Adaptation for mitigation

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Abstract

This paper develops a two-region (North and South) dynamic model in which regional stocks of effective labor are 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 labor 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 incentive compatible and Pareto improving.

Keywords: Adaptation; Climate change; Dynamic game, Mitigation; Strategic complements

JEL Classification: H23, O44, Q54, Q58

1 Introduction

The economic damage from climate change is almost exclusively modeled through what is called the damage function, a single channel of externality embedded in the production function (Stern, 2013). This approach seems fairly reasonable because what eventually matters is how the changing climate, passing through a variety of different channels, negatively influences the final economic output. In this sense, the damage function can be viewed as a reduced-form representation of the highly complex mechanism through which climate change affects the economic activities. This reduced-form approach, however, is not without loss of generality and we show that it can lead to misleading conclusions in a dynamic and strategic setting.

To provide more structure to the channel through which climate change interacts with the economy, we focus on its negative influences on the stock of effective labor. High temperatures increase mortality (Deschenes, 2014) and climate-related pollution in general causes long-lasting damages by reducing learning and productivity (Graff Zivin and Neidell, 2012; Graff Zivin and Shrader, 2016). There is robust evidence that changes in climatic conditions 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). Seemingly short-term impacts of climate change can transform into more permanent damages through health and human capital (UNDP, 2007; IPCC, 2014).

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 long-lasting damages (typically, negative growth 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 environment.

We develop a dynamic model of a North-South economy where regional stocks of effective labor are negatively influenced by the global stock of pollution. To the best of our knowledge, this paper is the first to examine the consequences of effective labor degradation caused by pollution in a dynamic and strategic environment. In the endogenous growth literature, Ikefuji and Horii (2012) consider possible destruction of physical and human capital due to pollution, but their analysis is based on a single-region model. Similar to our paper, a dynamic North-South framework is introduced by Bretschger and Suphaphiphat (2014) with a pollution-induced capital destruction mechanism. Their focus is, however, on the comparison of different policy scenarios, and the strategic interaction is absent in their model. As we shall see shortly, the interaction between effective labor stock 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.

To demonstrate how this finding can be significant in policy making, we apply the model in the context of international cooperation and examine the consequences of adaptation assistance from North to South. 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).

Unfortunately, financial and technological assistance available for these less wealthy countries is small compared to the projected needs. For example, the Adaptation Fund established under the Kyoto Protocol has so far financed about US$512 million, but the total cost of adaptation is estimated to be around US$280–500 billion by the year 2050 (UNEP, 2016). 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 commitment of assistance without any promise of mitigation efforts by developing countries.

We show in this paper that providing assistance 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. Given the dynamic complementarity effect, the prospect of South becoming more active in mitigation sets the stage for North to reduce its own emission as well. In this sense, the climate policy discussion can be viewed as 'adaptation for mitigation', not as 'adaptation or mitigation'. Our results suggest that the assistance should be targeted at those activities that effectively protect the labor stock in poor countries against pollution damage. This finding provides clear guidance for the existing international cooperation mechanism such as the Adaptation Fund, in which the limited financial resources need to be properly allocated among different adaptation activities (Biagini et al., 2014).

So far, the adaptation literature has been 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. 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. The optimal adaptation policy has been analytically examined based on various dynamic models (Bréchet et al., 2013; Tsur and Withagen, 2013; Zemel, 2015; Kama and Pommeret, 2016).

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), both of which consider strategic interactions in a static model. Perhaps the main message of these papers is that mitigation and adaptation are substitutes. But this result crucially depends on the static nature of the analysis. In a two-period North-South framework, Eyckmans et al. (2016) compare various types of transfer, including adaptation assistance. Their analysis shows that adaptation assistance crowds out the adaptation effort in the recipient region. This is true only when South already has access to the same adaptation technology as North. Our paper, in contrast, considers an alternative scenario where there remains a technological gap between the two regions and South can fully exploit its adaptation opportunities only with the help of North.

We make two contributions to the existing literature. First, we combine two strands of the existing climate-economy literature (one with a dynamic general equilibrium structure and one with a simpler game-theoretic setting) and develop a multi-region dynamic model where stock of effective labor 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 dynamic 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, in which adaptation assistance cannot make all parties better off. Although the results are interpreted in the context of adaptation, the model could fit other contexts as well such as technology transfer from North to South. Whenever one region can help the other to engage in mitigation, the dynamic complementarity effect helps reduce pollution at a global level. The complementary relationship established in this paper therefore opens up the possibility of mutually beneficial international cooperation in many ways.

2 The model

We consider an economy consisting of two regions: North (n) and South (s). Our model has three periods ($t = 0, 1, 2$) and 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. We note that the three-period assumption is just for simplicity and is not essential for our results. An infinite-period version of the model is presented in the online appendix (Sakamoto et al., 2018), where our numerical simulations and sensitivity analysis produce essentially the same results. Welfare of region $i \in \{n, s\}$ is

$$W_i := \log(C_{i,0}) + \beta \log(C_{i,1}) + \beta^2 \log(C_{i,2}),$$

where $C_{i,t}$ is consumption at period t and $\beta \in (0, 1)$ is the discount factor. The production function is

$$Y_{i,t} := \Delta^Y_{i,t} A_i \left(E^\rho_{i,t} + \tilde{E}^\rho_{i,t} \right)^{\frac{1}{\rho}},$$

where A_i is region i's total factor productivity, $E_{i,t}$ is the fossil-fuel energy production (measured in units of carbon) and $\tilde{E}_{i,t}$ is the carbon-free energy production. Here, $\Delta^Y_{i,t} \in (0, 1)$ captures the damage from pollution which we will elaborate on below. Following Acemoglu et al. (2012), we assume $0 < \rho < 1$ so that 'dirty' and 'clean' energies are substitutes.

Carbon-free energy is produced by the linear production technology

$$\tilde{E}_{i,t} := \tilde{A}_i L_{i,t},$$

where $L_{i,t}$ is the effective labor. For simplicity, we assume $\tilde{A}_i = 1$. As in Gerlagh and Liski (2018), we abstract from the scarcity of fossil-fuel resources and ignore extraction costs. Instead, we add a technological constraint

$$E_{i,t} \leq \bar{E}_i$$

for some exogenous upper bound $\bar{E}_i > 0$. This upper bound may be interpreted as the maximum amount of fossil-fuel energy that can be produced within a fixed length of time. This assumption is not necessary in the infinite-period setting analyzed in the online appendix; see Sakamoto et al. (2018). For the three-period model, we assume that $\bar{E}_i$ is sufficiently large so that the constraint is only binding in the final period.

As discussed in the introduction, we assume that the stock of effective labor is negatively influenced by pollution. More precisely, labor is governed by the dynamic equation

$$L_{i,t+1} = e^{g_i} \Delta^L_{i,t} L_{i,t},$$

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

The stock M_t of pollution changes over time according to

$$M_{t+1} = \phi_M M_t + E_{n,t} + E_{s,t}$$

for some $\phi_M \in (0, 1)$. The pollution stock in turn influences the economy through the damage terms $\Delta^Y_{i,t}$ and $\Delta^L_{i,t}$. We specify

$$\Delta^Y_{i,t} := e^{-\delta^Y_{i,t} M_t^{\xi}}, \quad \Delta^L_{i,t} := e^{-\delta^L_{i,t} M_t^{\xi}}$$

for some $\delta^Y_{i,t}, \delta^L_{i,t} > 0$ and $\xi \geq 1$. As far as the damage from climate change is concerned, one may reasonably assume $\xi = 1$ (Hassler et al., 2016). But we allow ξ to be greater than one so that potential nonlinearity can also be taken into account. In the literature of climate economics, the climate-related damages are usually all captured through a single damage term in the production function. Here, we divide it into two different channels, providing more structure to the mechanism through which climate change affects the economy. One might expect that these two channels play essentially the same role since both of them reduce the level of final output. As we will see shortly, however, their roles are quite different in a strategic setting.

The damage parameters $\delta^Y_{i,t}, \delta^L_{i,t}$ may be lowered if regions engage in adaptation activities. But explicitly modeling each region's adaptation decision makes the analysis quickly unmanageable. In order to focus on the role of adaptation assistance, we rather consider an ex-post situation where domestic adaptation policies have already been implemented and the values of $\delta^Y_{i,t}, \delta^L_{i,t}$ have already been optimized within each region. See Section 6 for a discussion about this set-up. We assume, however, that there remain adaptation opportunities in South which can only be exploited with the help of North. To capture this idea, let R_t denote 'adaptation capital' in South, by which we mean a stock of technology that can be used to reduce damage from pollution. We then specify

$$\delta^Y_{s,t} := \delta^Y_s(R_t), \quad \delta^L_{s,t} := \delta^L_s(R_t),$$

for some strictly decreasing and continuously differentiable functions δ^Y_s and δ^L_s. 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 $R_0 = R$. Adaptation capital depreciates over time (because it physically depreciates or/and the associated knowledge becomes obsolete) so that

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

for some $\phi_R \in (0, 1)$. 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. This assumption is relaxed in the infinite-period version of the model analyzed in the online appendix (Sakamoto et al., 2018), where a relatively short time step (a decade) is used.

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 $Z_t = (L_{n,t}, L_{s,t}, M_t)$, the second-stage equilibrium is defined by the value function $V_{i,t}$ and the policy variable $E_{i,t}$ which solve the Bellman equation

$$V_{i,t}(Z_t) = \max_{E_{i,t}} \{\log(C_{i,t}) + \beta V_{i,t+1}(Z_{t+1})\} \quad \forall i \in \{n, s\}$$

for $t = 0, 1, 2$ with $V_{i,3}(Z_3) = 0$, where

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

We begin by solving the second stage and clarify how the negative externality on effective labor 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.

It is worth emphasizing that although the current setting is very simple, our model can be generalized in a variety of ways without altering its essential features. For instance, one could make labor supply in the clean energy production sector endogenous. It is also possible to add physical capital into the model so that another channel of intertemporal resource allocation can be taken into account. Exogenous processes of technological development can be easily incorporated as well. Most of the parameters can be region specific.

3 Dynamic complementarity effect

Fix $R \geq 0$ arbitrarily and consider the second stage where the regions play the dynamic game. This game may have multiple equilibria. Here, we focus on a stable equilibrium in the sense of Dixit (1986).

Proposition 1. *There exists a Markov-perfect Nash equilibrium in which the stability conditions of Dixit (1986) are satisfied.*

All proofs are in the appendix. Let us now characterize the equilibrium. Observe first that reducing emission entails a cost in the form of lower current consumption. On the other hand, emission reduction 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 $E_{i,2} = \bar{E}_i$, where $\bar{E}_i$ is an exogenous upper bound.

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

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

where the left-hand side is the marginal benefit of emission and the right-hand side is the marginal damage of emission, both measured in units of utility. 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 are strategic substitutes (complements) if the marginal damage curve of one region shifts downwards (upwards) as a result of emission reduction in the other region.

For the problem of period $t = 1$, the marginal damage of emission may be written as

$$-\beta \frac{dV_{i,2}(Z_2)}{dM_2} = \beta \delta^Y_{i,2} \xi M_2^{\xi-1}.$$

For $\xi = 1$, this is a constant, which implies that there is no strategic interaction between regions. The damage function itself is convex because it is an exponential function. But, combined with the logarithmic utility function, the utility damage is linear in the stock of pollution. For $\xi > 1$, the damage function becomes even more convex, making marginal damage increasing in M_2. It follows that as one region reduces its level of emission, the best response of the other region is to increase its emission. In other words, regional emissions are strategic substitutes. These results are fairly standard. The novel feature of our model is not visible yet because the pollution's negative influence on effective labor requires at least two periods before it plays a part.

Now consider the problem of period $t = 0$, in which the marginal damage of pollution is given by

$$-\beta \frac{dV_{i,1}(Z_1)}{dM_1} = \beta \delta^Y_{i,1} \xi M_1^{\xi-1} + \beta^2 \delta^Y_{i,2} \xi M_2^{\xi-1} \left(\phi_M + \frac{dE_{j,1}}{dM_1} \right) + \beta^2 \frac{dV_{i,2}(Z_2)}{dL_{i,2}} \left(-\frac{dL_{i,2}}{dM_1} \right). \tag{2}$$

The first two terms on the right-hand side in this expression result from the standard channel of externality, $\Delta^Y_{i,t}$. The last term, on the other hand, captures how the negative influence on effective labor, $\Delta^L_{i,t}$, affects the marginal damage of emission. To see why this new channel of externality can change the nature of strategic interaction, consider the somewhat extreme (yet reasonable) case where $\xi = 1$. In that case, (2) simplifies to

$$-\beta \frac{dV_{i,1}(Z_1)}{dM_1} = \beta \delta^Y_{i,1} + \beta^2 \delta^Y_{i,2} \phi_M + \beta^2 \delta^L_{i,1} \frac{L^\rho_{i,2}}{\bar{E}^\rho_i + L^\rho_{i,2}}. \tag{3}$$

What is crucial here is the fact that the last term in (3) is decreasing in $M_1 = \phi_M M_0 + E_{n,0} + E_{s,0}$ because $L_{i,2}$ is decreasing in M_1. It follows that once region j reduces its emission $E_{j,0}$, the marginal damage curve of region $i \neq j$ shifts upwards, providing region i with an incentive to reduce its own emission $E_{i,0}$ as well.

Although common in the literature of climate economics, the assumption $\xi = 1$ may not hold exactly in reality and one might think that our argument would only be valid in the knife-edged case. However, the same observation can be made for $\xi > 1$ as long as ξ is close to 1.

Proposition 2. *There exists $\bar{\xi} > 1$ such that for any $\xi < \bar{\xi}$, 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 effective labor that survives the damage from pollution in the future. In other words, under the pollution externality in effective labor, pollution abatement can be regarded as 'investment' in effective labor. Then what matters for the choice of abatement level is the shadow value of the effective labor stock. When the pollution stock is expected to be large in the future, the corresponding damage to the effective labor is relatively large. The shadow value of the effective labor stock is then relatively small because a large fraction of investment in labor 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 effective labor in *both* regions will survive the damage from pollution. This means that emission reduction in one region increases the shadow value of labor stock in both regions. The larger shadow value of labor stock then leads to a stronger incentive to 'invest' in labor 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 state variable at another point in time. We call this the *dynamic complementarity effect*. As the proposition indicates, the dynamic complementarity effect may be counteracted by the standard strategic substitutability when the damage function is not exactly linear. Nevertheless, it will still be the case that the negative externality on labor stock works in favor of strategic complementarity and the dynamic complementarity effect still outweighs the standard substitution effect, at least when the nonlinearity of the damage function is moderate. This dynamic effect is largely ignored in the literature, but as will be exemplified below in the context of adaptation assistance, it can have important policy implications.

4 Adaptation assistance

Let us examine how the equilibrium will be affected when North provides assistance to South. For this purpose, we focus on the case $\xi = 1$, which allows us to better illustrate the mechanism behind our results without making the analysis unnecessarily complicated. One could relax this assumption and obtain essentially the same results as long as ξ is close to 1.

We know from the analysis in the preceding section that when $\xi = 1$, 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

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

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

We emphasize that a large part of the discussion below is not restricted to the context of adaptation assistance. Another interesting application would be international technology transfer. Contrary to the existing studies in the literature (Stranlund, 1996; Golombek and Hoel, 2004; and Stephan and Müller-Fürstenberger, 2015), our model indicates that technology transfer is less likely to cause carbon leakage. By transferring mitigation technologies to South, North may encourage South to reduce its emission, which in turn sets the stage for North to reduce its own emission. Wherever one region can help the other to engage in mitigation, the dynamic complementarity effect helps reduce global pollution.

Here we focus on adaptation assistance because it is much less trivial if the assistance of this form can actually induce such a desirable feedback loop. After all, the primary purpose of adaptation assistance is not to induce mitigation, but rather to provide necessary protection in less wealthy regions. It may even be the case that providing adaptation assistance weakens the case for mitigation in the recipient region, which under the dynamic complementarity effect could result in an increase of pollution at a global level. By showing that global mitigation can be facilitated in such a challenging context, we can clarify the importance of the additional channel of externality introduced in the paper.

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

$$\left.\frac{dE_{s,1}}{dR}\right|_{R=0} = -\frac{\rho L_{i,1}^{\rho} M_0 E_{s,1}}{E_{s,1}^{\rho} + (1-\rho) L_{s,1}^{\rho}} \varepsilon^L < 0. \tag{4}$$

This means that the long-run emission in South 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 short-run enhanced adaptation capability in South, the stock of effective labor becomes less scarce in the future. This effect enlarges productivity in the clean energy sector, which in turn makes the reduction of dirty energy consumption less costly. 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 more periods with a shorter time step.

4.2 Short-run emission

Unlike the long-run impact, the short-run consequences of adaptation assistance are 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. The income effect inevitably increases North's marginal utility of consumption. This implies a higher benefit from emission for North because consumption and emission are tightly linked. As a result, the marginal benefit curve of North shifts upwards, providing North with an incentive to increase its short-run 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 damage curve shifts in a nontrivial way. To analyze this shift, we decompose the impact of adaptation on the marginal damage curve as

$$\begin{aligned}\left.\frac{\partial}{\partial R}\left\{-\beta \frac{dV_{s,1}(Z_1)}{dM_1}\right\}\right|_{R=0} &= -\beta \phi_R \varepsilon^Y - \beta^2 \frac{L_{s,2}^{\rho}}{\bar{E}_s^{\rho} + L_{s,2}^{\rho}} \phi_R \varepsilon^L \\ &\quad + \beta^2 \frac{\bar{E}_s^{\rho} L_{s,2}^{\rho}}{\left(\bar{E}_s^{\rho} + L_{s,2}^{\rho}\right)^2} (M_0 + \phi_R M_1) \rho \delta_s^L \varepsilon^L. \end{aligned} \tag{5}$$

The first and the second terms on the right-hand side are both negative, making marginal damage 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 damage from pollution stock both in the production sector and in the labor stock. 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 its mitigation strategy at a global level.

The third term in (5) 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 labor, which increases the baseline labor stock in the absence of pollution damage. This change is exogenous to South. Given the increased baseline of labor, South then finds it more important to keep the growth rate from falling due to pollution. The larger is the stock of effective labor, the greater is the importance of its growth rate, implying a larger marginal damage of pollution.

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 fully depreciated. To illustrate this point, let us assume that even the short-term depreciation rate of adaptation capital is 100% ($\phi_R = 0$), which may be reasonable if the time step is very 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 (5) vanish when $\phi_R = 0$. But the third term (the complementarity effect) does not vanish. 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 effective labor, 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 long run.

In the immediate future, 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. Hence, the short-term consequence of adaptation assistance is ambiguous in general. Nevertheless, the sign of the net impact can be determined based on a simple condition.

Assumption 1. *In South, the damage parameter in labor stock is sufficiently large.*

In the context of climate change, this assumption seems reasonable. It basically states that there is a real risk that the effective labor is suppressed under severe pollution in less wealthy countries. 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 labor stock.

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

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

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

As (5) suggests, the effectiveness of adaptation in the output sector, which is captured by ε^Y, always works in favor of the substitution effect. On the other hand, the effectiveness ε^L of adaptation in labor increases both the substitution effect and the complementarity effect. While the overall role of ε^L 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 $\varepsilon^L_{E_{n,0}}$ is greater than South's $\varepsilon^L_{E_{s,0}}$ 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.

It should be worth observing that if the interaction between pollution and labor stock is ignored, only the first term in (5) remains and hence the substitution effect always dominates. Adaptation assistance would then never facilitate emission reduction. Capturing climate-related externality only through a single channel, which is common in the literature, can thus lead to misleading conclusions.

4.3 Influence on pollution stock

For society as a whole, what matters most is whether the level of global pollution stock can be well-managed. The discussion above suggests that long-run emission always decreases thanks to the cost-reduction effect. Moreover, short-run emission also decreases when the complementarity effect outweighs the substitution effect and the income effect combined. This happens in particular when adaptation in South is sufficiently effective for labor protection, in which case both short- and long-run pollution stocks decline.

When the effectiveness of adaptation for labor protection is not sufficiently large, the overall impact on the pollution stock is less obvious. More precisely, if $\varepsilon^L < \varepsilon^L_{E_{n,0}}$, 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 (4) that the cost-reduction effect is increasing in ε^L, we formalize the argument in the following proposition.

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

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

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

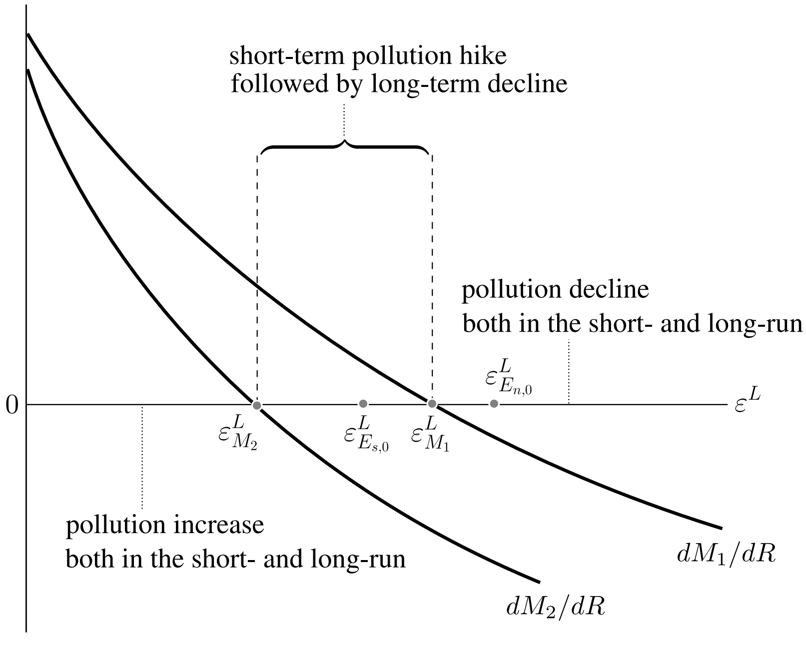

Figure 1: Impact of adaptation assistance on short- and long-run pollution

Figure 1 illustrates this result. When ε^L is smaller than $\varepsilon^L_{M_2}$, enhanced adaptation capability increases both the short-run and long-run levels of the pollution stock. When ε^L is larger than $\varepsilon^L_{M_1}$ the short-term and long-term levels of the pollution stock both decline. When ε^L 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 labor 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

$$\frac{dW_n}{dR} = -\frac{1}{Y_{n,0}} + \beta \frac{dV_{n,1}(Z_1)}{dM_1} \frac{dE_{s,0}}{dR}. \tag{6}$$

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 (6) 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 investigate this point, differentiate South's welfare $W_s(R)$ and evaluate the derivative at $R = 0$ to obtain

$$\begin{aligned} \frac{dW_s}{dR} = {} & \beta \frac{dV_{s,1}(Z_1)}{dM_1} \frac{dE_{n,0}}{dR} + (M_0 + \beta \phi_R M_1)\, \varepsilon^Y \\ & + \left(\beta \frac{dV_{s,1}(Z_1)}{dL_{s,1}} L_{s,1} M_0 + \beta^2 \phi_R \frac{dV_{i,2}(Z_2)}{dL_{i,2}} L_{i,2} M_1 \right) \varepsilon^L. \end{aligned} \tag{7}$$

The second and the third terms on the right-hand side are the direct welfare benefit of enhanced adaptation capability in final output and labor stock, respectively. The first term captures the welfare gain or loss due to the change in North's behavior. 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 (7) is positive.

Recall from Proposition 4 that $dE_{i,0}/dR$ is a strictly decreasing linear function of ε^L. Hence, the expressions (6) and (7) immediately prove the following proposition.

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

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

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

Again, a key issue is whether or not the adaptation assistance is sufficiently effective in protecting labor stock. Proposition 6 shows that as long as the effectiveness ε^L is greater than a certain threshold $\varepsilon^L_{W_n}$, North always has an incentive to provide a positive level of adaptation assistance to South. Similarly, there is another threshold $\varepsilon^L_{W_s}$ above which South's welfare is improved by North's adaptation assistance. We note that for South, the threshold $\varepsilon^L_{W_s}$ can be zero, meaning that adaptation assistance can make South always better off, regardless of its effectiveness in labor protection. When adaptation assistance is completely ineffective in terms of labor protection ($\varepsilon^L = 0$), there will be no complementarity or cost-reduction effect and so the first term in (7) will be unambiguously negative. As long as ε^Y is strictly positive, however, the second term in (7) is always positive, making the net impact potentially positive.

Intuitively, one might expect that South's threshold $\varepsilon^L_{W_s}$ is always smaller than North's $\varepsilon^L_{W_n}$. In general, however, one cannot rule out the possibility that $\varepsilon^L_{W_s}$ is larger than $\varepsilon^L_{W_n}$. North might be able to achieve a higher level of welfare at the cost of South's welfare. Comparing (6) with (7), we see that this is only possible if

$$\frac{dE_{s,0}}{dR} < 0 < \frac{dE_{n,0}}{dR}. \tag{8}$$

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, (8) is less likely to hold, and South's threshold $\varepsilon^L_{W_s}$ is always lower than North's $\varepsilon^L_{W_n}$, as our next proposition clarifies.

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

The direct cost of adaptation assistance becomes negligible when North is wealthy enough, which is ensured by high productivity. As a consequence, the income effect shrinks, eliminating the difference in regional reactions to adaptation assistance. This makes sure 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.

These results have a number of implications, of which we mention two. First, once the damage to labor stock 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 labor stock, 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, which is likely when North is sufficiently wealthy, 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. 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 labor stock in the poor countries against pollution damage.

5 Discussion

Let us briefly discuss some limitations of our analysis and thereby suggest possible areas for future research. First, our treatment of labor stock is not entirely satisfactory. The way we model pollution damage to labor, 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 labor stock and its relation to climate change will be useful, especially when the model is to be matched up with empirical data.

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 its 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 remove North's motive to assist 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 here.

Some of the knife-edged theoretical results in this paper depend on the specification of functions. A logarithmic utility function and an exponential damage function both 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 damage 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 extra channel of externality is added. This feature allows us to understand the strategic significance of one specific type of additional externality (pollution-induced destruction of effective labor), which makes the marginal damage curve upward-sloping. If the utility function or/and damage function is more convex, the baseline marginal damage curve will be upward-sloping instead of being flat, acting against the dynamic complementarity effect. If one or both of the functions is relatively more concave, on the other hand, the complementarity effect will be strengthened. Hence, more subtleties will be involved for other combinations of utility and damage functions.

Finally, our analysis lacks an important channel of regional interaction: trade. Apart from adaptation assistance, regions in our model interact 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 more effective policies.

6 Conclusions

In this paper we have developed a dynamic model of a North-South economy where regional stocks of effective labor are negatively influenced by the global stock of pollution. By characterizing the equilibrium strategy of each region, we have shown that the interaction between labor stock and global pollution has strategic significance in dynamic settings. More precisely, the regional best responses can be strategic complements. A key role is played by the dynamic complementarity effect: an action of one player at one point in time influences the shadow value of the other player's state variable at another point in time. This insight is particularly important for global environmental protection. Establishing the complementary relationship between regional behaviors opens up the possibility of mutually beneficial cooperation among otherwise non-cooperative 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 and therefore adaptation assistance makes economic sense for all parties. This, however, is only the case if the assistance is provided in such a way that labor stock is effectively protected against climate damage. Otherwise, the standard substitution effect discourages South from reducing emission and, as a result, the cooperation scheme will not be incentive compatible.

A Proofs of propositions

Proof of Proposition 1

Problem of period $t = 2$

Since $V_{i,3}(Z_3) = 0$, it follows that $E_{i,2} = \bar{E}_i$ for both regions. Hence, for each $i \in \{n, s\}$,

$$C_{i,2} = Y_{i,2} = \Delta^Y_{i,2} A_{i,2} \left(\bar{E}_i^\rho + L_{i,2}^\rho\right)^{\frac{1}{\rho}}$$

and therefore the value function is

$$\begin{aligned} V_{i,2}(Z_2) &= \ln(C_{i,2}) = \ln(\Delta^Y_{i,2} A_{i,2} \left(\bar{E}_i^\rho + L_{i,2}^\rho\right)^{\frac{1}{\rho}}) \\ &= -\delta^Y_{i,2} M_2^\xi + \ln(A_{i,2}) + \frac{1}{\rho} \ln\left(\bar{E}_i^\rho + L_{i,2}^\rho\right), \end{aligned} \tag{A.1}$$

where $Z_2 = (L_{n,2}, L_{s,2}, M_2)$. We note that

$$\frac{dV_{i,2}(Z_2)}{dL_{i,2}} = \frac{L_{i,2}^{\rho-1}}{\bar{E}_i^\rho + L_{i,2}^\rho}, \qquad \frac{dV_{i,2}(Z_2)}{dL_{j,2}} = 0, \tag{A.2}$$

and

$$\frac{dV_{i,2}(Z_2)}{dM_2} = -\delta^Y_{i,2} \xi M_2^{\xi-1}. \tag{A.3}$$

Problem of period $t = 1$

Combining (A.3) and (1), we may write the first-order condition as

$$\frac{E_{i,1}^{\rho-1}}{E_{i,1}^\rho + L_{i,1}^\rho} = \beta \delta^Y_{i,2} \xi \left(\phi_M M_1 + E_{n,1} + E_{s,1}\right)^{\xi-1} \quad \forall i \in \{n, s\}, \tag{A.4}$$

which determines $(E_{n,1}, E_{s,1})$ as a function of $Z_1 = (L_{n,1}, L_{s,1}, M_1)$. Notice that the left-hand side is decreasing in $E_{i,1}$ and is independent of $E_{j,1}$ whereas the right-hand side is increasing in both $E_{i,1}$ and $E_{j,1}$. It follows that the equilibrium combination of $(E_{n,1}, E_{s,1})$ satisfies the stability conditions of Dixit (1986).

Totally differentiating (A.4) yields

$$\frac{dE_{i,1}}{dM_1} = -\frac{\Psi_i}{1+\Psi_n+\Psi_s}\phi_M \leq 0, \tag{A.5}$$

$$\frac{dE_{i,1}}{dL_{i,1}} = -\frac{1+\Psi_j}{1+\Psi_n+\Psi_s}\Phi_i < 0,$$

$$\frac{dE_{i,1}}{dL_{j,1}} = \frac{\Psi_i}{1+\Psi_n+\Psi_s}\Phi_j \geq 0,$$

where we define

$$\Psi_i := \frac{E_{i,1}\left(E_{i,1}^{\rho}+L_{i,1}^{\rho}\right)}{E_{i,1}^{\rho}+(1-\rho)L_{i,1}^{\rho}}\frac{\xi-1}{\phi_M M_1 + E_{n,1}+E_{s,1}} \geq 0,$$

$$\Phi_i := \frac{\rho E_{i,1} L_{i,1}^{\rho-1}}{E_{i,1}^{\rho}+(1-\rho)L_{i,1}^{\rho}} > 0.$$

Notice that $\lim_{\xi\to 1}\Psi_i = 0$ and therefore

$$\lim_{\xi\to 1}\frac{dE_{i,1}}{dM_1} = 0, \quad \lim_{\xi\to 1}\frac{dE_{i,1}}{dL_{i,1}} = -\lim_{\xi\to 1}\Phi_i(Z_1) < 0, \quad \lim_{\xi\to 1}\frac{dE_{i,1}}{dL_{j,1}} = 0.$$

The value function is

$$\begin{aligned}
V_{i,1}(Z_1) &= \ln(C_{i,1}) + \beta V_{i,2}(Z_2) \\
&= \ln(\Delta_{i,1}^{Y} A_{i,1}\left(E_{i,1}^{\rho}+L_{i,1}^{\rho}\right)^{\frac{1}{\rho}}) + \beta V_{i,2}(Z_2) \\
&= -\delta_{i,1}^{Y} M_1^{\xi} + \ln(A_{i,1}) + \frac{1}{\rho}\ln\left(E_{i,1}^{\rho}+L_{i,1}^{\rho}\right) + \beta V_{i,2}(Z_2),
\end{aligned}$$

where $E_{i,1}$ is implicitly defined by (A.4) and $V_{i,2}$ is given by (A.1). Using (A.2), (A.3) and (A.4), we obtain

$$
\begin{aligned}
\frac{dV_{i,1}(Z_1)}{dM_1} &= -\delta^Y_{i,1}\xi M_1^{\xi-1} + \frac{E^{\rho-1}_{i,1}}{E^{\rho}_{i,1}+L^{\rho}_{i,1}}\frac{dE_{i,1}}{dM_1} \\
&\quad + \beta\frac{\partial V_{i,2}(Z_2)}{\partial M_2}\frac{dM_2}{dM_1} + \beta\frac{\partial V_{i,2}(Z_2)}{\partial L_{i,2}}\frac{dL_{i,2}}{dM_1} + \beta\frac{\partial V_{i,2}(Z_2)}{\partial L_{j,2}}\frac{dL_{j,2}}{dM_1} \\
&= -\delta^Y_{i,1}\xi M_1^{\xi-1} - \beta\delta^Y_{i,2}\xi M_2^{\xi-1}\left(\phi_M + \frac{dE_{j,1}}{dM_1}\right) - \beta\frac{L^{\rho}_{i,2}}{\bar{E}^{\rho}_i + L^{\rho}_{i,2}}\delta^L_{i,1}\xi M_1^{\xi-1},
\end{aligned}
\tag{A.6}
$$

where $dE_{j,1}/dM_1$ is given by (A.5). Moreover,

$$
\begin{aligned}
\frac{d^2V_{i,1}(Z_1)}{dM_1^2} &= -\delta^Y_{i,1}\xi(\xi-1)M_1^{\xi-2} \\
&\quad - \beta\delta^Y_{i,2}\xi(\xi-1)M_2^{\xi-2}\left(\phi_M + \frac{dE_{j,1}}{dM_1}\right)\left(\phi_M + \frac{dE_{i,1}}{dM_1} + \frac{dE_{j,1}}{dM_1}\right) \\
&\quad - \beta\delta^Y_{i,2}\xi M_2^{\xi-1}\frac{d^2E_{j,1}}{dM_1^2} \\
&\quad - \beta\frac{L^{\rho}_{i,2}}{\bar{E}^{\rho}_i + L^{\rho}_{i,2}}\delta^L_{i,1}\xi M_1^{\xi-2}\left\{\xi - 1 - \frac{\bar{E}^{\rho}_i}{\bar{E}^{\rho}_i + L^{\rho}_{i,2}}\rho\delta^L_{i,1}M_1^{\xi}\right\},
\end{aligned}
$$

where

$$
\frac{d^2E_{j,1}}{dM_1^2} = -\frac{\phi_M}{1+\Psi_n+\Psi_s}\left(\frac{1+\Psi_j}{1+\Psi_n+\Psi_s}\frac{\partial\Psi_i}{\partial M_1} - \frac{\Psi_i}{1+\Psi_n+\Psi_s}\frac{\partial\Psi_j}{\partial M_1}\right)
$$

and

$$
\begin{aligned}
\frac{\partial\Psi_i}{\partial M_1}\frac{M_1}{\Psi_i} &= -\phi_M - \frac{\partial E_{i,1}}{\partial M_1} - \frac{\partial E_{j,1}}{\partial M_1} \\
&\quad + \left(1 + \rho\frac{E^{\rho}_{i,1}}{E^{\rho}_{i,1}+L^{\rho}_{i,1}} - \rho\frac{E^{\rho}_{i,1}}{E^{\rho}_{i,1}+(1-\rho)L^{\rho}_{i,1}}\right)\frac{\partial E_{i,1}}{\partial M_1}\frac{M_1}{E_{i,1}}.
\end{aligned}
$$

Since $\lim_{\xi\to1}\Psi_i = 0$, it follows that

$$
\lim_{\xi\to1}\frac{\partial\Psi_i}{\partial M_1} = 0, \quad \lim_{\xi\to1}\frac{d^2E_{j,1}}{dM_1^2} = 0,
$$

and therefore

$$
\lim_{\xi\to1}\frac{d^2V_{i,1}(Z_1)}{dM_1^2} = \lim_{\xi\to1}\beta\rho\bar{E}^{\rho}_i L^{\rho}_{i,2}\left(\frac{\delta^L_{i,1}}{\bar{E}^{\rho}_i + L^{\rho}_{i,2}}\right)^2 > 0. \tag{A.7}
$$

Problem of period $t = 0$

Combining (A.6) and (1), we may write the first-order condition as

$$MB_i(E_{i,0}) = MD_i(E_{i,0}, E_{j,0}), \tag{A.8}$$

where $MB_i(E_{i,0})$ is the marginal benefit from emission defined by

$$MB_i(E_{i,0}) := \frac{Y_{i,0}}{C_{i,0}} \frac{E_{i,0}^{\rho-1}}{E_{i,0}^{\rho} + L_{i,0}^{\rho}} = \begin{cases} \frac{Y_{n,0}}{Y_{n,0}-R} \frac{E_{n,0}^{\rho-1}}{E_{n,0}^{\rho}+L_{n,0}^{\rho}}, & i = n \\ \frac{E_{s,0}^{\rho-1}}{E_{s,0}^{\rho}+L_{s,0}^{\rho}}, & i = s \end{cases} \tag{A.9}$$

and $MD_i(E_{i,0}, E_{j,0})$ is the marginal damage from pollution defined by

$$MD_i(E_{i,0}, E_{j,0}) := -\beta \frac{dV_{i,1}(Z_1)}{dM_1}\bigg|_{M_1 = \phi_M M_0 + E_{i,0} + E_{j,0}}. \tag{A.10}$$

Notice that for any $E_{j,0} \geq 0$, we have

$$\lim_{E_{,0} \to 0} MB_i(E_{i,0}) = \infty > \lim_{E_{i,0} \to 0} MD_i(E_{i,0}, E_{j,0}) \tag{A.11}$$

and

$$\lim_{E_{,0} \to \infty} MD_i(E_{i,0}, E_{j,0}) > 0 = \lim_{E_{i,0} \to \infty} MB_i(E_{i,0}). \tag{A.12}$$

Hence, for each $E_{j,0} \geq 0$, there exists $E_{i,0} > 0$ at which the left-hand side of (A.8) crosses the right-hand side from above. Let $E_i^*(E_{j,0}) > 0$ denote the smallest of such points, which is the reaction function of region i. We characterize the equilibrium level of $E_{s,0}$ by $E_{s,0} = E_s^*(E_n^*(E_{s,0}))$, which is the smallest solution of

$$MB_s(E_{s,0}) = MD_s(E_{s,0}, E_n^*(E_{s,0})). \tag{A.13}$$

This equation always has a solution because of (A.11) and (A.12). The equilibrium level of $E_{n,0}$ is then determined by $E_{n,0} = E_n^*(E_{s,0})$. We note that, for both regions, the second-order condition is satisfied because the marginal benefit curve crosses the marginal damage curve from above.

To see that this equilibrium is stable, let us define

$$MB_{i,i} := \frac{\partial MB_i}{\partial E_{i,0}}, \quad MD_{i,j} := \frac{\partial MD_i}{\partial E_{j,0}} \quad \forall j \in \{n, s\}$$

for each $i \in \{n, s\}$. The second-order condition implies

$$MB_{i,i} < MD_{i,i} \quad \forall i \in \{n, s\} \tag{A.14}$$

at equilibrium. Also, by the definition of E_n^*, we have

$$MB_n(E_n^*(E_{s,0})) = MD_n(E_n^*(E_{s,0}), E_{s,0}) \quad \forall E_{s,0} \geq 0$$

and hence

$$MB_{n,n}\frac{dE_n^*}{dE_{s,0}} = MD_{n,n}\frac{dE_n^*}{dE_{s,0}} + MD_{n,s}. \tag{A.15}$$

Moreover, since the left-hand side of (A.13) crosses the right-hand side from above, we must have

$$MB_{s,s} < MD_{s,s} + MD_{s,n}\frac{dE_n^*}{dE_{s,0}} \tag{A.16}$$

at equilibrium. Combining (A.14), (A.15), and (A.16) yields

$$(MD_{s,s} - MB_{s,s})(MD_{n,n} - MB_{n,n}) - MD_{s,n}MD_{n,s} > 0, \tag{A.17}$$

meaning that the stability conditions of Dixit (1986) are satisfied.

Proof of Proposition 2

To characterize $E_{i,0}$, observe first that the marginal benefit $MB_i(E_{i,0})$ of emission is decreasing in $E_{i,0}$. On the other hand, (A.7) implies that at least when ξ is in the neighborhood of $\xi = 1$, the marginal damage $MD_i(E_{i,0}, E_{j,0})$ of emission is decreasing in $E_{j,0}$, meaning that the marginal damage curve of a region shifts upwards as the other region reduce its emission. Therefore, we conclude that there exists $\bar{\xi} > 1$ such that the short-run regional emissions are strategic complements as long as $\xi < \bar{\xi}$.

Proof of Proposition 3

See text.

Proof of Proposition 4

Totally differentiating (A.8) with respect to R for both $i \in \{n, s\}$ and evaluating every term at $R = 0$ yields

$$\begin{pmatrix} dE_{n,0}/dR \\ dE_{s,0}/dR \end{pmatrix} = \frac{D}{\det(D)} \begin{pmatrix} \partial MB_n/\partial R \\ -\partial MD_s/\partial R \end{pmatrix}, \tag{A.18}$$

where

$$\frac{\partial MB_n}{\partial R} = \frac{E_{n,0}^{\rho-1}}{E_{n,0}^{\rho} + L_{n,0}^{\rho}} \frac{1}{Y_{n,0}} > 0, \tag{A.19}$$

$$\frac{\partial MD_s}{\partial R} = -\beta\phi_R\varepsilon^Y + \beta^2 \frac{L_{s,2}^{\rho}}{\bar{E}_s^{\rho} + L_{s,2}^{\rho}} \left[\frac{\bar{E}_s^{\rho}}{\bar{E}_s^{\rho} + L_{s,2}^{\rho}} (M_0 + \phi_R M_1)\rho\delta_s^L - \phi_R \right] \varepsilon^L, \tag{A.20}$$

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

We first note that every element of the matrix D is strictly positive: the diagonal elements because of the second-order condition and the off-diagonal elements because of (A.10) and (A.7). The determinant of D is also strictly positive due to the stability condition (A.17).

Since every entry of the matrix $D/\det(D)$ is strictly positive, (A.18) indicates that $dE_{i,0}/dR$ is a positive linear combination of $\partial MB_n/\partial R$ and $-\partial MD_s/\partial R$. We observe from (A.19) that $\partial MB_n/\partial R$ is strictly positive. This term represents the income effect we discussed in the main text. The other partial derivative $\partial MD_s/\partial R$ in (A.20) may be positive or negative, depending on the relative importance of substitution and complementarity effects.

Notice that the terms in square brackets are strictly positive if the damage parameter δ_s^L is sufficiently large. Accordingly, under Assumption 1, $\partial MD_s/\partial R$ is a strictly increasing linear function of ε^L. On the other hand, the income effect, $\partial MB_n/\partial R$, is independent of ε^L, as is clear from (A.19). Hence, by (A.18), we know that $dE_{i,0}/dR$ is a strictly decreasing linear function of ε^L. In particular, if we define

$$\varepsilon_{E_{n,0}}^L := \frac{\frac{MD_{s,s} - MB_{s,s}}{-MD_{n,s}} \frac{\partial MB_n}{\partial R} + \beta\phi_R\varepsilon^Y}{\beta^2 \frac{L_{s,2}^{\rho}}{\bar{E}_s^{\rho} + L_{s,2}^{\rho}} \left[\frac{\bar{E}_s^{\rho}}{\bar{E}_s^{\rho} + L_{s,2}^{\rho}} (M_0 + \phi_R M_1)\rho\delta_s^L - \phi_R \right]} > 0 \tag{A.21}$$

and

$$\varepsilon^L_{E_{s,0}} := \frac{\frac{-MD_{s,n}}{MD_{n,n}-MB_{n,n}}\frac{\partial MB_n}{\partial R} + \beta\phi_R\varepsilon^Y}{\beta^2 \frac{L^\rho_{s,2}}{\bar{E}^\rho_s + L^\rho_{s,2}}\left[\frac{\bar{E}^\rho_s}{\bar{E}^\rho_s + L^\rho_{s,2}}(M_0 + \phi_R M_1)\rho\delta^L_s - \phi_R\right]} > 0, \qquad \text{(A.22)}$$

it follows that for each region i, $dE_{i,0}/dR < 0$ if and only if $\varepsilon^L > \varepsilon^L_{E_{i,0}}$.

Finally, (A.17) implies

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

which, together with (A.21) and (A.22), yields $\varepsilon^L_{E_{n,0}} > \varepsilon^L_{E_{s,0}}$. For the sake of completeness, we also note that the two thresholds coincide if there is no income effect (i.e., if $\partial MB_n/\partial R = 0$ in (A.21) and (A.22)).

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^L. Also, Proposition 4 shows that there exist thresholds $\varepsilon^L_{E_{n,0}}$ and $\varepsilon^L_{E_{s,0}}$ with $0 < \varepsilon^L_{E_{s,0}} < \varepsilon^L_{E_{n,0}}$ such that

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

and

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

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

$$\frac{dM_1}{dR} = \frac{dE_{n,0}}{dR} + \frac{dE_{s,0}}{dR} < 0 \iff \varepsilon^L > \varepsilon^L_{M_1}. \qquad \text{(A.23)}$$

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 (4), the third term is strictly negative and strictly increasing in ε^L. Therefore, combined with (A.23), this implies that there exists $\varepsilon^L_{M_2} < \varepsilon^L_{M_1}$ such that

$$\frac{dM_2}{dR} < 0 \iff \varepsilon^L > \varepsilon^L_{M_2},$$

which completes the proof.

Proof of Proposition 6

See text.

Proof of Proposition 7

We first prove the second half of the proposition. Since A_n does not affect the equilibrium levels of emission (when evaluated at $R = 0$), it follows from (A.18) and (A.19) that for each $i \in \{n, s\}$, $dE_{i,0}/dR$ is strictly decreasing in A_n. Then, for each given level of ε^L, (6) and (7) show that dW_i/dR is strictly increasing in A_n. Since dW_i/dR is strictly increasing in ε^L, this implies that the threshold $\varepsilon^L_{W_i}$ is strictly decreasing in A_n.

To prove the first half of the proposition, observe from (A.20) that

$$\frac{\partial MD_s}{\partial R} > 0 \iff \varepsilon^L > \varepsilon^L_\infty,$$

where ε^L_∞ is defined as

$$\varepsilon^L_\infty := \frac{\beta\phi_R\varepsilon^Y}{\beta^2\frac{L^\rho_{s,2}}{\bar{E}^\rho_s+L^\rho_{s,2}}\left[\frac{\bar{E}^\rho_s}{\bar{E}^\rho_s+L^\rho_{s,2}}(M_0+\phi_R M_1)\rho\delta^L_s-\phi_R\right]}. \tag{A.24}$$

Since $\lim_{A_n\to\infty} Y_{n,0} = \infty$, combining (A.18), (A.19), (A.20), (6), and (7) yields

$$\lim_{A_n\to\infty}\frac{dW_n}{dR} = -\beta\frac{dV_{n,1}(Z_1)}{dM_1}\frac{MD_{n,n}-MB_{n,n}}{\det(D)}\frac{\partial MD_s}{\partial R} \tag{A.25}$$

and

$$\lim_{A_n\to\infty}\frac{dW_s}{dR} = -\beta\frac{dV_{s,1}(Z_1)}{dM_1}\frac{-MD_{n,s}}{\det(D)}\frac{\partial MD_s}{\partial R} + (M_0+\beta\phi_R M_1)\,\varepsilon^Y + \left(\beta\frac{dV_{s,1}(Z_1)}{dH_{s,1}}H_{s,1}M_0 + \beta^2\phi_R\frac{dV_{i,2}(Z_2)}{dH_{i,2}}H_{i,2}M_1\right)\varepsilon^L. \tag{A.26}$$

It is clear from (A.25) that

$$\lim_{A_n\to\infty}\frac{dW_n}{dR} > 0 \iff \frac{\partial MD_s}{\partial R} > 0 \iff \varepsilon^L > \varepsilon^L_\infty,$$

which implies that the threshold $\varepsilon^L_{W_n}$ converges to ε^L_∞ as $A_n \to \infty$. On the other hand, the first term in (A.26) is positive whenever $\lim_{A_n\to\infty} dW_n/dR$ is positive. Since the second and third terms in (A.26) are strictly positive, $\varepsilon^L_{W_s}$ converges to a different threshold which is strictly lower than ε^L_∞. Therefore, we conclude that $\varepsilon^L_{W_s} < \varepsilon^L_{W_n}$ for sufficiently large A_n.

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B Online appendix: Infinite-period setting

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

B.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 consider the case where the damage parameters converge to a constant level for some sufficiently large t. Especially, we assume that $\delta_{i,t}^L$ 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 $\delta_{i,t}^L = 0$ for all $t \geq \bar{t}$.*

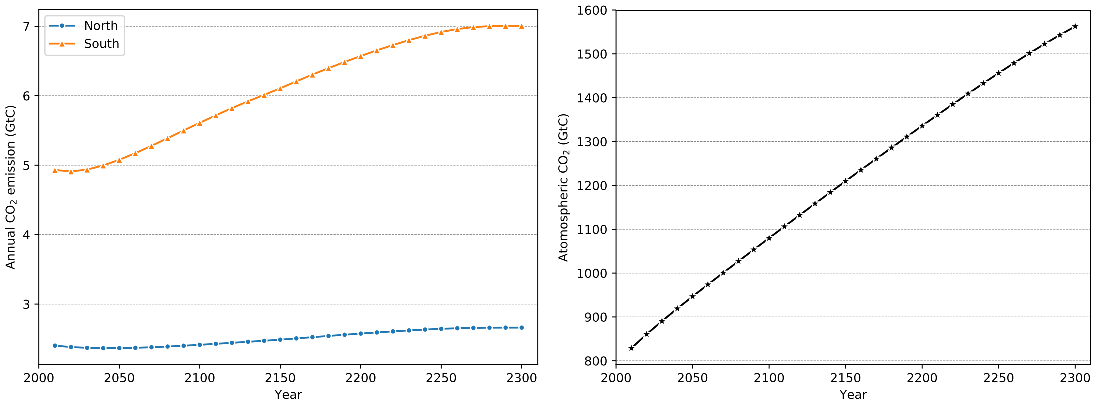
This assumption is reasonable as long as $\bar{t}$ is sufficiently large. The long-run value of the damage parameter in the final-output sector, δ_i^Y, can be arbitrarily small, but needs to be strictly positive. Otherwise, there would be no damage from pollution at all, which would make the optimal choice of emission unbounded. Under Assumption 2, for each $t \geq \bar{t}$, the first-order condition of each region is given by

$$\frac{E_{i,t}^{\rho-1}}{E_{i,t}^{\rho} + L_{i,t}^{\rho}} = \frac{\beta\delta_i^Y}{1-\beta\phi_M}, \tag{B.1}$$

which implicitly defines the equilibrium level $E_{i,t}$ of emission as a function of $L_{i,t}$. With this information, we can numerically compute the value function at period $t = \bar{t}$ for each region in a straightforward manner. Given the value function $V_{i,\bar{t}}$ at period $t = \bar{t}$, we numerically solve the Bellman equation and obtain $V_{i,\bar{t}-1}$, using the collocation method and the Chebyshev polynomials approximation (Judd, 1998; Miranda and Fackler, 2002). The function $V_{i,\bar{t}-1}$ is then used to compute $V_{i,\bar{t}-2}$, and so on until we obtain $V_{i,0}$.

B.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



(a) Regional emissions

(b) Carbon concentration

Figure 2: Equilibrium paths of regional emission and global concentration

time step with 2010 being the initial period. The discount factor is $\beta = 0.86$, which means that the annualized discount rate is 1.5%. The value of total factor productivity A_i is chosen so that the equilibrium value of final-good production matches the regional aggregate GDP in 2010. The initial stock $L_{i,0}$ of effective labor is calibrated in such a way that the equilibrium level $E_{i,0}$ of initial regional emission matches the observed data. As for the elasticity of substitution, Acemoglu et al. (2012) assume that $\rho = 0.33$ for one of their baseline scenarios. To be on the conservative side, we set $\rho = 0.10$ 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 starts from 829 GtC, steadily increasing over time, reaching to 1600 GtC in the next 300 years (Figure 2). The equilibrium levels of regional emission are fairly constant, due to the absence of exogenous technological progress in the model.

South's damage parameters are specified as

$$\delta^Y_{s,t} = \bar{\delta}^Y_{s,t} \exp\left(-\frac{\varepsilon^Y R_t}{\bar{\delta}^Y_{s,t}}\right), \qquad \delta^L_{s,t} = \bar{\delta}^L_{s,t} \exp\left(-\frac{\varepsilon^L R_t}{\bar{\delta}^L_{s,t}}\right), \tag{B.2}$$

where $\bar{\delta}^Y_{s,t}$ and $\bar{\delta}^L_{s,t}$ 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 $\delta^Y_{n,t} = 0.0000440$ and $\bar{\delta}^Y_{s,t} = 0.0000460$ for all t. This implies that when the stock of carbon in the atmosphere reaches 1600 GtC, which is the long-run level of pollution in the equilibrium path, 6.8% and 7.1% of annual GDP will be lost in

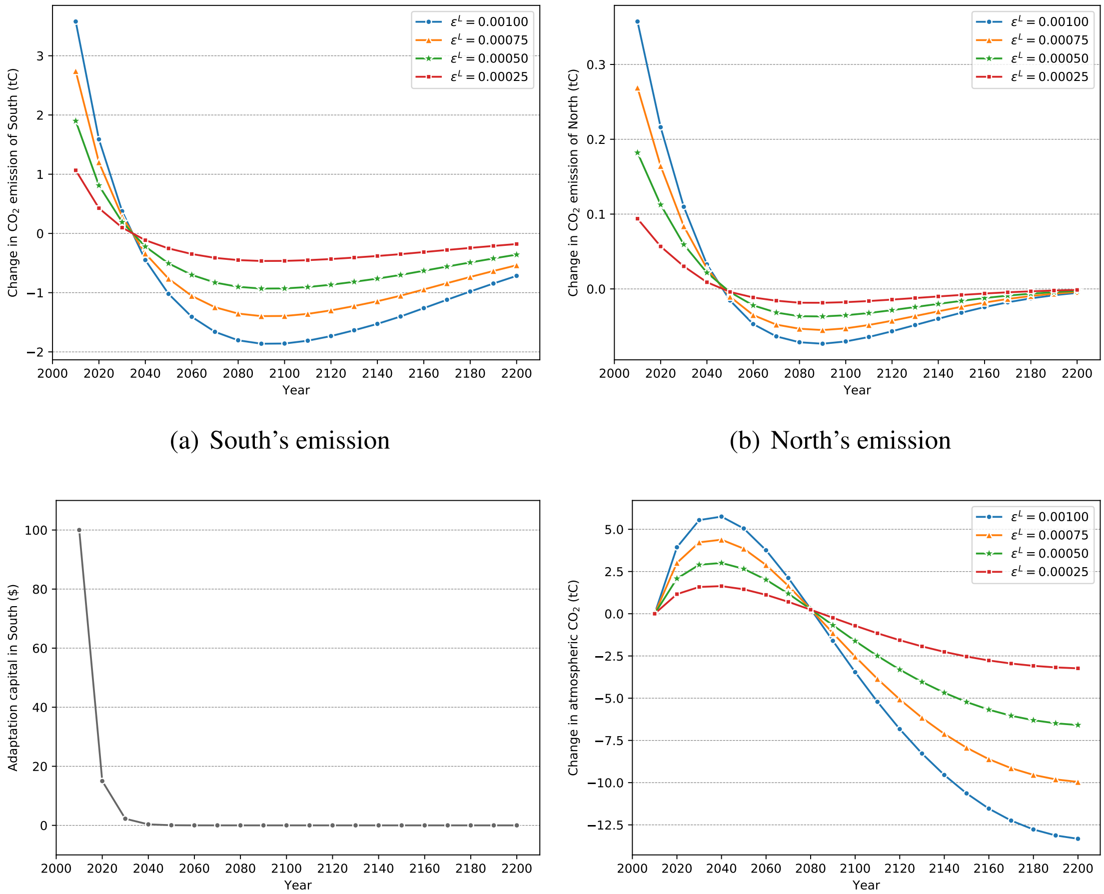
Table 1: Parameter values for numerical exercises

Symbol	Value	Description
β	0.86	Discount factor (per decade)
$L_{n,0}$	10^{24}	North's initial stock of effective labor
$L_{s,0}$	10^{21}	South's initial stock of effective labor
ρ	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	829	Initial pollution stock
$\delta^Y_{n,t}$	0.0000440	North's damage to final-good sector (constant)
$\bar{\delta}^Y_{s,t}$	0.0000460	South's damage to final-good sector (constant)
$\delta^L_{n,0}$	0.000001	North's damage to labor
$\bar{\delta}^L_{s,0}$	0.000003	South's damage to labor
ε^Y	0.001	Effectiveness of assistance (final-good production)
ε^L_{high}	0.001	Effectiveness of assistance (labor protection)
ε^L_{low}	0.00025	Effectiveness of assistance (labor protection)

North and South, respectively. The associated global loss of GDP is 6.9%, which is fairly consistent with the existing literature (Golosov et al., 2014). The damage parameters $\delta^L_{i,t}$ in the labor dynamics are not easy to calibrate. As a benchmark, we set their initial values at $\delta^L_{n,0} = 0.000001$ and $\bar{\delta}^L_{s,0} = 0.000003$, 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 1.5% and 4.5% of effective labor 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 B.4.

B.3 Results

We report in Figure 3 the consequences of a marginal investment (100US$ in 2010) in South's adaptation capital for different values of ε^L. As Figure 3(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 3(c). When the adaptation capital depreciates sufficiently, the combined effect of complementarity and cost reduction becomes important due to the additional labor 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 labor protection (ε^L 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



(a) South's emission (b) North's emission

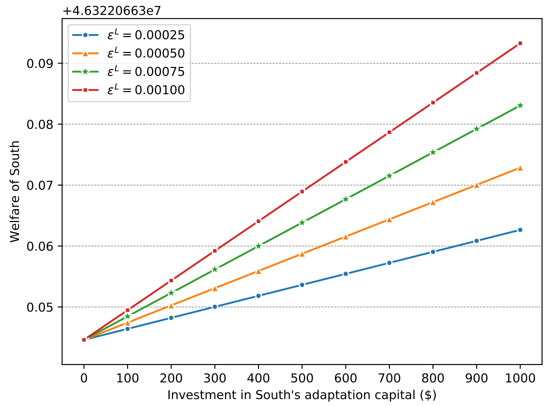
(c) Adaptation capital (d) Pollution stock

Figure 3: Consequences of adaptation assistance (relative to the case with $R = 0$)

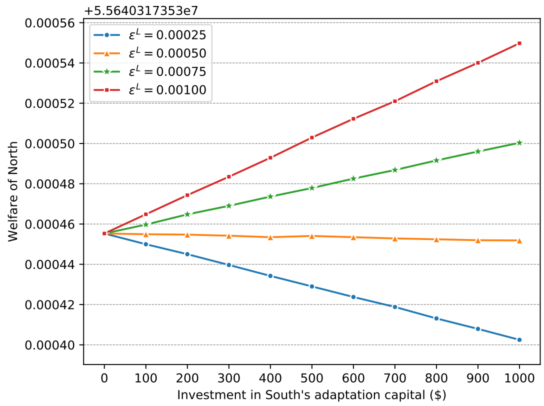
can more effectively protect labor (ε^L is large). This is consistent with our theoretical findings in the three-period setting.

In Figure 3(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 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 3(d). Again, the qualitative characteristics of the three-period model are replicated: a short-term hike of pollution followed by a long-term pollution decline.

Figure 4 shows the equilibrium welfare as a function of R. Adaptation assistance makes South always better off, regardless of its effectiveness in labor 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 effective labor in South. This indicates



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



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

Figure 4: Welfare implications of adaptation assistance

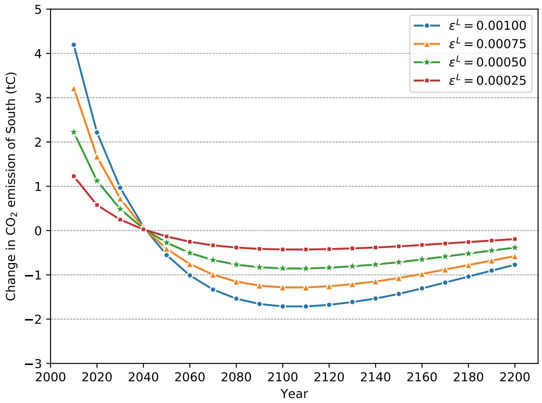
that for our numerical specification here, the income effect is sufficiently small.

B.4 Sensitivity analysis

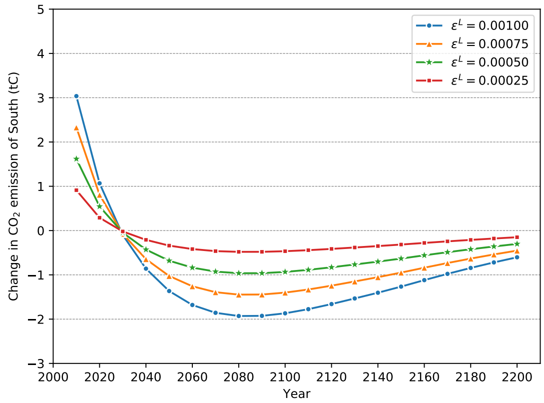
We present a brief sensitivity analysis with respect to the parameters: $\delta_{i,0}^L$ (damage parameter in labor dynamics) and ε^Y (effectiveness of adaptation for output production).

Figure 5 depicts the consequences of a marginal investment (100US$ in 2010) in South's adaptation capital for lower and higher values of $\bar{\delta}_{s,0}^L$. For the lower values we assume that $\bar{\delta}_{s,0}^L = 0.0000027$ (10% smaller than the baseline values). For the higher values we assume that $\bar{\delta}_{s,0}^L = 0.0000033$ (10% larger than the baseline values). When $\delta_{i,0}^L$ 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 $\delta_{i,0}^L$ is relatively high, the short-term pollution 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.

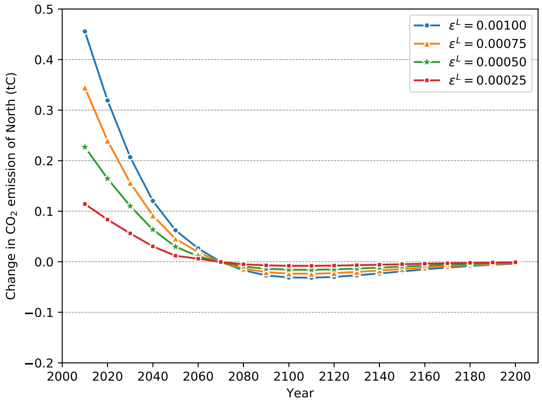
Figure 6 depicts the consequences of the same marginal adaptation investment for lower and higher values of ε^Y. We set $\varepsilon^Y = 0.0005$ (half the baseline value) for the lower value and $\varepsilon^Y = 0.0020$ (twice the baseline value) for the higher value. It is clear from the figure that 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.



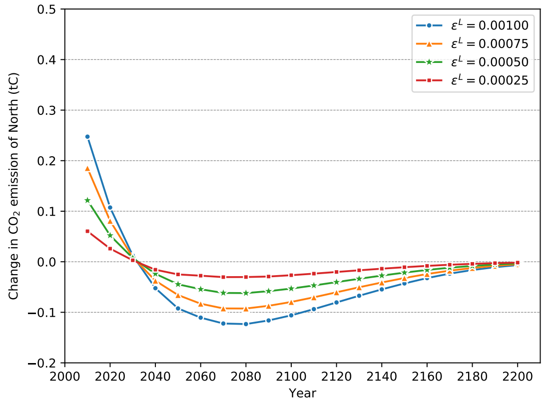
(a) South's emission (lower δ^L)



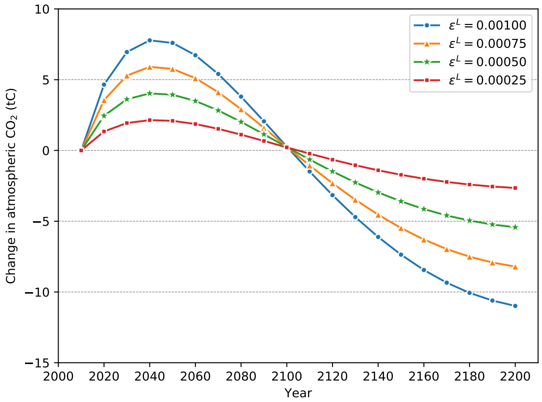
(b) South's emission (higher δ^L)



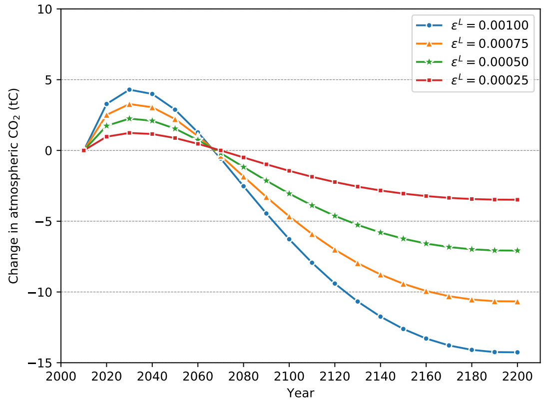
(c) North's emission (lower δ^L)



(d) North's emission (higher δ^L)

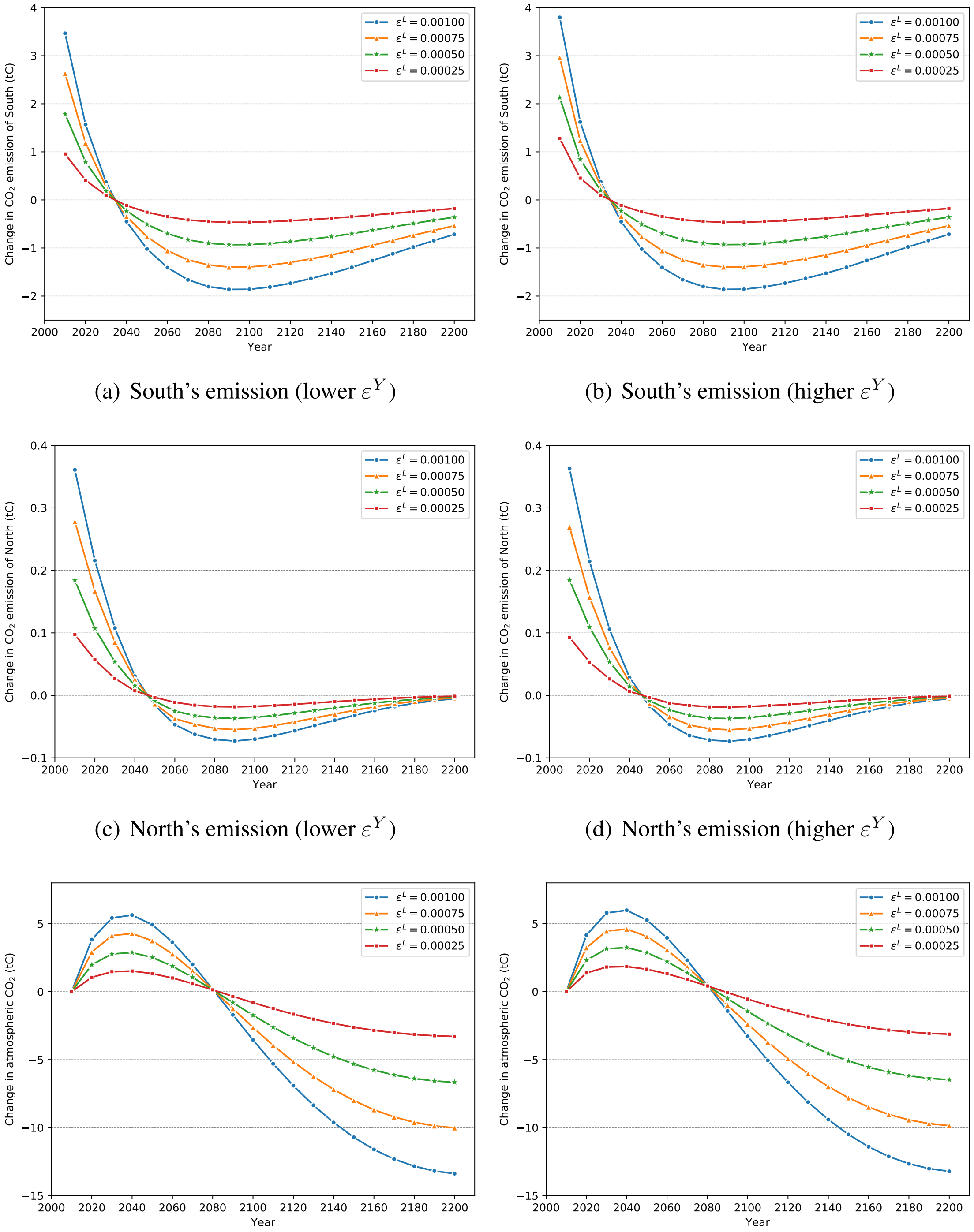


(e) Pollution stock (lower δ^L)



(f) Pollution stock (higher δ^L)

Figure 5: Consequences of adaptation assistance with varying $\delta^L_{i,0}$



(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 6: Consequences of adaptation assistance with varying ε^Y

In summary, our sensitivity analysis suggests that a higher value of damage parameter $\delta_{i,0}^{L}$ 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 labor destruction and should be targeted at the protection of labor 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.

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