assessment models, but are often tractable enough for theoretical analysis (Hassler and Krusell, 2012; Gerlagh and Liski 2012; Iverson, 2013; Gerlagh and Liski, 2014; Traeger, 2015; Karp, 2016). The current study follows this literature and formulates the climate-economy interaction in such a way that the baseline model is sufficiently tractable. Unlike the existing models, our model has an additional channel of externality in the form of human capital destruction, which makes it harder to maintain tractability of the model. Nevertheless, our analysis allows for straightforward theoretical results and provides comparative statics in a transparent manner.

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, quite intuitively, the optimal level of adaptation 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. 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. 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 assume that adaptation is only possible for one region, and they 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.

Our paper makes two contributions. First, building upon the dynamic general equilibrium model of Golosov et al. (2014), 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. This allows us to demonstrate how the extra channel of externality changes the nature of strategic interaction. 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.

The plan of the paper is as follows. Section 2 describes the model and introduces a set of assumptions that are used in the analysis that follows. In Sections 3 and 4 we focus on a finite-period setting, characterize the equilibrium, and explain in detail the mechanism behind our main results. In Section 5 we turn to the infinite-period setting, solve the model numerically, and provide quantitative analysis with a brief sensitivity analysis. Section 6 discusses some limitations of our analysis and concludes the paper. All proofs are in the appendix.

2 The model

We consider an economy consisting of two regions: North (n) and South (s). Our model builds upon the dynamic general equilibrium model of Gosolov et al. (2014). Welfare of region $i \in \{n, s\}$ is

$$W_i = \sum_{t=0}^{T} \beta_i^t \log(C_{i,t}), \tag{1}$$

where $C_{i,t}$ is consumption and $\beta_i \in (0, 1)$ is the discount factor. The time horizon T can be finite or infinite. As in Gosolov et al. (2014), we assume that physical capital fully depreciates between periods. This is obviously not appropriate when the time step is short, but when the time step is taken to be sufficiently long, say a decade or longer, only a small fraction of physical capital remains at the end of each period anyway, so that the full depreciation assumption is reasonable. Output $Y_{i,t}$ is divided into consumption and physical capital investment $K_{i,t+1}$:

$$C_{i,t} + K_{i,t+1} = \tilde{Y}_{i,t} := \begin{cases} Y_{i,t} - R & \text{for } (i,t) = (n,0), \\ Y_{i,t} & \text{otherwise,} \end{cases} \tag{2}$$

where R is North's investment in South's adaptation capital, which we will explain below. The variable $\tilde{Y}_{i,t}$ is the net output after adaptation investment is subtracted. The production function for the final good sector is

$$Y_{i,t} = \Delta_{i,t}^Y A_{i,t} K_{i,t}^{\kappa_i} L_{i,t}^{\lambda_i} X_{i,t}^{1-\kappa_i-\lambda_i}, \tag{3}$$

where $A_{i,t}$ is the total factor productivity which captures the exogenous process of technical change. Here, $L_{i,t}$ is the effective labor used in the final good sector, $X_{i,t}$ is the energy composite, and $\Delta_{i,t}^Y \in (0, 1)$ captures the damage from pollution which we will elaborate on below.

The energy composite is produced through a CES production function

$$X_{i,t} = \left(E_{i,t}^{\rho_i} + \tilde{E}_{i,t}^{\rho_i} \right)^{\frac{1}{\rho_i}} \tag{4}$$

for some $\rho_i < 1$, where $E_{i,t}$ is the fossil-fuel energy production (measured in units of carbon) and $\tilde{E}_{i,t}$ is the carbon-free energy production. As in Gerlagh and Liski (2012), we abstract from the scarcity of fossil-fuel resource and ignore extraction cost. For the final period, if any, we add a technological constraint

$$E_{i,T} \leq \bar{E}_{i,T} \tag{5}$$

for some exogenous upper bound $\bar{E}_{i,T} > 0$. This upper bound may be interpreted as the maximum amount of fossil-fuel energy that can be produced within a fixed length of time. Following Acemoglu et al. (2012), we assume $\rho_i > 0$ so that 'dirty' and 'clean' energies are substitutes. Carbon-free energy is produced by the linear production technology

$$\tilde{E}_{i,t} = \tilde{A}_{i,t} \tilde{L}_{i,t}, \tag{6}$$

where $\tilde{L}_{i,t}$ is the effective labor used for the clean energy sector.

The feasibility constraint for labor allocation is

$$L_{i,t} + \tilde{L}_{i,t} = H_{i,t}, \tag{7}$$

where $H_{i,t}$ is the stock of human capital. Letting $\theta_{i,t} \in [0,1]$ be the share of raw labor used in the clean energy sector, we may write

$$L_{i,t} = (1 - \theta_{i,t}) H_{i,t}, \quad \tilde{L}_{i,t} = \theta_{i,t} H_{i,t}. \tag{8}$$

As discussed in the introduction, we assume that the stock of human capital is negatively influenced by pollution. More precisely, the process of human capital accumulation is governed by

$$H_{i,t+1} = e^{g_{i,t}} \Delta_{i,t}^{H} H_{i,t}, \tag{9}$$

where $g_{i,t}$ is the exogenous growth rate and $\Delta_{i,t}^{H} \in (0,1)$ is the damage from pollution which we will describe shortly.

The stock M_t of pollution changes over time according to

$$M_{t+1} = \phi_M M_t + \sum_{i \in \{n,s\}} E_{i,t} \tag{10}$$

for some $\phi_M \in (0,1)$. The pollution stock in turn influences the economy through the damage terms $\Delta_{i,t}^Y$ and $\Delta_{i,t}^H$. More specifically, we assume

$$\Delta_{i,t}^Y = e^{-\delta_{i,t}^Y M_t}, \quad \Delta_{i,t}^H = e^{-\delta_{i,t}^H M_t} \tag{11}$$

for some $\delta_{i,t}^Y, \delta_{i,t}^H > 0$. Notice that if $\delta_{i,t}^H = 0$, our model boils down to a special case of Golosov et al. (2014), for which a tractable solution is available. Since we assume $\delta_{i,t}^H > 0$, our model is not analytically solvable in general. In particular, allowing for infinite time horizon ($T = \infty$) forces us to use numerical methods, which we do in Section 5. As we demonstrate in Sections 3 and 4, however, the main mechanism can be well explained based on a three-period version of the model ($T = 2$), for which we can characterize the solution analytically.

The damage parameters $\delta_{i,t}^Y, \delta_{i,t}^H$ may be lowered if regions engage in adaptation activities. In order to focus on the role of adaptation assistance, we consider an ex-post situation where domestic adaptation policies have already been implemented and the values of these parameters have been optimized within each region. We assume, on the other hand, that there remain adaptation opportunities in South which can be further exploited with the help of North. To capture this idea, let R_t denote 'adaptation capital' in South, by which we mean a durable good which can be used to reduce damage from pollution. We then specify

$$\delta_{s,t}^Y = \delta_s^Y(R_t), \quad \delta_{s,t}^H = \delta_s^H(R_t), \tag{12}$$

for some strictly decreasing and continuously differentiable functions δ_s^Y and δ_s^H. At the beginning of the initial period ($t = 0$), North invests a fraction $R \in [0, Y_{n,0})$ of output in South's adaptation capital. For simplicity, we assume that this is a one-off investment. By measuring R_t in the unit of final good, we may write $R_0 = R$. We assume that adaptation capital depreciates over time so that

$$R_{t+1} = \phi_R R_t \tag{13}$$

for some $\phi_R \in (0, 1)$.

Regions are assumed to behave in a non-cooperative manner and we shall focus on Markov-perfect Nash equilibria. The game proceeds in two stages. In the first stage, at the beginning of the initial period, North decides if and how much it invests in South's adaptation capital. In doing so, North takes into account how its investment decision will affect the strategic interaction in the stage that follows. In the second stage, which begins after the investment is made, the two regions solve the dynamic game given North's adaptation assistance. Collecting the state variables as $Z_t = (K_{n,t}, K_{s,t}, H_{n,t}, H_{s,t}, M_t, R_t)$, the second-stage equilibrium is defined by the value function $V_{i,t}$ and the policy variables $(C_{i,t}, E_{i,t}, \theta_{i,t})$ which solve the Bellman equation

$$V_{i,t}(Z_{i,t}) = \max_{C_{i,t},E_{i,t},\theta_{i,t}} \{\log(C_{i,t}) + \beta_i V_{i,t+1}(Z_{t+1})\} \quad \forall i \in \{n, s\} \tag{14}$$

for $t = 0, 1, 2, ..., T$ with $V_{i,T+1}(Z_{T+1}) = 0$. We begin by solving the second stage and clarify how the negative externality on human capital affects the results in a dynamic and strategic environment. Then, in the first stage, we examine whether or not North has an incentive to invest a positive amount of resource to enhance South's adaptation capacity. We are also interested in whether such an adaptation assistance, if any, can simultaneously make both regions better off.

3 Three periods: Dynamic complementarity effect

We first consider the case where $T = 2$. Each period spans the same time interval, say fifty years. We interpret period 0 as the immediate or short-run future, period 1 as the long-run future, and period 2 as the distant future. Since each period is sufficiently long, we assume $\phi_R^2 \approx 0$, which means that the stock of adaptation capital invested by North will fully depreciate in the distant future.

Fix $R \geq 0$ arbitrarily and let us focus on the second stage where the regions play the dynamic game. To facilitate the discussion, we define the savings rate as

$$s_{i,t} = K_{i,t+1}/\tilde{Y}_{i,t}, \tag{15}$$

and put $\bar{\theta}_i := (1 - \kappa_i - \lambda_i)/(1 - \kappa_i)$, which proves to be an upper bound of $\theta_{i,t}$.

Our first proposition shows the existence of an equilibrium and provides a basic characterization of the equilibrium.

Proposition 1. *There exists a Markov-perfect Nash equilibrium, in which (a) the savings rate is given by*

$$s_{i,0} = \frac{\beta_i \kappa_i + (\beta_i \kappa_i)^2}{1 + \beta_i \kappa_i + (\beta_i \kappa_i)^2}, \quad s_{i,1} = \frac{\beta_i \kappa_i}{1 + \beta_i \kappa_i}, \qquad s_{i,2} = 0, \tag{16}$$

and (b) the relation between pollution emission and labor allocation is determined by

$$E_{i,t} = \tilde{A}_{i,t} H_{i,t} \left(\frac{1 - \kappa_i}{\lambda_i} \right)^{\frac{1}{\rho_i}} \left(\bar{\theta}_i - \theta_{i,t} \right)^{\frac{1}{\rho_i}} \theta_{i,t}^{-\frac{1-\rho_i}{\rho_i}}, \tag{17}$$

for $t = 0, 1, 2$.

The savings rate declines over time and there are no savings in the final period. For a fixed level $E_{i,t}$ of emission, (17) pins down $\theta_{i,t}$, which determines the labor allocation between final good production and clean energy production. This condition simply requires that the marginal product of labor should be equalized across the two channels of contribution to the final output.

With (16) and (17) given, output $Y_{i,t}$ becomes a strictly increasing function of emission $E_{i,t}$ and so does consumption $C_{i,t}$. Hence, reducing emission entails a cost in the form of lower current consumption. Emission reduction, on the other hand, may induce a benefit in subsequent periods by mitigating future pollution damages. In the final period, however, there is no benefit of emission reduction. Consequently, we have a corner solution $E_{i,2} = \bar{E}_{i,2}$, where $\bar{E}_{i,2}$ is an exogenous upper bound. The corresponding value of $\theta_{i,2}$ is determined by (17) with $E_{i,2}$ being fixed at $\bar{E}_{i,2}$. It is worth observing here that $\theta_{i,2}$ is increasing in $H_{i,2}$. As the stock of human capital increases, the clean energy sector becomes more productive relative to the dirty one and, as a result, a larger fraction of labor is allocated to clean energy production.

For earlier periods, the equilibrium level of emission is characterized by the first-order condition

$$\frac{1}{1 - s_{i,t}} \frac{dC_{i,t}}{dE_{i,t}} = -\beta_i \frac{dV_{i,t+1}(Z_{t+1})}{dM_{t+1}} C_{i,t}, \tag{18}$$

where the left-hand side is the marginal cost of emission reduction and the right-hand side is the marginal benefit of emission reduction, both measured in units of current final good. Emission reduction leads to a loss of current output, which does not only suppress consumption, but also lowers investment. This is why the marginal cost on the left-hand side is scaled up by the savings rate. Solving backwards from the final period, we can compute the next-period value function, which in turn determines $E_{i,t}$ and $\theta_{i,t}$ via (18) and (17). Recall that the value function $V_{i,t+1}(Z_{t+1})$ captures all future values associated with the state variables. Since the state variables are influenced by both regions' actions, strategic interaction may emerge through the term $dV_{i,t+1}/dM_{t+1}$. In particular, regional emissions can be strategic complements if the marginal benefit curve of one region shifts upwards as a result of emission reduction in the other region.

For the problem of period $t = 1$, the shadow cost of next-period pollution stock is

$$-\frac{dV_{i,2}(Z_2)}{dM_2} = \delta^Y_{i,2}, \tag{19}$$

which together with (18) implies that the marginal benefit of emission reduction is proportional to the current level of consumption. This is a signature feature of the model introduced by Golosov et al. (2014), on which our model is built. Intuitively, the convexity of the damage function and the concavity of the utility function cancel each other, resulting in linear utility damage. The novel feature of our model does not fully kick in here yet because the pollution's negative influence on human capital requires at least two periods before it plays a part. Notice that with (19), the first-order condition (18) can be solved independently for each region. In other words, the best response of one region is not affected by the action of the other region.

Now consider the problem of period $t = 0$, in which the shadow cost of next-period pollution stock is

$$-\frac{dV_{i,1}(Z_1)}{dM_1} = (1 + \beta_i\kappa_i)\delta^Y_{i,1} + \beta_i\phi_M\delta^Y_{i,2} + \beta_i\frac{dV_{i,2}(Z_2)}{dH_{i,2}}\left(-\frac{dH_{i,2}}{dM_1}\right). \tag{20}$$

This expression succinctly reveals how the additional channel of externality introduced in this paper affects the nature of strategic interaction. To clarify the point, suppose for the moment that $\delta^H_{i,1} = 0$ so that the pollution externality only exists in the final-good production sector. Then we have $dH_{i,2}/dM_1 = 0$ and the right-hand side of (20) becomes constant, just as in (19). As a result, the marginal benefit of emission reduction is independent of the action of the other region. When $\delta^H_{i,1} > 0$, on the other hand, the last term in (20) becomes strictly positive, capturing the additional shadow cost of pollution due to the negative influence on human capital. As we show in the proof of Proposition 1 in the Appendix, this additional shadow cost is increasing in the stock of human capital. Accordingly, we have

$$\frac{d}{dH_{i,2}}\left\{-\frac{dV_{i,1}(Z_1)}{dM_1}\right\} > 0, \tag{21}$$

meaning that a larger stock of human capital in the future implies a larger marginal benefit of emission reduction today. Since $H_{i,2}$ is decreasing in $M_{i,1}$ and since M_1 is increasing in $E_{n,0} + E_{s,0}$, we thus conclude that

$$-\frac{d}{dE_{j,0}}\left\{-\frac{dV_{i,1}(Z_1)}{dM_1}\right\} > 0. \tag{22}$$

This means that once region j reduces its emission, the marginal benefit curve of region $i \neq j$ shifts upwards, providing region i with an incentive to reduce its own emission as well. This leads to our next proposition.

Proposition 2. *The short-run regional emissions are strategic complements.*

To understand this result intuitively we need to realize that any decrease in emission today 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. Then 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. The shadow value of human capital is then 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. In fact, if we swap the order of differentiation in (21), we obtain

$$-\frac{d}{dM_1}\left\{\frac{dV_{i,1}(Z_1)}{dH_{i,2}}\right\} > 0, \tag{23}$$

which suggests that the shadow value of human capital in the future increases as a result of emission reduction today. 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 strategic complementarity follows solely from the fact that an action of one player at one point in time influences the shadow value of the other player’s capital at another point in time. We call this the *dynamic complementarity effect*. As we discuss in Section 6, the statement of Proposition 2 can be less clear-cut if a different combination of utility and damage functions is used. Nevertheless, it will still be the case that the negative externality on human capital works in favor of strategic complementarity. This dynamic effect is largely ignored in the literature, but it can have important policy implications as will be exemplified below in the context of adaptation assistance.

4 Three periods: Adaptation assistance

Let us next examine, still within the three-period framework, how the equilibrium will be affected when North provides assistance to South. We know from the analysis in the preceding section that the equilibrium level of regional emissions in periods $t = 1, 2$ is determined independently of what the other region does. In period $t = 0$, on the other hand, emissions of North and South are strategic complements due to the dynamic complementarity effect. This result suggests that if a higher adaptation capability implies a greater willingness of South to reduce 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. As one might expect, what plays an important role in this experiment is the effectiveness of adaptation assistance. So, as a measure of effectiveness, we define

$$\varepsilon^Y := -\frac{d\delta_s^Y(R_t)}{dR_t}\bigg|_{R_t=0} > 0, \qquad \varepsilon^H := -\frac{d\delta_s^H(R_t)}{dR_t}\bigg|_{R_t=0} > 0, \tag{24}$$

which represents how effectively the marginal assistance from North can protect output and human capital in South, respectively.

4.1 Long-run emission

Since regional emissions in period $t = 2$ are corner solutions, they are not affected by any adaptation assistance. In period $t = 1$, on the other hand, the behavior of South is influenced by North's assistance through the changes in damage parameters. In particular, by totally differentiating the first-order condition, we obtain

$$\left.\frac{dE_{s,1}}{dR}\right|_{R=0} = -\frac{\rho(1-\bar{\theta}_s)\theta_{s,1}M_0 E_{s,1}}{(1-\rho_i)\bar{\theta}_s(1-\theta_{s,1}) + \rho(\bar{\theta}_s - \theta_{s,1})\theta_{s,1}}\varepsilon^H < 0. \tag{25}$$

This means that the long-run emission in South unambiguously declines as a result of enhanced adaptation capability. The long-run emission in North does not change because the first-order condition is not affected by R. Therefore, we have proved the following result.

Proposition 3. *At least in the long run, adaptation assistance from North to South helps decrease pollution emission at a global level.*

The mechanism behind this result is quite simple. Thanks to the enhanced adaptation capability in South, human capital increases and this enlarges productivity in the clean energy 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. While the cost-reduction effect only applies in the long run here, it will also be effective at a relatively early point in time if the model has a shorter time step.

4.2 Short-run emission

Unlike the long-run impact, the short-run consequence of adaptation assistance is not straightforward. Several things happen at once. First, there is an *income effect* for North. Adaptation assistance is not possible without giving up part of North's consumption, at least in the short run. This income effect inevitably increases North's marginal utility of consumption. Since there is a trade-off between consumption and emission reduction, this implies a higher cost of emission reduction for North. As a result, the marginal cost curve of North shifts upwards, providing North with an incentive to increase its emission. Since regional emissions are strategic complements, this will result in an increase of short-run emission at a global level, if everything else stays fixed.

At the same time, however, South's marginal benefit curve shifts in a non-trivial way. To analyze this shift, we decompose the impact of adaptation on the marginal benefit curve as

$$\frac{\partial}{\partial R}\left\{-\frac{dV_{s,1}(Z_1)}{dM_1}\right\}\bigg|_{R=0} = -(1+\beta_s\kappa_s)\phi_R\varepsilon^Y - \frac{\beta_s\lambda_s\phi_R}{1-\theta_{s,2}}\varepsilon^H + \frac{\beta_s\lambda_s\theta_{s,2}}{(1-\theta_{s,2})^2}\frac{\rho_s(\bar{\theta}_s-\theta_{s,2})}{\bar{\theta}_s-\rho_s(\bar{\theta}_s-\theta_{s,2})}(M_0+\phi_R M_1)\delta_s^H\varepsilon^H. \tag{26}$$

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 pollution stock both in the production sector and in human capital accumulation. As a result, the case for mitigation efforts is weakened in South. From the perspective of North, this poses a dilemma in integrating adaptation assistance into mitigation policy.

The third term in (26) is strictly positive, acting against the substitution effect. We call this the *complementarity effect* of adaptation because adaptation and mitigation can be complements when this effect is sufficiently strong. An increase in adaptation capital R 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.

Compared to the substitution effect, the complementarity effect has one noteworthy feature: it is long-lasting and does not vanish even after the adaptation capital has depreciated. To illustrate this point, let us assume that the depreciation rate of adaptation capital is 100% ($\phi_R = 0$), which is reasonable if the time step is sufficiently long. In this case, there is no additional adaptation capital remaining in period 1. Notice that the substitution effect is only active to the extent that future damage caused by current emission can be avoided by the presence of adaptation capital. Hence, as the adaptation capital disappears, so does the substitution effect. In fact, the first two terms in (26) vanish when $\phi_R = 0$. The complementarity effect, on the other hand, remains valid. Adaptation assistance creates a period of extra protection against pollution damage. And during that period, no matter how short it is, South can accumulate the stock of human capital, which helps reduce its emission even after the protection is removed. This suggests that the complementarity effect eventually dominates, as the direct influence of adaptation assistance dissipates.

In the immediate future, however, it is not clear whether the complementarity effect outweighs the substitution effect. Even if it does, it is still possible that the global level of emission temporarily increases because of the income effect we discussed above. Nevertheless, the sign of the net impact can be determined based on a simple set of conditions. To this end, we introduce the following assumption.

Assumption 1. *In South, (a) the level of human capital in the distant future is sufficiently large in the absence of pollution damage, and (b) the damage parameter in human capital accumulation is sufficiently large.*

In the context of climate change, these conditions seem reasonable. The first part of the assumption requires that South has a decent amount of human capital in the distant future, at least when it is not hindered by pollution. What is assumed in the second part is that there is a real risk that the growth of human capital is suppressed under severe pollution. Technically, this assumption sets a stage for the complementarity effect to potentially play an important role. If the baseline level of human capital is very low or if there is no serious threat to the accumulation of human capital, there is little to lose in the presence of pollution.

Hereafter, we maintain Assumption 1. Our next proposition states that even short-run regional emissions will decline if adaptation assistance is sufficiently effective in preventing damage to human capital.

Proposition 4. *For each region $i \in \{n, s\}$, $dE_{i,0}/dR$ is a strictly decreasing linear function of ε^H and there exists a threshold $\varepsilon^H_{E_{i,0}}$ such that*

$$\left.\frac{dE_{i,0}}{dR}\right|_{R=0} < 0 \iff \varepsilon^H > \varepsilon^H_{E_{i,0}},$$

with $0 < \varepsilon^H_{E_{s,0}} < \varepsilon^H_{E_{n,0}}$. Therefore, if the effectiveness ε^H of adaptation for human capital protection is greater than $\varepsilon^H_{E_{n,0}}$, North's marginal investment *in South's adaptation capital induces a global emission reduction even in the short-run future.*

As (26) suggests, the effectiveness of adaptation in the final-good production sector, which is captured by ε^Y, always works in favor of the substitution effect. On the other hand, the effectiveness ε^H of adaptation in human capital accumulation increases both the substitution effect and the complementarity effect. While the overall role of ε^H is unclear in general, its contribution to the complementarity effect is always greater than its contribution to the substitution effect under Assumption 1. The fact that North's threshold $\varepsilon^H_{E_{n,0}}$ is greater than South's $\varepsilon^H_{E_{s,0}}$ is due to the income effect, which only directly applies to North. As shown in the proof of Proposition 4 in the Appendix, the two thresholds coincide if there is no income effect.

If the interaction between pollution and human capital is ignored, only the first term in (26) remains and hence the substitution effect always dominates. Adaptation assistance would then never facilitate emission reduction. Ignoring human capital damage, which is common in the literature, can thus lead to misleading conclusions.

4.3 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 and the income effect combined. This happens in particular when the adaptation in South is sufficiently effective for human capital protection, in which case both short- and long-run pollution stocks obviously decline.

When the effectiveness of adaptation for human capital protection is not sufficiently large, the overall impact on the pollution stock is less obvious. More precisely, if $\varepsilon^H < \varepsilon^H_{E_{n,0}}$, Proposition 4 shows that the short-run level of global pollution stock can increase as a result of adaptation assistance. Even in this case, however, the stock of pollution can be smaller in the long run thanks to the cost-reduction effect. If the long-run cost-reduction effect is sufficiently large, it can compensate for the short-run substitution effect. Noticing from (25) that the cost-reduction effect is increasing in ε^H, we formalize the argument in the following proposition.

Proposition 5. *For each future period $t \in \{1, 2\}$, there exists a threshold $\varepsilon^H_{M_t}$ such that*

$$\left.\frac{dM_t}{dR}\right|_{R=0} < 0 \iff \varepsilon^H > \varepsilon^H_{M_t}$$

and $0 < \varepsilon^H_{M_2} < \varepsilon^H_{M_1} < \varepsilon^H_{E_{n,0}}$. Therefore, as long as the effectiveness ε^H of adaptation for human capital protection is greater than the relatively low threshold $\varepsilon^H_{M_2}$, even if it is below the threshold $\varepsilon^H_{E_{n,0}}$ identified in Proposition 4, North's marginal investment in South's adaptation capital can reduce global pollution, at least in the long-run.

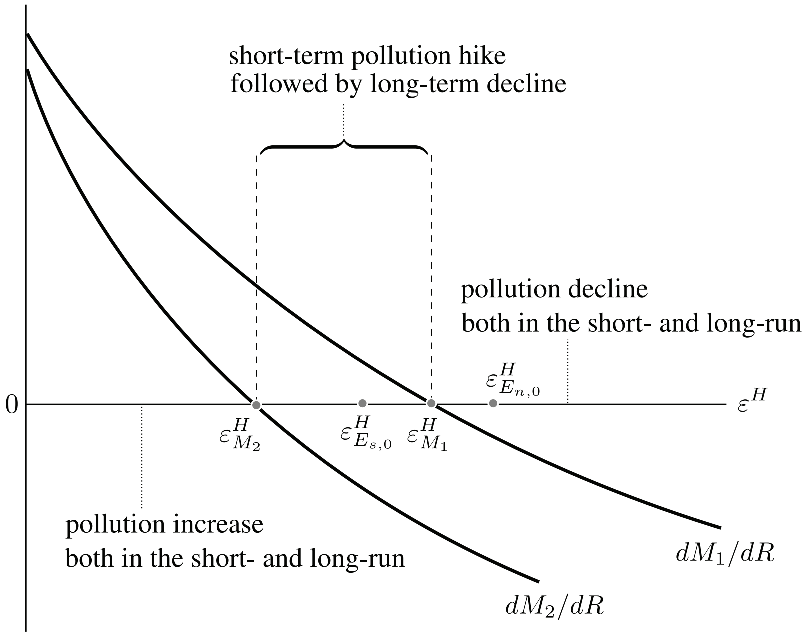


Figure 1: Impact of adaptation assistance on short- and long-run pollution

Figure 1 illustrates this result. When ε^H is smaller than $\varepsilon^H_{M_2}$, enhanced adaptation capability increases both the short-run and long-run levels of the pollution stock. When ε^H is larger than $\varepsilon^H_{M_1}$ the short-term and long-term levels of the pollution stock both decline. When ε^H is in-between these two thresholds, the level of the pollution stock increases in the short run, but decreases in the long run.

4.4 Welfare implications

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 $W_i(R)$ denote equilibrium welfare of region i in the second stage, where R is chosen by North in the first stage. North chooses R in such a way that $W_n(R)$ is maximized. For our purpose, however, it is sufficient to check if and under what conditions $dW_n/dR > 0$ evaluated at $R = 0$. When this is the case, then the equilibrium level of R is always positive. Differentiating $W_n(R)$ and evaluating it at $R = 0$ yields

$$\frac{dW_n}{dR} = -\frac{1}{Y_{n,0}} + \beta_n \frac{dV_{n,1}(Z_1)}{dM_1} \frac{dE_{s,0}}{dR}. \tag{27}$$

The first term on the right-hand side is the direct welfare cost of reduced consumption. The second term captures the welfare gain or loss due to the change in South's behavior. In addition to these terms, there are indirect costs and benefits associated with the change in North's control variables. But these indirect consequences cancel out by the envelope theorem. What is clear from (27) is that adaptation assistance results in North's welfare loss unless South reduces its emission in response. Hence, $dE_{s,0}/dR < 0$ is necessary for $dW_n/dR > 0$. Provided that $dE_{s,0}/dR$ is negative, a sufficient condition is that the emission reduction $-dE_{s,0}/dR$ is large enough to compensate for the direct cost of assistance by North.

We are also interested in whether or not assistance from North to South can be Pareto-improving. To clarify this point, differentiate South's welfare $W_s(R)$

and evaluate the derivative at $R = 0$ to obtain

$$\frac{dW_s}{dR} = \beta_s \frac{dV_{s,1}(Z_1)}{dM_1}\frac{dE_{n,0}}{dR} + (M_0 + (1+\beta_s\kappa_s)\beta_s\phi_R M_1)\,\varepsilon^Y + \left(\beta_s \frac{dV_{s,1}(Z_1)}{dH_{s,1}} H_{s,1} M_0 + \beta_s^2 \phi_R \frac{dV_{i,2}(Z_2)}{dH_{i,2}} H_{i,2} M_1\right)\varepsilon^H. \tag{28}$$

The second and the third terms on the right-hand side are the direct welfare benefit of enhanced adaptation capability in final output and human capital, respectively. The first term captures the welfare gain or loss due to the change in North's behavior. Again, the other indirect costs and benefits cancel out. Obviously, in order for South's welfare to improve, $dE_{n,0}/dR < 0$ is sufficient, but not necessary as long as the sum of the last two terms in (28) is positive.

Recall from Proposition 1 that $dE_{i,0}/dR$ is a strictly decreasing linear function of ε^H. Hence, the expressions (27) and (28) immediately prove the following proposition.

Proposition 6. *For each region $i \in \{n, s\}$, there exists a threshold $\varepsilon^H_{W_i}$ such that*

$$\left.\frac{dW_i}{dR}\right|_{R=0} > 0 \iff \varepsilon^H > \varepsilon^H_{W_i}.$$

Therefore, if the effectiveness ε^H of adaptation for human capital protection is greater than $\varepsilon^H_{W_n}$, North's marginal investment in South's adaptation capital is incentive compatible. Moreover, if ε^H is greater than $\max\{\varepsilon^H_{W_n}, \varepsilon^H_{W_s}\}$, it is Pareto-improving.

Again, a key issue is whether or not the adaptation assistance is sufficiently effective in protecting human capital. Proposition 6 shows that as long as the effectiveness ε^H is greater than a certain threshold $\varepsilon^H_{W_n}$, North always has an incentive to provide a positive level of adaptation assistance to South. Similarly, there is another threshold $\varepsilon^H_{W_s}$ above which South's welfare is improved by North's adaptation assistance. We note that for South, the threshold $\varepsilon^H_{W_s}$ can be zero, meaning that adaptation assistance can make South always better off, regardless of its effectiveness in human capital protection. When adaptation assistance is completely ineffective in terms of human capital protection ($\varepsilon^H = 0$), there will be no complementarity or cost-reduction effect and so the first term in (28) will be unambiguously negative. As long as ε^Y is strictly positive, however, the second term in (28) is always positive, making the net impact potentially positive.

Intuitively, one might expect that South's threshold $\varepsilon^H_{W_s}$ is always smaller than North's $\varepsilon^H_{W_n}$. In general, however, one cannot rule out the possibility that $\varepsilon^H_{W_s}$ is larger than $\varepsilon^H_{W_n}$. North might be able to achieve a higher level of welfare at the cost of South's welfare. Comparing (27) with (28), we see that this is only possible if

$$\frac{dE_{s,0}}{dR} < 0 < \frac{dE_{n,0}}{dR}. \tag{29}$$

When this is the case, North takes advantage of South's emission reduction in response to adaptation assistance and, at the same time, increases its own emission. As we discussed in the interpretation of Proposition 4, it is the income effect that drives the difference in regional reactions to adaptation assistance. Hence, when the income effect is sufficiently small, (29) is less likely to hold, and South's threshold $\varepsilon^H_{W_s}$ is always lower than North's $\varepsilon^H_{W_n}$, as our next proposition clarifies.

Proposition 7. *Let $\varepsilon^H_{W_n}$, $\varepsilon^H_{W_s}$ be the thresholds identified in Proposition 6. If North's total factor productivity $A_{n,0}$ or North's stock of physical capital $K_{n,0}$ is sufficiently large, we have $\varepsilon^H_{W_n} > \varepsilon^H_{W_s}$, meaning that providing adaptation assistance achieves a Pareto improvement whenever North has an incentive to do so. Moreover, $\varepsilon^H_{W_n}$ and $\varepsilon^H_{W_s}$ are decreasing in $A_{n,0}$ and $K_{n,0}$. Therefore, adaptation assistance is more likely to be incentive-compatible and Pareto-improving if the assistance is provided by a region with more advanced technology and a larger stock of capital.*

The direct cost of adaptation assistance becomes negligible when North is wealthy enough, which is ensured by high productivity and/or a large amount of capital stock. As a consequence, the income effect shrinks, eliminating the difference in regional reactions to adaptation assistance. This ensures that whenever North is better off, so is South, as the first half of the Proposition 7 states. Also, when North is sufficiently wealthy, adaptation assistance is more likely to be incentive compatible for North. This is because the indirect welfare gain is likely to dominate the direct welfare cost of assistance. The second half of Proposition 7 formalizes this argument.

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 can 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 four distinct effects: income effect, cost-reduction effect, substitution effect, and complementarity effect. While the substitution effect weakens South's incentive to reduce pollution, the cost-reduction and complementarity effects work in favor of a greater abatement incentive for South. In particular, if the adaptation assistance 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. If the net effect in South outweighs the income effect in North, this in turn provides an additional incentive for North to engage in emission abatement 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. In terms of welfare, however, both regions can be compensated for the negative impact of such a temporary intensification of pollution as long as the donor 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.

5 Infinite-period setting

Since the model in the two preceding sections has only three periods, one might argue that our results are only valid for finite-period settings. We now address this issue by numerically analyzing the infinite-period version of the model.

5.1 Methodology

Solving for Markov-perfect Nash equilibria in infinite-period settings can be computationally challenging. Unlike the open-loop solution, the concept of Markov-perfect Nash equilibria requires that the model be specified in a recursive form and then be solved iteratively until convergence is reached. The iteration process can take a long time and can get stuck or not converge, especially when the model involves strategic interaction with many state variables. To ease the computational burden, we use the fact that the equilibrium savings rate is constant over time.

Proposition 8. *For the model with $T = \infty$, the equilibrium savings rate of region i is given by $s_{i,t} = \beta_i \kappa_i$ for all t.*

A constant savings rate is consistent with the existing data (Golosov et al., 2014) and it allows us to reduce the number of state variables in computing the value function. To see how this works, consider the Bellman equation, for $i = n, s$,

$$v_{i,t} = \max_{E_{i,t}, \theta_{i,t}} \left\{ \log(\Delta_{i,t}^{Y} A_{i,t} L_{i,t}^{\lambda_i} X_{i,t}^{1-\kappa_i-\lambda_i}) + \beta_i v_{i,t+1} \right\}, \tag{30}$$

where $v_{i,t} := v_{i,t}(H_{n,t}, H_{s,t}, M_t, R_t)$ and the maximization is subject to the constraints described in Section 2. Solving this problem is much faster and easier than solving the original Bellman equation (14). Instead of working with the entire state space, we can focus on its subspace, dropping the two state variables $K_{n,t}$ and $K_{s,t}$. Our next proposition shows how the solution $v_{i,t}$ of (30) can be used to compute the value function of the original problem (14).

Proposition 9. *For period $t \geq 1$, the value function of region i is given by*

$$V_{i,t}(Z_{i,t}) = a_i + \frac{\kappa_i}{1 - \beta_i \kappa_i} \log(K_{i,t}) + \frac{1}{1 - \beta_i \kappa_i} v_{i,t} \tag{31}$$

and the value function for period $t = 0$ is given by

$$V_{i,0}(Z_{i,0}) = \max_{E_{i,0}, \theta_{i,0}} \left\{ a_i + \frac{1}{1 - \beta_i \kappa_i} \log(\tilde{Y}_{i,0}) + \frac{\beta_i}{1 - \beta_i \kappa_i} v_{i,1} \right\}, \tag{32}$$

where a_i is a region-specific constant defined by

$$a_i = \frac{1}{1 - \beta_i} \left(\log(1 - \beta_i \kappa_i) + \frac{\beta_i \kappa_i}{1 - \beta_i \kappa_i} \log(\beta_i \kappa_i) \right). \tag{33}$$

With this result in mind, we solve the problem as follows. Suppose that we know the function $v_{i,t+1}$ for some t. Given $v_{i,t+1}$, we numerically solve the Bellman equation (30) and obtain $v_{i,t}$, using the collocation method and the Chebyshev polynomials approximation (Judd, 1998; Miranda and Fackler, 2002). The function $v_{i,t}$ is then used to compute $v_{i,t-1}$, and so on until we obtain $v_{i,1}$, and hence $V_{i,0}$ by (32).

This algorithm requires knowledge of the function $v_{i,t+1}$ for some t. In order to obtain this information, we consider the case where the damage parameters converge to a constant level for some sufficiently large t. Especially, we assume that $\delta_{i,t}^{H}$ converges to 0 in the long run, due to the technological development in the future.

Assumption 2. *There exists $\bar{t}$ such that $\delta_{i,t}^{Y} = \delta_{i}^{Y} > 0$ and $\delta_{i,t}^{H} = 0$ for all $t \geq \bar{t}$.*

This is reasonable as long as $\bar{t}$ is sufficiently large. The long-run value of the damage parameter in the final-output sector, δ_{i}^{Y}, can be arbitrarily small, but needs to be strictly positive. Otherwise, there would be no damage from pollution at all, which would make the optimal choice of emission unbounded. Some straightforward but tedious algebra (available upon request) shows that, under Assumption 2, the solution $v_{i,t}$ of the Bellman equation (30) can be solved directly for any $t \geq \bar{t}$. Hence, we can use $v_{i,\bar{t}}$ as a starting point for the algorithm described above.

5.2 Parameter selection

We define North as a group of countries which are categorized as high-income economies by World Bank (2016). The rest of the world is labeled as South. We consider a decadal time step with 2010 being the initial period. The discount factor is $\beta_i = 0.86$, which means that the annualized discount rate is 1.5%. The parameter values in the final-good production sector closely follow those used by Golosov et al. (2014). The initial values of total factor productivity $A_{i,0}$ and physical capital $K_{i,0}$ are chosen so that the equilibrium value of final-good production matches the regional aggregate GDP in 2010. Notice that it is not necessary to specify how the total factor productivity evolves over time because it only affects welfare through constant terms and hence is irrelevant for computing the equilibrium. The initial stock of human capital is calibrated to match the regional population that attains tertiary education as defined by Barro and Lee (2013). We normalize the initial productivity of the clean energy sector by $\tilde{A}_{i,0} = 1$ and assume that, in the absence of pollution damage, the maximum capacity of clean energy production $\tilde{A}_{i,t}H_{i,t}$ initially grows at the

Table 1: Parameter values for numerical exercises

Symbol	Value	Description
β_i	0.86	Discount factor (per decade)
κ_i	0.3	Parameter in production function
λ_i	0.65	Parameter in production function
$H_{n,0}$	36926630	North's initial stock of human capital
$H_{s,0}$	29110530	South's initial stock of human capital
$A_{n,0}K_{n,0}^{\kappa_n}$	234	North's (normalized) initial stock of physical capital
$A_{s,0}K_{s,0}^{\kappa_s}$	110	South's (normalized) initial stock of physical capital
ρ_i	0.1	Parameter in energy composite production function
ϕ_M	0.95	Retention rate of carbon stock (per decade)
ϕ_R	0.15	Retention rate of adaptation capital (per decade)
$\bar{t}$	30	Period of convergence (300 years)
M_0	800	Initial pollution stock
$\delta_{n,t}^Y$	0.0000350	North's damage to final-good sector (constant)
$\bar{\delta}_{s,t}^Y$	0.0000526	South's damage to final-good sector (constant)
$\delta_{n,0}^H$	0.0000025	North's damage to human capital
$\bar{\delta}_{s,0}^H$	0.0000050	South's damage to human capital
ε^Y	0.00000100	Effectiveness of assistance (final-good production)
ε_{low}^H	0.00000005	Effectiveness of assistance (human capital protection)
ε_{high}^H	0.00000020	Effectiveness of assistance (human capital protection)

rate of 4% per year, but that the growth rate declines over time at a rate of 5% per decade. As for the elasticity of substitution, Acemoglu et al. (2012) assume that $\rho_i = 0.33$ for one of their baseline scenarios. To be on the conservative side, we set $\rho_i = 0.10$ so that the different sources of energy are substitutes, but not as easily substitutable. We set $\phi_M = 0.95$, which means that atmospheric carbon decays at a rate of 5% per decade. Our equilibrium path of carbon concentration then resembles the IPCC RCP6.5 scenario, starting from 800 GtC, gradually increasing over time, reaching to 1500 GtC in the next 300 years, and being stabilized at that level.

South's damage parameters are specified as

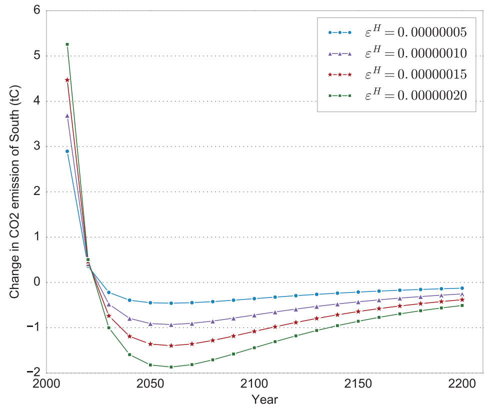
$$\delta_{s,t}^Y = \bar{\delta}_{s,t}^Y \exp\left(-\frac{\varepsilon^Y R_t}{\bar{\delta}_{s,t}^Y}\right), \qquad \delta_{s,t}^H = \bar{\delta}_{s,t}^H \exp\left(-\frac{\varepsilon^H R_t}{\bar{\delta}_{s,t}^H}\right), \tag{34}$$

where $\bar{\delta}_{s,t}^Y$ and $\bar{\delta}_{s,t}^H$ are the baseline values in the absence of assistance. We set $\phi_R = 0.15$ so that adaptation capital depreciates at the rate of 17.3% per year. This means that there is almost no direct influence of adaptation assistance after thirty years. The damage parameter $\delta^Y_{i,t}$ in the final-good production sector is assumed to be time-invariant for simplicity and is set at $\delta^Y_{n,t} = 0.000035$ and $\bar{\delta}^Y_{s,t} = 0.000052$ for all t. This implies that when the stock of carbon in the atmosphere reaches 1500 GtC, which is the long-run level of pollution in the equilibrium path, 5.1% and 7.6% of annual GDP will be lost in North and South, respectively. The associated global loss of GDP is 5.8%, which is fairly consistent with the existing literature (Golosov et al., 2014). The damage parameters $\delta^H_{i,t}$ in the human capital accumulation are not easy to calibrate. As a benchmark, we set their initial values at $\delta^H_{n,0} = 0.0000025$ and $\bar{\delta}^H_{s,0} = 0.0000050$, and assume that they gradually decline over time, converging to 0 in 300 years. Along the equilibrium path, this means that North and South will respectively lose 1.25% and 5% of human capital in the next 300 years relative to the case with no pollution. Table 1 summarizes the parameter values we employ. We present a brief sensitivity analysis in Section 5.4.

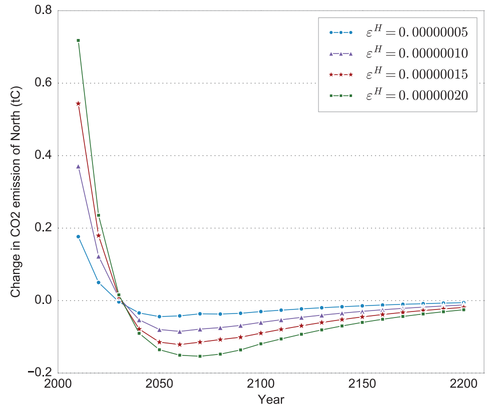
5.3 Results

We report in Figure 2 the consequences of a marginal investment (100US$ in 2010) in South's adaptation capital for different values of ε^H. As Figure 2(a) shows, 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. The substitution effect does not go away until the adaptation capital is depreciated; see Figure 2(c). When the adaptation capital depreciates sufficiently, the combined effect of complementarity and cost reduction becomes important due to the additional human capital protected by the adaptation. As a result, the temporary hike of regional emission is followed by a decrease of emission in subsequent periods. When adaptation assistance is not very effective for human capital protection (ε^H is small), the magnitude of the long-term emission reduction is relatively small. The role of complementarity and cost-reduction is more pronounced when the adaptation assistance can more effectively protect human capital (ε^H is large). This is consistent with our theoretical findings in the three-period setting.

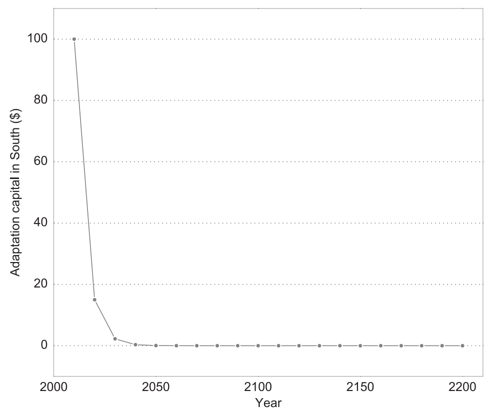
In Figure 2(b), we depict the equilibrium emission of North. The short-term increase of North's emission reflects, at least partially, the income effect. Clearly, the qualitative characteristics of North's emission are similar to those



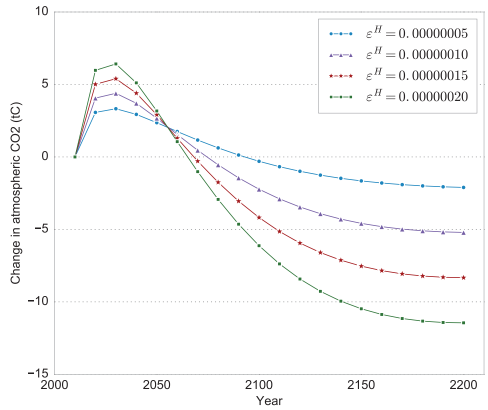
(a) South's emission



(b) North's emission



(c) Adaptation capital

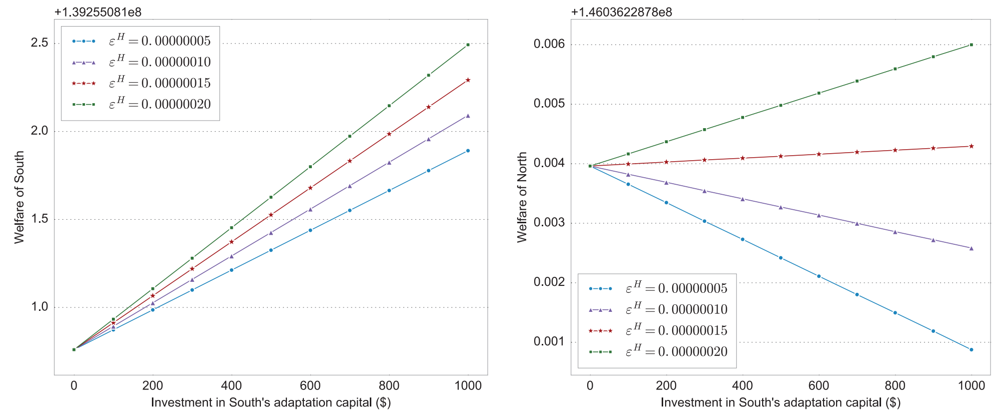


(d) Pollution stock

Figure 2: Consequences of adaptation assistance (relative to the case with $R = 0$)

of South. This indicates that the emissions of the two regions are strategic complements, in agreement with the analytic results of the three-period model.

The equilibrium pollution stock is reported in Figure 2(d). Again, the qualitative characteristics of the three-period model are replicated. When adaptation assistance is not effective in terms of human capital protection, the pollution stock rises for a relatively long period of time. If the assistance is targeted at those adaptation activities with more effective human capital protection, the increase in short-term pollution becomes slightly larger (recall that ε^H increases the substitution effect as well), but the period of pollution hike ends at an earlier point in time. Moreover, the pollution reduction thereafter is significantly larger



(a) South's welfare as a function of R

(b) North's welfare as a function of R

Figure 3: Welfare implications of adaptation assistance

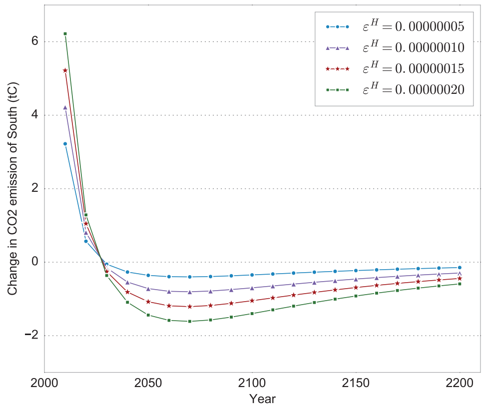
and the gap becomes wider over time.

Figure 3 shows the equilibrium welfare as a function of R. 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 to human capital in South. This indicates that for our numerical specification here, the income effect is sufficiently small.

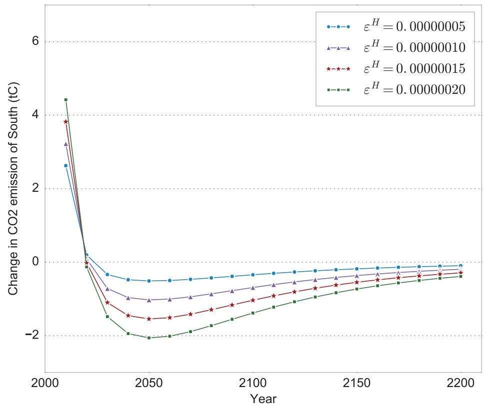
5.4 Sensitivity analysis

We present a brief sensitivity analysis with respect to the parameters: $\delta^H_{i,0}$ (damage parameter in human capital accumulation) and ε^Y (effectiveness of adaptation for output production).

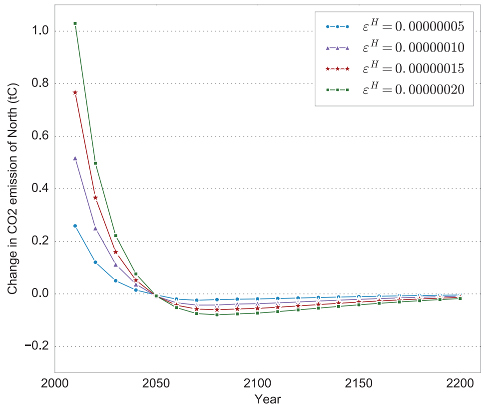
Figure 4 depicts the consequences of a marginal investment (100US$ in 2010) in South's adaptation capital for lower and higher values of $\delta^H_{i,0}$. For the lower values we assume that $\delta^H_{n,0} = 0.00000225$ and $\bar{\delta}^H_{s,0} = 0.00000450$ (10% smaller than the baseline values). For the higher values we assume that $\delta^H_{n,0} = 0.00000275$ and $\bar{\delta}^H_{s,0} = 0.00000550$ (10% larger than the baseline values). When $\delta^H_{i,0}$ is relatively low, adaptation assistance results in a relatively large emission increase in the short-run, followed by a relatively small emission decrease in the long-run. When $\delta^H_{i,0}$ is relatively high, the short-term pollution



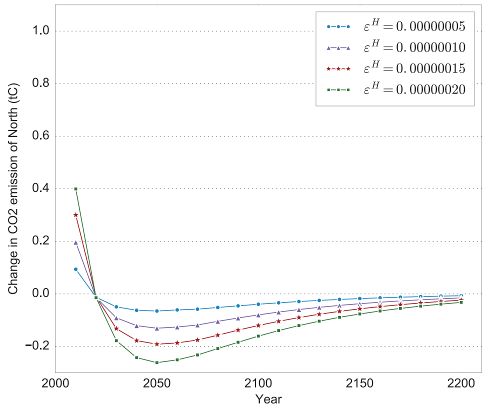
(a) South's emission (lower δ^H)



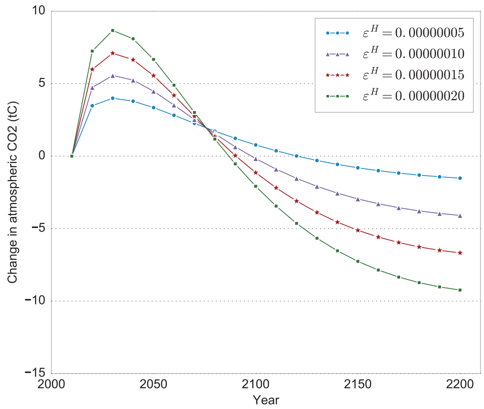
(b) South's emission (higher δ^H)



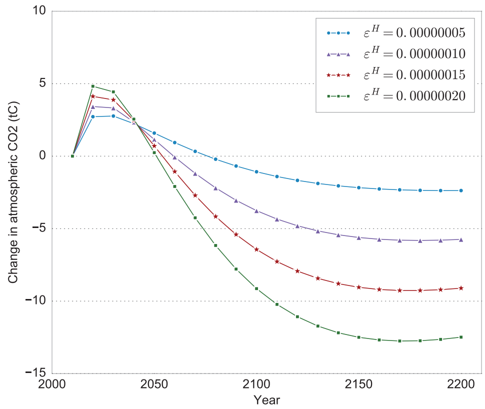
(c) North's emission (lower δ^H)



(d) North's emission (higher δ^H)

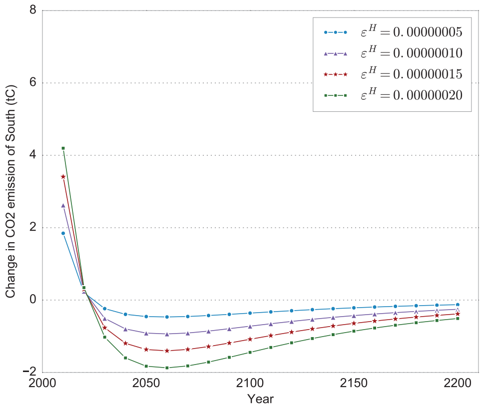


(e) Pollution stock (lower δ^H)

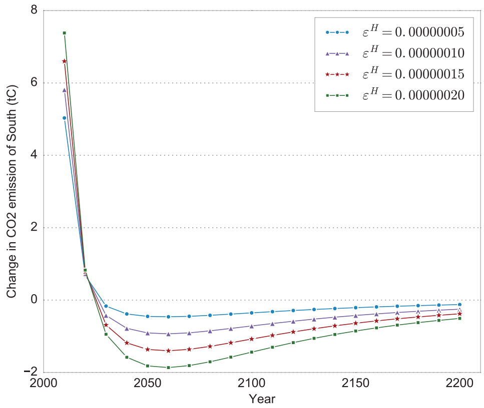


(f) Pollution stock (higher δ^H)

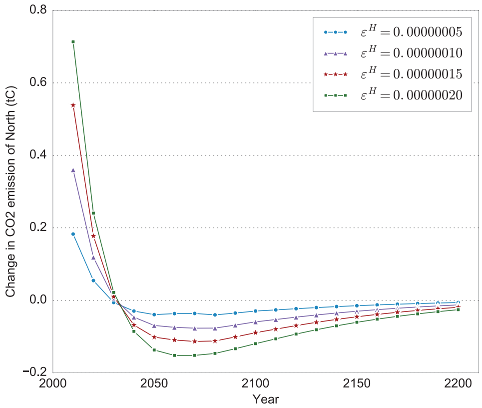
Figure 4: Consequences of adaptation assistance with varying $\delta^H_{i,0}$



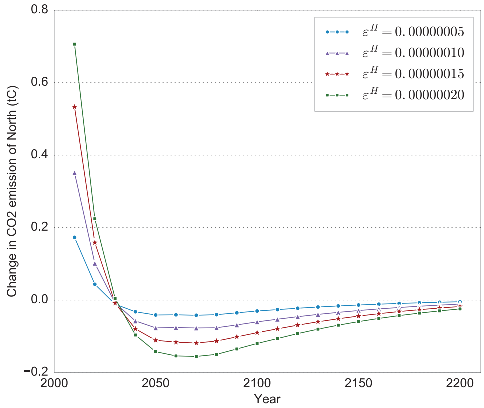
(a) South's emission (lower ε^Y)



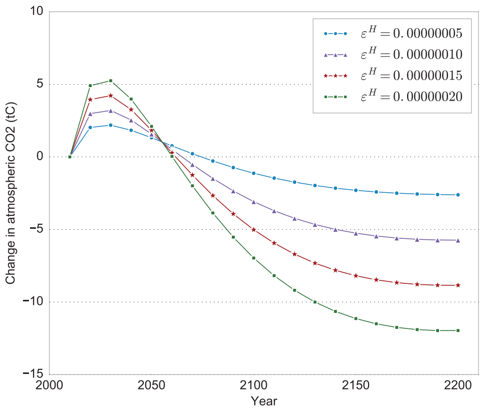
(b) South's emission (higher ε^Y)



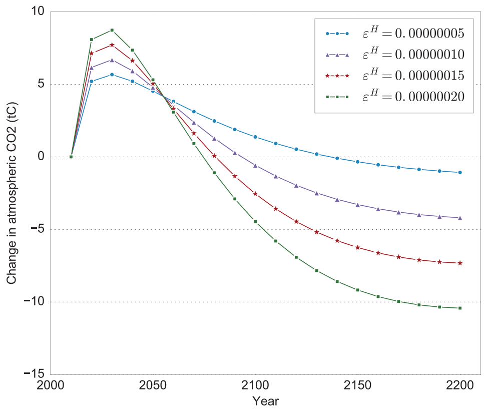
(c) North's emission (lower ε^Y)



(d) North's emission (higher ε^Y)



(e) Pollution stock (lower ε^Y)



(f) Pollution stock (higher ε^Y)

Figure 5: Consequences of adaptation assistance with varying ε^Y

hike is less pronounced while the long-term emission reduction is more visible and the period of environmental degradation ends at an early point in time. This indicates that when the damage parameter is large, the complementarity effect plays a more important role but the substitution effect is not affected much, yet another confirmation of our theoretical results.

Figure 5 depicts the consequences of the same marginal adaptation investment for lower and higher values of ε^Y. We set $\varepsilon^Y = 0.00000050$ (half the baseline value) for the lower value and $\varepsilon^Y = 0.00000200$ (twice the baseline value) for the higher value. It is clear from the figure that South's short-run emission is sensitive to this parameter, but everything else remains the same. This is an indication that the effectiveness of adaptation for output production only affects the substitution effect, precisely what one would expect from our theoretical results.

In summary, our sensitivity analysis suggests that a higher value of damage parameter $\delta_{i,0}^H$ strengthens the complementarity effect, making it more likely to achieve emission reduction both in short- and long-run. A higher value of effectiveness ε^Y of adaptation for final output, on the other hand, bolsters the substitution effect, which makes the temporary environmental degradation more painful. Therefore, as a rule of thumb, adaptation assistance should be primarily given to those who suffer most in terms of human capital destruction and should be targeted at the protection of human capital rather than the prevention of purely physical damages. With appropriate caution we thus claim that our numerical exercises are robust and consistent with the theoretical results in the preceeding sections. The three-period framework may seem restrictive, but the same qualitative results are obtained for a model with the infinite time horizon.

6 Conclusions and discussion

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. When 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. This, however, 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.

Let us briefly discuss some limitations of our analysis and thereby suggest possible areas for future research. First, our treatment of human capital is not entirely satisfactory. The way we model pollution damage to human capital, especially the exponential damage function, may be a little simplistic given the fact that a growing number of empirical studies reveal the complex nature of climate-economy interaction (Carleton and Hsiang, 2016). Although the schematic treatment of pollution-induced capital destruction is common in the literature (Ikefuji and Horii, 2012; Bretschger and Suphaphiphat, 2014), a more realistic description of human capital and its relation to climate change will be useful, especially when the model is to be matched up with empirical data. Also, aside from pollution damage, the baseline path of human capital is assumed to be exogenous here. Ideally, the growth rate of human capital should be endogenously determined through a separate investment decision. Allowing for endogenous human capital investment will certainty change the quantitative implications of adaptation, although it would not invalidate the mechanism we identified.

One might also argue that our treatment of adaptation is too simplistic. For instance, North's adaptation is not explicitly modeled and adaptation assistance to South is only possible at the initial period. Hence, explicitly modeling North's adaptation and/or allowing for more flexible timings of transfer would bring the model closer to reality. We note, however, that such an extension is not likely to produce substantially new insights. If we explicitly introduce North's adaptation behavior as a separate decision variable, the optimal level of adaptation assistance to South depends on how effectively North can use its resource for enhancing their own adaptation capacity. As its own adaptation possibilities get exhausted, the rate of return will be tilted in favor of investment in South's adaptation opportunities. This suggests that North's adaptation will not kill the motive for assistance to South. Likewise, our exclusive focus on the one-off adaptation investment is innocuous. In fact, even if we allow for adaptation investment from North to South in periods 1 and 2 in the three-period setting, assistance in these periods will never be incentive compatible for North. In order for North to reap the benefit of adaptation investment, at least two remaining periods are required. The consequence is less obvious in the infinite-period setting and North might have an incentive to 'smooth out' its adaptation investment in South over multiple periods. But the condition for the incentive compatibility at each point in time will not be much different from the one we identified.

Some of the knife-edged theoretical results in this paper depend on the specification of functions. A logarithmic utility function, an exponential damage function, and a Cobb-Douglas production function all play a part for ensuring tractability of the model. The logarithmic-exponential combination introduced by Golosov et al. (2014) makes the model essentially linear in pollution stock. In other words, the marginal benefit curve, when measured in units of utility, is completely flat in their model. In multi-regional settings, this means that each region's equilibrium strategy is independently determined unless an additional channel of externality is added. This feature allows us to nail down the strategic significance of one specific type of additional externality (pollution-induced human capital destruction), which makes the marginal benefit curve upward-sloping. If the utility function or/and damage function is more concave, the baseline marginal benefit curve will be downward-sloping instead of being flat, acting against the dynamic complementarity effect. If one or both of the functions is relatively more convex, on the other hand, the complementarity effect will be strengthened. Hence, more subtleties will be involved for other combinations of utility and damage functions.

The assumption of a Cobb-Douglas production function, together with the logarithmic utility function and full depreciation of physical capital, makes the equilibrium savings rate independent of the other control variables. This greatly simplifies the theoretical and numerical analyses, but it forces us to assume that the elasticity of substitution among physical capital, labor, and energy composite is one. It is not immediately clear if the unit-elasticity assumption in the production function is restrictive or not. But one could relax the assumption if the elasticity of intertemporal substitution is adjusted exactly to offset the change in the elasticity of input substitution (Antoniadou et al., 2013). In fact, such an extension was pursued by Quaas and Brocker (2016) in an overlapping generations framework and they found that the elasticity of substitution quantitatively influences the results. Although assuming the exact match between the two types of elasticities is still restrictive, pushing the boundary of possible functional combinations would be an interesting avenue for further research.

Finally, our analysis lacks an important channel of regional interaction: trade. Apart from adaptation assistance, regions in our model have interaction only through changes in pollution stock. It is well-known, however, that when regions are connected through a market, unilateral policies of one region can cause unintended environmental consequences in other regions (Copeland and Taylor, 2003). In particular, there has been a widespread concern about potential carbon-leakage. Combined with the dynamic complementarity effect, the market-based interaction among regions may have qualitatively different implications. Also, since the analysis of trade naturally requires a multi-good setting, this line of extension will allow regions to be asymmetric in a more fundamental way through comparative advantages. The single-good model used in this paper, although regions can be highly asymmetric, is limited in this regard. Clarifying the roles of dynamic complementarity and adaptation in such a flexible framework would help us design a more affective policies.

Appendix: Proofs of propositions

Proof of Proposition 1

Notice first that in each period, for a given level $E_{i,t}$ of emission, $\theta_{i,t}$ is chosen so as to maximize the current output. So, for each $E_{i,t}$, define

$$Y_{i,t}(E_{i,t}) := \max_{\theta_{i,t}} \Delta^Y_{i,t} A_{i,t} K^{\kappa_i}_{i,t} ((1-\theta_{i,t})H_{i,t})^{\lambda_i} \left(E^{\rho_i}_{i,t} + (\tilde{A}_{i,t}\theta_{i,t}H_{i,t})^{\rho_i} \right)^{\frac{1-\kappa_i-\lambda_i}{\rho_i}},$$

which is the maximized output for a given level of emission. The first-order condition of this maximization problem implies

$$E_{i,t} = \tilde{A}_{i,t} H_{i,t} \left(\frac{1-\kappa_i}{\lambda_i} \right)^{\frac{1}{\rho_i}} \left(\bar{\theta}_i - \theta_{i,t} \right)^{\frac{1}{\rho_i}} \theta_{i,t}^{-\frac{1-\rho_i}{\rho_i}}, \tag{35}$$

where

$$\bar{\theta}_i := \frac{1-\kappa_i-\lambda_i}{1-\kappa_i} < 1.$$

This gives (17). Since $\theta_{i,t} < \bar{\theta}_i$ for all $E_{i,t} > 0$, it follows that

$$\frac{d\theta_{i,t}}{dE_{i,t}} \frac{E_{i,t}}{\theta_{i,t}} = -\frac{\rho_i(\bar{\theta}_i - \theta_{i,t})}{\bar{\theta}_i - \rho_i(\bar{\theta}_i - \theta_{i,t})} < 0, \tag{36}$$

meaning that $\theta_{i,t}$ is strictly decreasing in $E_{i,t}$. Using (35), we may write

$$Y_{i,t}(E_{i,t}) = \Delta^Y_{i,t} \bar{A}_{i,t} K^{\kappa_i}_{i,t} H^{1-\kappa_i}_{i,t} \frac{(1-\theta_{i,t})^{\lambda_i + \frac{1-\kappa_i-\lambda_i}{\rho_i}}}{(\theta_{i,t})^{\frac{1-\rho_i}{\rho_i}(1-\kappa_i-\lambda_i)}}, \tag{37}$$

where $\bar{A}_{i,t} := A_{i,t}\tilde{A}^{1-\kappa_i-\lambda_i}_{i,t} \left((1-\kappa_i-\lambda_i)/\lambda_i\right)^{\frac{1-\kappa_i-\lambda_i}{\rho_i}}$. Since

$$\begin{aligned}
\frac{dY_{i,t}(E_{i,t})}{dE_{i,t}} \frac{E_{i,t}}{Y_{i,t}(E_{i,t})} &= -\frac{d\theta_{i,t}}{dE_{i,t}} \frac{E_{i,t}}{\theta_{i,t}} \left(\bar{\theta}_i \frac{1-\rho_i}{\rho_i} + \theta_{i,t} \right) \frac{1-\kappa_i}{1-\theta_{i,t}} \\
&= \frac{\bar{\theta}_i - \theta_{i,t}}{1-\theta_{i,t}} (1-\kappa_i) > 0,
\end{aligned}$$

we know that $Y_{i,t}(E_{i,t})$ is a strictly increasing function of $E_{i,t}$. Letting $s_{i,t}$ denote the savings rate defined by (15), the recursive formulation of the problem may be rewritten as

$$V_{i,t}(Z_t) = \max_{E_{i,t}, s_{i,t}} \left\{ \log((1 - s_{i,t})\tilde{Y}_{i,t}(E_{i,t})) + \beta_i V_{i,t+1}(Z_{t+1}) \right\},$$

where

$$\tilde{Y}_{i,t}(E_{i,t}) := \begin{cases} Y_{i,t}(E_{i,t}) - R & \text{for } (i,t) = (n,0), \\ Y_{i,t}(E_{i,t}) & \text{otherwise.} \end{cases}$$

We solve this problem backwards from period $T = 2$. Hereafter, to simplify the notation, we write $Y_{i,t}$ and $\tilde{Y}_{i,t}$ to mean $Y_{i,t}(E_{i,t})$ and $\tilde{Y}_{i,t}(E_{i,t})$, respectively.

Problem of period $t = 2$

Since $V_{i,3}(Z_3) = 0$, it is immediate that $E_{i,2} = \bar{E}_{i,2}$ and $s_{i,2} = 0$. Hence, by (35), the equilibrium level of $\theta_{i,2}$ is determined by

$$\bar{E}_{i,2} = \tilde{A}_{i,2} H_{i,2} \left(\frac{1 - \kappa_i}{\lambda_i} \right)^{\frac{1}{\rho_i}} \left(\bar{\theta}_i - \theta_{i,2} \right)^{\frac{1}{\rho_i}} \theta_{i,2}^{-\frac{1-\rho_i}{\rho_i}}. \tag{38}$$

Notice that differentiating (38) with respect to $H_{i,2}$ yields

$$\frac{d\theta_{i,2}}{dH_{i,2}} \frac{H_{i,2}}{\theta_{i,2}} = \frac{\rho_i(\bar{\theta}_i - \theta_{i,2})}{\bar{\theta}_i - \rho_i(\bar{\theta}_i - \theta_{i,2})} > 0, \tag{39}$$

implying that $\theta_{i,2}$ is increasing in $H_{i,2}$. Also, by the envelope theorem, we have

$$\frac{dV_{i,2}(Z_2)}{dK_{i,2}} = \frac{\kappa_i}{K_{i,2}}, \qquad \frac{dV_{i,2}(Z_2)}{dK_{j,2}} = 0, \tag{40}$$

$$\frac{dV_{i,2}(Z_2)}{dH_{i,2}} = \frac{\lambda_i}{1 - \theta_{i,2}} \frac{1}{H_{i,2}}, \qquad \frac{dV_{i,2}(Z_2)}{dH_{j,2}} = 0, \tag{41}$$

and

$$\frac{dV_{i,2}(Z_2)}{dM_2} = -\delta^Y_{i,2}. \tag{42}$$

Problem of period $t = 1$

The first-order condition with respect to $s_{i,1}$ is

$$\frac{1}{1 - s_{i,1}} = \beta_i \frac{dV_{i,2}(Z_2)}{dK_{i,2}} \frac{dK_{i,2}}{ds_{i,1}} = \beta_i \frac{dV_{i,2}(Z_2)}{dK_{i,2}} Y_{i,1}. \tag{43}$$

Combined with (40), this yields

$$s_{i,1} = \frac{\beta_i \kappa_i}{1 + \beta_i \kappa_i}.$$

The first-order condition with respect to $E_{i,1}$, on the other hand, is

$$\begin{aligned}\frac{dY_{i,1}}{dE_{i,1}} &= -\beta_i \frac{dV_{i,2}(Z_2)}{dM_2} Y_{i,1} - \beta_i \frac{dV_{i,2}(Z_2)}{dK_{i,2}} Y_{i,1} \frac{dK_{i,2}}{dY_{i,1}} \frac{dY_{i,1}}{dE_{i,1}} \\ &= -\beta_i \frac{dV_{i,2}(Z_2)}{dM_2} Y_{i,1} - \frac{s_{i,1}}{1 - s_{i,1}} \frac{dY_{i,1}}{dE_{i,1}},\end{aligned}$$

where the second line uses (43). Rearranging terms gives

$$\frac{1}{1 - s_{i,1}} \frac{dY_{i,1}}{dE_{i,1}} = -\beta_i \frac{dV_{i,2}(Z_2)}{dM_2} Y_{i,1}. \tag{44}$$

Since $C_{i,1} = (1 - s_{i,1}) Y_{i,1}$ and $s_{i,1}$ is independent of $E_{i,1}$, this implies (18) for $t = 1$.

Combining (35), (37), (42), and (44), we obtain

$$\left(\frac{\theta_{i,1}}{\bar{\theta}_i - \theta_{i,1}} \right)^{\frac{1-\rho_i}{\rho_i}} \frac{1 - \kappa_i}{1 - \theta_{i,1}} \left(\frac{\lambda_i}{1 - \kappa_i} \right)^{\frac{1}{\rho_i}} \frac{1}{\tilde{A}_{i,1} H_{i,1}} = (1 - s_{i,1}) \beta_i \delta^Y_{i,2},$$

which determines the equilibrium level of $\theta_{i,1}$. Since the left-hand side is strictly increasing in $\theta_{i,1}$, ranging from 0 to ∞, there exists a unique $\theta_{i,1}$ which solves this equation. Straightforward but somewhat tedious algebra then yields

$$\frac{dV_{i,1}(Z_1)}{dK_{i,1}} = \frac{\kappa_i \left(1 + \beta_i \kappa_i\right)}{K_{i,1}}, \qquad \frac{dV_{i,1}(Z_1)}{dK_{j,1}} = 0, \tag{45}$$

$$\frac{dV_{i,1}(Z_1)}{dH_{i,1}} = \frac{(1 + \beta_i \kappa_i) \lambda_i (1 - \rho_i) \bar{\theta}_i}{(1 - \rho_i)(1 - \theta_{i,1}) \bar{\theta}_i + \rho_i (\bar{\theta}_i - \theta_{i,1}) \theta_{i,1}} \frac{1}{H_{i,1}}, \qquad \frac{dV_{i,1}(Z_1)}{dH_{j,1}} = 0, \tag{46}$$

and

$$\begin{aligned}\frac{dV_{i,1}(Z_1)}{dM_1} &= \frac{d \log(C_{i,1})}{dM_{i,1}} + \beta_i \frac{dV_{i,2}(Z_2)}{dM_2} \frac{dM_2}{dM_1} + \beta_i \frac{dV_{i,2}(Z_2)}{dH_{i,2}} \frac{dH_{i,2}}{dM_1} \\ &= -(1 + \beta_i \kappa_i) \delta^Y_{i,1} - \beta_i \phi_M \delta^Y_{i,2} - \frac{\beta_i \lambda_i}{1 - \theta_{i,2}} \delta^H_{i,1}.\end{aligned} \tag{47}$$

The last term in (47) captures the shadow cost of pollution due to its negative influence on human capital. Since $\theta_{i,2}$ is increasing in $H_{i,2}$ by (39), it follows that

$$\frac{d}{dH_{i,2}}\left\{\beta_i \frac{dV_{i,2}(Z_2)}{dH_{i,2}}\left(-\frac{dH_{i,2}}{dM_1}\right)\right\} = \frac{d}{dH_{i,2}}\left\{\frac{\beta_i\lambda_i}{1-\theta_{i,2}}\delta^H_{i,1}\right\} > 0.$$

In other words, a larger stock of human capital in the future implies a larger marginal benefit of emission reduction today.

Problem of period $t = 0$

The first-order condition with respect to $s_{i,0}$ is

$$\frac{1}{1-s_{i,0}} = \beta_i \frac{dV_{i,1}(Z_1)}{dK_{i,1}}\frac{dK_{i,1}}{ds_{i,0}} = \beta_i \frac{dV_{i,1}(Z_1)}{dK_{i,1}}\tilde{Y}_{i,0}. \tag{48}$$

Combined with (45), this yields

$$s_{i,0} = \frac{\beta_i\kappa_i + (\beta_i\kappa_i)^2}{1+\beta_i\kappa_i + (\beta_i\kappa_i)^2}.$$

The first-order condition with respect to $E_{i,1}$, on the other hand, is

$$\begin{aligned}\frac{d\tilde{Y}_{i,0}}{dE_{i,0}} &= -\beta_i \frac{dV_{i,1}(Z_1)}{dM_1}\tilde{Y}_{i,0} - \beta_i \frac{dV_{i,1}(Z_1)}{dK_{i,1}}\tilde{Y}_{i,0}\frac{dK_{i,1}}{d\tilde{Y}_{i,0}}\frac{d\tilde{Y}_{i,0}}{dE_{i,0}} \\ &= -\beta_i \frac{dV_{i,1}(Z_1)}{dM_1}\tilde{Y}_{i,0} - \frac{s_{i,0}}{1-s_{i,0}}\frac{d\tilde{Y}_{i,0}}{dE_{i,0}},\end{aligned}$$

where the second line uses (48). Rearranging terms gives

$$\frac{1}{1-s_{i,0}}\frac{d\tilde{Y}_{i,0}}{dE_{i,0}} = -\beta_i \frac{dV_{i,1}(Z_1)}{dM_1}\tilde{Y}_{i,0}. \tag{49}$$

Since $C_{i,0} = (1-s_{i,0})\tilde{Y}_{i,0}$ and $s_{i,0}$ is independent of $E_{i,0}$, this implies (18) for $t = 0$.

Combining (35), (37), (47), and (49), we have

$$\frac{Y_{i,0}}{\tilde{Y}_{i,0}} MC_i(\theta_{i,0}) = MB_i(\theta_{i,0}, \theta_{j,0}), \tag{50}$$

where we define the functions MC_i and MB_i as

$$MC_i(\theta_{i,0}) := \frac{\lambda_i^{\frac{1}{\rho_i}}(1-\kappa_i)^{-\frac{1-\rho_i}{\rho_i}}}{(1-s_{i,0})\tilde{A}_{i,0}H_{i,0}}\left(\frac{\theta_{i,0}}{\bar{\theta}_i-\theta_{i,0}}\right)^{\frac{1-\rho_i}{\rho_i}}\frac{1}{1-\theta_{i,0}}, \tag{51}$$

and

$$MB_i(\theta_{i,0},\theta_{j,0}) := -\beta_i\frac{dV_{i,1}}{dM_1} = \beta_i(1+\beta_i\kappa_i)\delta^Y_{i,1}+\beta_i^2\phi_M\delta^Y_{i,2}+\frac{\beta_i^2\lambda_i}{1-\theta_{i,2}}\delta^H_{i,1}, \tag{52}$$

respectively. The left-hand side of (50) is the marginal cost of emission reduction while the right-hand side is the marginal benefit of emission reduction, both measured in the unit of utility. Recall that $\theta_{i,2}$ in the last term of MB_i is increasing in $H_{i,2}$ by (38). Since $H_{i,2}$ is decreasing in M_1 and since $M_1 = \phi_M M_0 + E_{n,0} + E_{s,0}$ is decreasing in $\theta_{n,0}$ and $\theta_{s,0}$ by (36), it follows that $\theta_{i,2}$ is an increasing function of $\theta_{n,0}$ and $\theta_{s,0}$. This means that, for a given level of $\theta_{j,0}$, the function MB_i is increasing in $\theta_{i,0}$. Since $\theta_{i,2}$ is contained in the interval $[0,\bar{\theta}_i]$, we also know that

$$0 < \lim_{\theta_{i,0}\to 0} MB_i(\theta_{i,0},\theta_{j,0}) < \lim_{\theta_{i,0}\to\bar{\theta}_i} MB_i(\theta_{i,0},\theta_{j,0}) < \infty.$$

On the other hand, (36) and (37) show that $Y_{i,0}$ is decreasing in $\theta_{i,0}$ with $\lim_{\theta_{i,0}\to 0} Y_{i,0} = \infty$ and $\lim_{\theta_{i,0}\to\bar{\theta}_i} Y_{i,0} > 0$. This means that $Y_{i,0}/\tilde{Y}_{i,0}$ is at least weakly increasing in $\theta_{i,0}$ with $\lim_{\theta_{i,0}\to 0}(Y_{i,0}/\tilde{Y}_{i,0}) = 1$ and $\lim_{\theta_{i,0}\to\bar{\theta}_i}(Y_{i,0}/\tilde{Y}_{i,0}) < \infty$. Since $MC_i(\theta_{i,0})$ tends to zero as $\theta_{i,0}\to 0$ and to ∞ as $\theta_{i,0}\to\bar{\theta}_i$, it follows that for each $\theta_{j,0}$, there exists $\theta_{i,0}\in(0,\bar{\theta}_i)$ at which the left-hand side of (50) crosses the right-hand side from below. Let $\varphi_i(\theta_{j,0})$ denote this point. This is the best response function of region i.

The equilibrium level of $\theta_{s,0}$ is characterized by a fixed point

$$\theta_{s,0} = \varphi_s(\varphi_n(\theta_{s,0})),$$

which in turn pins down the equilibrium level of $\theta_{n,0}$ by $\theta_{n,0} = \varphi_n(\theta_{s,0})$. The existence of a fixed point follows from the fact that $MB_s(\theta_{s,0},\varphi_n(\theta_{s,0}))$ remains positive as $\theta_{s,0}\to 0$ and remains finite as $\theta_{s,0}\to\bar{\theta}_s$. We note that, for both regions, the second-order condition is satisfied at the fixed point because the marginal cost curve crosses the marginal benefit curve from below.

Proof of Proposition 2

Observe that $MB_i(\theta_{i,0}, \theta_{j,0})$ defined by (52) is increasing in $\theta_{j,0}$ whereas $MC_i(\theta_{i,0})$ defined by (51) is independent of $\theta_{j,0}$. Hence, the point $\theta_{i,0}$ at which $MC_i(\theta_{i,0})$ crosses $MB_i(\theta_{i,0}, \theta_{j,0})$ from below is increasing in $\theta_{j,0}$. In other words, the best response $\theta_{i,0} = \varphi_i(\theta_{j,0})$ is a strictly increasing function of $\theta_{j,0}$. Since $E_{i,0}$ is strictly decreasing in $\theta_{i,0}$ by (36), we conclude that $E_{n,0}$ and $E_{s,0}$ are strategic complements.

Proof of Proposition 3

See text.

Proof of Proposition 4

Totally differentiating (50) with respect to R for both $i \in \{n, s\}$ and evaluating every term at $R = 0$ yields

$$\begin{pmatrix} d\theta_{n,0}/dR \\ d\theta_{s,0}/dR \end{pmatrix} = \frac{D}{\det(D)} \begin{pmatrix} \partial MC_n/\partial R \\ \partial MB_s/\partial R \end{pmatrix}, \tag{53}$$

where

$$\frac{\partial MC_n}{\partial R} = -\frac{\lambda_n^{\frac{1}{\rho_n}}(1-\kappa_n)^{-\frac{1-\rho_n}{\rho_n}}}{(1-s_{n,0})\tilde{A}_{n,0}H_{n,0}} \left(\frac{\theta_{n,0}}{\bar{\theta}_n - \theta_{n,0}}\right)^{\frac{1-\rho_n}{\rho_n}} \frac{1}{1-\theta_{n,0}} \frac{1}{Y_{n,0}}, \tag{54}$$

$$\begin{aligned} \frac{\partial MB_s}{\partial R} &= -\beta_s(1+\beta_s\kappa_s)\phi_R\varepsilon^Y - \frac{\beta_s^2\lambda_s\phi_R}{1-\theta_{s,2}}\varepsilon^H \\ &\quad + \frac{\beta_s^2\lambda_s\theta_{s,2}}{(1-\theta_{s,2})^2} \frac{\rho_s(\bar{\theta}_s - \theta_{s,2})}{\bar{\theta}_s - \rho_s(\bar{\theta}_s - \theta_{s,2})}(M_0 + \phi_R M_1)\delta_s^H\varepsilon^H, \end{aligned} \tag{55}$$

$$D := \begin{pmatrix} MC_{s,s} - MB_{s,s} & MB_{n,s} \\ MB_{s,n} & MC_{n,n} - MB_{n,n} \end{pmatrix},$$

and

$$MC_{i,i} := \frac{\partial MC_i}{\partial \theta_{i,0}}, \quad MB_{i,j} := \frac{\partial MB_i}{\partial \theta_{j,0}} \quad \forall j \in \{n, s\}.$$

We first note that every entry of the matrix D is strictly positive. By the second-order condition, $(MC_{s,s} - MB_{s,s})$ and $(MC_{n,n} - MB_{n,n})$ are both strictly positive. Also, since $\theta_{i,2}$ is a strictly increasing function of $\theta_{j,0}$, (52) shows that $MB_{s,n}$ and $MB_{n,s}$ are strictly positive. The determinant of D is strictly positive, too. To see this, notice that by definition of the best response function φ_n, we have

$$MC_n(\varphi_n(\theta_{s,0})) = MB_n(\varphi_n(\theta_{s,0}), \theta_{s,0}) \quad \forall \theta_{s,0} \in [0, 1]$$

and hence

$$MC_{n,n}\varphi_n' = MB_{n,n}\varphi_n' + MB_{n,s} \tag{56}$$

at equilibrium, where $\varphi_n' = d\varphi_n(\theta_{s,0})/d\theta_{s,0}$. Also, by the definition of equilibrium,

$$MC_s(\theta_{s,0}) = MB_s(\theta_{s,0}, \varphi_n(\theta_{s,0})).$$

Since the left-hand side crosses the right-hand side from below, it must be the case that

$$MC_{s,s} > MB_{s,s} + MB_{s,n}\varphi_n'. \tag{57}$$

Combining (56) with (57) yields

$$(MC_{s,s} - MB_{s,s})(MC_{n,n} - MB_{n,n}) - MB_{s,n}MB_{n,s} > 0, \tag{58}$$

which means that $\det(D) > 0$.

Since every entry of the matrix $D/\det(D)$ is strictly positive, (53) indicates that $d\theta_{i,0}/dR$ is a positive linear combination of $\partial MC_n/\partial R$ and $\partial MB_s/\partial R$. We observe from (54) that $\partial MC_n/\partial R$ is strictly negative. This term represents the income effect we discussed in the main text. The other partial derivative $\partial MB_s/\partial R$ in (55) may be positive or negative, depending on the relative importance of substitution and complementarity effects. We shall show that for any sufficiently large ε^H, the complementarity effect outweighs the income and substitution effects combined. To this end, we explicitly write

$$\begin{aligned}\frac{\partial MB_s}{\partial R} &= -\beta_s(1+\beta_s\kappa_s)\phi_R\varepsilon^Y + \frac{\beta_s^2\lambda_s\theta_{s,2}}{(1-\theta_{s,2})^2}\frac{\rho_s(\bar{\theta}_s - \theta_{s,2})}{\bar{\theta}_s - \rho_s(\bar{\theta}_s - \theta_{s,2})}\delta_s^H M_0\varepsilon^H \\ &\quad + \left[\frac{\theta_{s,2}}{1-\theta_{s,2}}\frac{\rho_s(\bar{\theta}_s - \theta_{s,2})}{\bar{\theta}_s - \rho_s(\bar{\theta}_s - \theta_{s,2})}\delta_s^H M_1 - 1\right]\frac{\beta_s^2\lambda_s\phi_R}{1-\theta_{s,2}}\varepsilon^H,\end{aligned} \tag{59}$$

where the sum of the terms in the square bracket is strictly positive if the damage parameter δ_s^H is sufficiently large. Assumption 1 makes sure that this is the case. We should mention, though, that the future level $e^{g_{s,0}+g_{s,1}}H_{i,0}$ of human capital in the absence of pollution damage needs to be large enough, too. Otherwise, for very large δ_s^H, the actual level $H_{s,2}$ of human capital (and thus $\theta_{s,2}$) would be small, which can make the first term in the square brackets smaller than one.

Accordingly, under Assumption 1, $\partial MB_s/\partial R$ is a strictly increasing linear function of ε^H. On the other hand, the income effect, $\partial MC_n/\partial R$, is independent of ε^H, as is clear from (54). Hence, by (53), we know that $d\theta_{i,0}/dR$ is a strictly increasing linear function of ε^H. In particular, if we define

$$\varepsilon^H_{E_{n,0}} := \frac{\beta_s(1+\beta_s\kappa_s)\phi_R\varepsilon^Y + \frac{MC_{s,s}-MB_{s,s}}{MB_{n,s}}\left(-\frac{\partial MC_n}{\partial R}\right)}{\left(\frac{\theta_{s,2}}{1-\theta_{s,2}}\frac{\rho_s(\bar{\theta}_s-\theta_{s,2})}{\bar{\theta}_s-\rho_s(\bar{\theta}_s-\theta_{s,2})}\delta_s^H(M_0+\phi_R M_1)-\phi_R\right)\frac{\beta_s^2\lambda_s}{1-\theta_{s,2}}} > 0 \tag{60}$$

and

$$\varepsilon^H_{E_{s,0}} := \frac{\beta_s(1+\beta_s\kappa_s)\phi_R\varepsilon^Y + \frac{MB_{s,n}}{MC_{n,n}-MB_{n,n}}\left(-\frac{\partial MC_n}{\partial R}\right)}{\left(\frac{\theta_{s,2}}{1-\theta_{s,2}}\frac{\rho_s(\bar{\theta}_s-\theta_{s,2})}{\bar{\theta}_s-\rho_s(\bar{\theta}_s-\theta_{s,2})}\delta_s^H(M_0+\phi_R M_1)-\phi_R\right)\frac{\beta_s^2\lambda_s}{1-\theta_{s,2}}} > 0, \tag{61}$$

it follows that for each region i, $d\theta_{i,0}/dR > 0$ if and only if $\varepsilon^H > \varepsilon^H_{E_{i,0}}$. In order to restate the result in terms of emission, use (35) to obtain

$$\frac{dE_{i,0}}{dR} = -\frac{\bar{\theta}_i - \rho_i(\bar{\theta}_i-\theta_{i,0})}{\rho_i(\bar{\theta}_i-\theta_{i,0})}\frac{E_{i,0}}{\theta_{i,0}}\frac{d\theta_{i,0}}{dR}.$$

From this, we conclude that $dE_{i,0}/dR$ is a strictly decreasing linear function of ε^H and $dE_{i,0}/dR < 0$ if and only if $\varepsilon^H > \varepsilon^H_{E_{i,0}}$.

Finally, (58) implies

$$\frac{MC_{s,s}-MB_{s,s}}{MB_{n,s}} > \frac{MB_{s,n}}{MC_{n,n}-MB_{n,n}},$$

which, together with (60) and (61), yields $\varepsilon^H_{E_{n,0}} > \varepsilon^H_{E_{s,0}}$. For the sake of completeness, we also note that the two thresholds coincide if there is no income effect (i.e., if $\partial MC_n/\partial R = 0$ in (60) and (61)).

Proof of Proposition 5

First notice

$$\frac{dM_1}{dR} = \frac{dE_{n,0}}{dR} + \frac{dE_{s,0}}{dR},$$

where, by Proposition 4, the right-hand side is strictly decreasing in ε^H. Also, Proposition 4 shows that there exist thresholds $\varepsilon^H_{E_{n,0}}$ and $\varepsilon^H_{E_{s,0}}$ with $0 < \varepsilon^H_{E_{s,0}} < \varepsilon^H_{E_{n,0}}$ such that

$$\frac{dE_{n,0}}{dR} + \frac{dE_{s,0}}{dR} > 0 \quad \forall \varepsilon^H < \varepsilon^H_{E_{s,0}}$$

and

$$\frac{dE_{n,0}}{dR} + \frac{dE_{s,0}}{dR} < 0 \quad \forall \varepsilon^H > \varepsilon^H_{E_{n,0}}.$$

Then there must exist $\varepsilon^H_{M_1}$ in the open interval $(\varepsilon^H_{E_{s,0}}, \varepsilon^H_{E_{n,0}})$ such that

$$\frac{dM_1}{dR} = \frac{dE_{n,0}}{dR} + \frac{dE_{s,0}}{dR} < 0 \iff \varepsilon^H > \varepsilon^H_{M_1}. \tag{62}$$

Next, observe

$$\frac{dM_2}{dR} = \phi_M \frac{dM_1}{dR} + \frac{dE_{n,1}}{dR} + \frac{dE_{s,1}}{dR},$$

where the second term on the right-hand side is zero. By (25), the third term is strictly negative and strictly increasing in ε^H. Therefore, combined with (62), this implies that there exists $\varepsilon^H_{M_2} < \varepsilon^H_{M_1}$ such that

$$\frac{dM_2}{dR} < 0 \iff \varepsilon^H > \varepsilon^H_{M_2},$$

which completes the proof.

Proof of Proposition 6

See text.

Proof of Proposition 7

Put $x := A_{n,0} K^{\kappa_n}_{n,0}$ for the sake of conciseness. It suffices to show that the statement of the proposition holds for x instead of $A_{n,0}$ or $K_{n,0}$.

We first prove the second half of the proposition. Since x does not affect the equilibrium level of $\theta_{n,0}$ (when evaluated at $R = 0$), we know that $Y_{n,0}$ is strictly increasing in x. Since $d\theta_{i,0}/dR$ is strictly increasing in $\partial MC_n/\partial R$ by (53), and since $\partial MC_n/\partial R$ is strictly increasing in $Y_{n,0}$ by (54), it follows from (6) that $dE_{i,0}/dR$ is strictly decreasing in x. Then, for each given level of ε^H, (27) and (28) show that dW_i/dR is strictly increasing in x. Since dW_i/dR is strictly increasing in ε^H, this implies that the threshold $\varepsilon^H_{W_i}$ is strictly decreasing in x.

To prove the first half of the proposition, observe from (59) that

$$\frac{\partial MB_s}{\partial R} > 0 \iff \varepsilon^H > \varepsilon^H_\infty,$$

where ε^H_∞ is defined as

$$\varepsilon^H_\infty := \frac{\beta_s(1+\beta_s\kappa_s)\phi_R\varepsilon^Y}{\left(\frac{\theta_{s,2}}{1-\theta_{s,2}}\frac{\rho_s(\bar{\theta}_s-\theta_{s,2})}{\bar{\theta}_s-\rho_s(\bar{\theta}_s-\theta_{s,2})}\delta^H_s(M_0+\phi_R M_1)-\phi_R\right)\frac{\beta_s^2\lambda_s}{1-\theta_{s,2}}} > 0.$$

Since $\lim_{x\to\infty} Y_{n,0} = \infty$, combining (53), (54), (6), (27), and (28) yields

$$\lim_{x\to\infty}\frac{dW_n}{dR} = -\beta_n\frac{dV_{n,1}(Z_1)}{dM_1}\frac{\partial MB_s}{\partial R}\frac{\bar{\theta}_s-\rho_s(\bar{\theta}_s-\theta_{s,0})}{\rho_s(\bar{\theta}_s-\theta_{s,0})}\frac{E_{s,0}}{\theta_{s,0}}\frac{MC_{nn}-MB_{n,n}}{\det(D)} \tag{63}$$

and

$$\begin{aligned}\lim_{x\to\infty}\frac{dW_s}{dR} &= -\beta_s\frac{dV_{s,1}(Z_1)}{dM_1}\frac{\partial MB_s}{\partial R}\frac{\bar{\theta}_n-\rho_n(\bar{\theta}_n-\theta_{n,0})}{\rho_n(\bar{\theta}_n-\theta_{n,0})}\frac{E_{n,0}}{\theta_{n,0}}\frac{MB_{n,s}}{\det(D)} \\ &\quad + (M_0+(1+\beta_s\kappa_s)\beta_s\phi_R M_1)\,\varepsilon^Y \\ &\quad + \left(\beta_s\frac{dV_{s,1}(Z_1)}{dH_{s,1}}H_{s,1}M_0+\beta_s^2\phi_R\frac{dV_{i,2}(Z_2)}{dH_{i,2}}H_{i,2}M_1\right)\varepsilon^H. \end{aligned} \tag{64}$$

It is clear from (63) that

$$\lim_{x\to\infty}\frac{dW_n}{dR} > 0 \iff \frac{\partial MB_s}{\partial R} > 0 \iff \varepsilon^H > \varepsilon^H_\infty,$$

which implies that the threshold $\varepsilon^H_{W_n}$ converges to ε^H_∞ as $x \to \infty$. On the other hand, since the second term in (64) is strictly positive, $\varepsilon^H_{W_s}$ converges to a different threshold which is strictly lower than ε^H_∞. Therefore, we conclude that $\varepsilon^H_{W_s} < \varepsilon^H_{W_n}$ for sufficiently large x.

Proof of Proposition 8

Notice that starting at an arbitrary period $t \geq 0$, the discounted sum of per-period utilities of region i may be expressed as

$$\begin{aligned}\sum_{\tau=t}^{\infty} \beta_i^{\tau-t} \log(C_{i,\tau}) = \frac{1}{1-\beta_i\kappa_i} \sum_{\tau=t}^{\infty} \beta_i^{\tau-t} \log(\Delta_{i,t}^{Y} A_{i,t} L_{i,t}^{\lambda_i} X_{i,t}^{1-\kappa_i-\lambda_i}) \\ + \sum_{\tau=t}^{\infty} \beta_i^{\tau-t} \left(\log(1-s_{i,\tau}) + \frac{\kappa_i\beta_i}{1-\kappa_i\beta_i} \log(s_{i,\tau}) \right) \\ + \frac{\kappa_i}{1-\beta_i\kappa_i} \log(K_{i,t}) + \frac{1}{1-\beta_i\kappa_i} \log(\tilde{Y}_{i,t}/Y_{i,t}). \qquad (65)\end{aligned}$$

This expression is valid for any path of state and control variables. Observe that the second term in (65) is maximized at $s_{i,\tau} = \beta_i\kappa_i$ for all $\tau \geq t$. Since the other terms are not affected by the savings rates, it follows that the equilibrium savings rate is constant over time and given by $\beta_i\kappa_i$.

Proof of Proposition 9

Observe that a_i is the maximized value of the second term in (65). Also, recall from (2) that $\tilde{Y}_{i,t} = Y_{i,t}$ except for $t = 0$, so that the last term in (65) vanishes for all $t \geq 1$. Since the stock of physical capital appears only in the last line of (65), this implies that the equilibrium levels of $E_{i,t}$ and $\theta_{i,t}$ are independent of $K_{i,t}$. Therefore, for each $t \geq 1$, we can solve for Markov-perfect Nash equilibria by focusing on the first term in (65). This proves (31).

By Proposition 8, we know that the savings rate of the initial period is $s_{i,0} = \beta_i\kappa_i$. Hence, combining (31) with (14) yields

$$\begin{aligned}V_{i,0}(Z_{i,0}) &= \max_{E_{i,0},\theta_{i,0}} \left\{ \log((1-\beta_i\kappa_i)\tilde{Y}_{i,0}) + \beta_i V_{i,1}(Z_{i,1}) \right\} \\ &= \max_{E_{i,0},\theta_{i,0}} \left\{ \log((1-\beta_i\kappa_i)\tilde{Y}_{i,0}) + \beta_i \left(a_i + \frac{\kappa_i}{1-\beta_i\kappa_i} \log(\beta_i\kappa_i\tilde{Y}_{i,0}) \right) \right. \\ &\qquad \left. + \frac{\beta_i}{1-\beta_i\kappa_i} v_{i,1}(H_{n,1}, H_{s,1}, M_1, R_1) \right\} \\ &= \max_{E_{i,0},\theta_{i,0}} \left\{ a_i + \frac{1}{1-\beta_i\kappa_i} \log(\tilde{Y}_{i,0}) + \frac{\beta_i}{1-\beta_i\kappa_i} v_{i,1}(H_{n,1}, H_{s,1}, M_1, R_1) \right\},\end{aligned}$$

which proves (32).

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