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Optimal Climate Change Adaptation and Mitigation Expenditures in Environmentally Small Economies

ABSTRACT We study the optimal role of mitigation and adaptation strategies for environmentally small economies, that is, economies that are witnessing an exogenous increase in emissions to which they are contributing very little. Our results lead to three main conclusions. First, small economies should concentrate their environmental efforts, if any, on adaptation. This is a recommendation based on cost effectiveness rather than on any idea about these economies indulging in free riding. Second, environmentally small economies that are unable to spend enough on adaptation may end up spending less on mitigation in the long term, owing to their impoverishment as a result of negative climate shocks. Third, higher mitigation expenditures may arise not only as a result of greater optimal adaptation expenditures, but also because of increased adaptation to the incentives for mitigation provided by richer countries. For the simulations, we use a calibrated optimal growth model for Brazil, Chile, and the United States.

JEL classifications: Q52, Q54
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Anthropogenic climate change constitutes a perfect example of a large-scale market failure. According to the leading authority in this area, the Intergovernmental Panel on Climate Change (IPCC), it also poses a serious threat to humanity's welfare. The Fourth IPCC Assessment Report states that the concentration of greenhouse gases produced by the burning of fossil fuels is likely to cause a significant temperature rise by the end of

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the century, whose consequences will include drier soils, changes in weather extremes, the retreat of mountain glaciers, and rising sea levels.[1] These effects are expected to exhibit a great deal of geographical variation and may range from impacts that cause severe damage to productivity-enhancing changes. In spite of this consensus, the complexity of the climate makes any precise prediction of the relationship between specific concentrations of greenhouse gases and changes in global temperatures extremely difficult to make. We are thus doomed to live with uncertainty. Nevertheless, estimates of the net annual cost of a warmer world are in the neighborhood of 2 to 3 percent of global gross domestic product (GDP).[2]

These changes are expected to have a strong impact on developing countries—most of which are responsible for only a small share of total emissions—since their societies tend to be dependent on extremely climate-sensitive resources.[3] The Latin American and Caribbean countries are one example: their contribution to carbon dioxide in the atmosphere, the chief greenhouse gas generated by human activities, represents a scant 3.9 percent of the world total, whereas the United States is responsible for 23.8 percent.[4]

Mitigation and adaptation are the two basic elements of the strategy for dealing with climate change. Mitigation encompasses all actions that help to reduce greenhouse gas emissions or increase their capture from the atmosphere, thereby lowering the probability of negative climate-change shocks in the future. Adaptation involves actions to anticipate or compensate for these shocks. Countries' choices as to what kinds of policies they adopt will be driven by the relative costs and effectiveness of the different options.

Given the above statistics, a reduction in the growth rate of carbon dioxide emissions would prove to be an ineffective strategy for the Latin American and Caribbean countries, but it would be a comparatively more effective one, for example, for the United States. This suggests that optimal strategies may differ across countries, with larger economies (in terms of the emissions they produce) perhaps choosing quite different policies from smaller ones, in the absence of a binding global agreement.

1. Solomon and others (2007).
2. Nordhaus (2008); Smit and Pilifosova (2001).
3. Adger and others, (2003).
4. U.S. Energy Information Administration (EIA), "Total Carbon Dioxide Emissions from the Consumption of Energy (Million Metric Tons)," various years (www.eia.gov/cfapps/ipdbproject/IEDIndex3.cfm?tid=90&pid=44&aid=8 [June 2013]).

The literature, however, is primarily devoted to the optimal choice of mitigation policies.[5] Adaptation policies are only recently starting to attract attention and to be recognized as a potentially useful instrument.[6] Discussions of the optimal choice when both types of policy actions are simultaneously available are even thinner on the ground.

We seek to contribute to a more balanced discussion by presenting a model that is in the spirit of the dynamic integrated climate-economy (DICE) model, but includes both mitigation and adaptation expenditures.[7] Our analysis, however, is positive. We study what different economies are likely to do if they act optimally with respect to adaptation and mitigation in the absence of a global policy—in other words, if there is not a binding constraint to the environmental policies that countries could pursue. Although this, in itself, would represent an important development in the literature, we go further by allowing for the possibility that the effects of these (mostly mitigation) policies will differ from country to country depending on the size of each country's contribution to total emissions relative to that of the rest of the world. For this reason, we not only derive our main results analytically, but also calibrate and simulate our model. The idea is to provide orders of magnitude for the different policies likely to be adopted across different types of countries under existing international agreements.

To depict the optimal trajectories for mitigation and adaptation expenditures under different scenarios, we calibrate the model for environmentally large, medium-sized, and small economies.[8] Our results provide us with the following insights. First, small economies will tend to concentrate their environmental efforts, if any, on adaptation. Although larger countries may spend more, in absolute terms, on both mitigation and adaptation, the mitigation-adaptation ratio will be greater for larger economies. Second, small economies unable to spend enough on adaptation may be forced to spend even less on mitigation because of their increased impoverishment under climate shocks. Third, higher mitigation expenditures may arise not only as a result of greater optimal adaptation expenditures, but also because of increased adaptation to the mitigation incentives provided by richer countries.

5. See, for example, Copeland and Taylor (1994); Stokey (1998); Brock and Taylor (2010); Nordhaus (2008).

6. Lecocq and Shalizi (2007); de Bruin, Dellink, and Tol (2009); Chisari and Galiani (2010); Hallegatte, Lecocq, and de Perthuis (2011).

7. See Nordhaus (2008).

8. We discuss the criteria for this classification later in the paper.

These findings provide a new perspective on the Nordhaus-type solution, which requires that the marginal costs of reducing greenhouse gases be equalized in each sector and country, while at the same time ensuring that in every year the marginal cost is equal to the marginal benefit in terms of less future damage. As Nordhaus himself notes, "If inefficient implementation occurs (say, through inefficient allocation of permits, differential standards, exclusions, inefficient taxation, or regional exemptions), then the costs will rise and the benefit-cost ratio of even the optimal policy could easily decline."[9] The first and second findings mentioned in the preceding paragraph suggest that there are tensions between the high level of coordination required by those policies and the optimal responses of economies having different environmental profiles (or sizes) and structural characteristics.

The rest of the paper is organized as follows. The next section presents a brief discussion of the literature on the subject. The paper presents the model, along with the criteria used for classifying a country as environmentally small. The idea is to present the basic qualitative characteristics of the model and describe the properties of the steady state. We then present the results of the model's calibration and several simulations of comparative dynamics. The final section concludes.

Literature Review

The DICE model, which was first introduced by Nordhaus in 1994, includes economic growth and geophysical functions, taking into account emissions, concentrations, climate change, damage, and emissions controls.[10] Nordhaus later updated the model in one of the most exhaustive studies available on the economic impact of human activity on climate.[11] He finds that mitigation expenditures ultimately lower total emissions (which in turn affect temperatures, which in turn influence how much of aggregate production is lost), but the possibility that countries will adapt or adjust to climatic stimuli is not systematically explored. Other early papers highlight the need to integrate mitigation and adaptation strategies into climate-based development policy.[12] Here, we present a far simpler model than Nordhaus in order to focus on the

9. Nordhaus (2008, p. 88).
10. Nordhaus (1994).
11. Nordhaus (2008).
12. Tol (2005); Klein, Schipper, and Dessai (2005).

effects of both mitigation and adaptation policies in economies of different environmental sizes.

Our paper also fits in nicely with other work on this subject. For example, Lecocq and Shalizi recognize that optimal policies may vary depending on the environmental size of the economy: "Since the extent of mitigation is for the most part exogenous for individual country policymakers, to what extent does the optimal adaptation strategy depend on this exogenous parameter? This . . . requires a numerical estimation of the model, which is not attempted in this paper."[13] Our model addresses this question by including this parameter, which enables us to consider the case of a pollutant stock with a negative depreciation rate, since the emissions of the rest of the world are higher than the environment's natural rate of absorption.

Another closely related work is that of de Bruin, Dellink, and Tol, who include adaptation in both DICE and regional integrated climate-economy (RICE) models.[14] Although they consider multiple regions when they study adaptation within the framework of the RICE model, they make no distinction among the region-specific factors that contribute to temperature increases, which suggests that their analysis can be expanded and that the discussion can profit from the numerical explorations that we conduct in this paper. What sets our work apart from theirs is the functional form we choose for the damage function, which enables us to separate out the contributions of different factors to different countries' temperature increases and to focus on environmentally small economies. With regard to emissions, the main such factors are population growth, per capita consumption, the intensity of emissions with respect to GDP, and a country's relative contribution to the world's total emissions (which are almost negligible for many economies).

We also model the cost of adaptation and mitigation. In particular, we assume that marginal adaptation and mitigation costs are positive and increasing (quadratic). This seems to be realistic, especially given our focus on small economies that need to incorporate new and often capital-intensive technologies (which tend to be a scarce resource in this type of economy).

The analysis of adaptation and mitigation policies needs to be based on cost and effectiveness considerations. The increasing marginal sacrifice of consumption made by small economies in order to mitigate their environmental impact has to be compared with a very marginal reduction in the flow of new emissions and in the stock of greenhouse gases in the atmosphere.

13. Lecocq and Shalizi (2007, p. 34).
14. De Bruin, Dellink, and Tol (2009).

Meanwhile, the marginal cost of adaptation has to be viewed in relation to compensation for the damages suffered directly due to climate change.

Adaptation can be driven spontaneously by the market, as happens in the case of agriculture, for example, when more resistant varieties are introduced.[15] However, in a macroeconomic optimal growth model such as the type used in the literature, adaptation has to be understood as either private or public investment. For instance, in 1936, the U.S. Department of Agriculture (USDA) began campaigning for the introduction of a hybrid variety of corn that proved to be more heat resistant. Even before that, it had been engaged in its own research on the subject, while also subsidizing the dissemination of knowledge and seed samples.[16] The USDA also invested heavily in irrigation infrastructure throughout the twentieth century. Dams and irrigation canals helped to mitigate the effects of severe droughts, thus overcoming the collective-action problem stemming from their character as a public good.[17]

To sum up, our main contribution to the climate change literature is that we differentiate among countries, not only by their economic size, but also by their relative degree of responsibility in terms of greenhouse gas emissions. This provides us with a clearer picture of the incentives for environmentally small economies to incur adaptation and mitigation expenses. We use the case of the United States as a benchmark for the comparison of the policies followed by these small economies and those pursued by a big economy with a greater extent of responsibility in terms of total global emissions.

The Model

In this section, we present an optimal growth model that includes a climate component. The basic model has several characteristics that are, to some extent, inspired by the DICE model, but it also includes our own model of climate shocks. We then extend this basic model to incorporate mitigation and adaptation expenses.

Since we are not concerned with distributional issues, the basic model is a standard Ramsey model of a representative agent that maximizes the present value of its infinite flow of consumption, although we add the stock of emissions as a state variable into the optimization program. These emissions are assumed to affect productivity by reducing total output, which in turn can be

15. Mendelsohn (2000).
16. Sutch (2011).
17. Hansen, Libecap, and Lowe (2011).

equated with the production activity that is responsible for those emissions. This enables us to study the conditions under which governments incur mitigation and adaptation expenses and to run simulations that depict the optimal trajectories for countries of different sizes in terms of the environmental dimensions discussed above, along with some comparative statics exercises.

The Basic Model

Assume that the representative agent of this economy chooses a sequence of consumption to maximize:[18]

$$\int_0^\infty u\big(c(t)\big)e^{-rt}\,dt, \tag{1}$$

where $u(.)$ satisfies the standard assumptions of being monotonically increasing in c, but at a diminishing rate ($\partial u/\partial c > 0$, and $\partial^2 u/\partial^2 c < 0$). The flow of future consumption is discounted at a constant rate $r > 0$.

We assume that the production function of the economy has the regular properties of neoclassical production functions. The representative agent's consumption c is produced with a single input k, capital, using the production function $F(k)$. Again, this function satisfies the standard conditions of being increasing and strictly concave, $\partial F/\partial k > 0$, $\partial^2 F/\partial^2 k < 0$.

The differences from a standard growth model arise in the constraints that the representative agent faces. The first concerns the trend of capital, where the harmful effects of emissions make themselves felt: we model them as downscaling output by a fraction $\Theta(S) \in (0,1)$.

For now, theta will only depend on S, the stock of greenhouse gases in the atmosphere of the planet (which thus depends on the emissions of all countries).[19] To capture the fact that an increase in emissions further diminishes output, we assume that $\Theta(S)$ satisfies $\partial\Theta/\partial S < 0$. However, we will not necessarily assume concavity of $\Theta(S)$, since that would mean that it could be zero for some level of pollution (and could imply that it will become zero for some level of S).

The first constraint is therefore

$$\frac{dk}{dt} = \Theta(S)F(k) - \delta k - c. \tag{2}$$

18. For the sake of notational simplicity, we omit the time subscript from all variables.
19. This is similar to Nordhaus (2008).

That is, capital increases with savings—the difference between output $F(k)$ and consumption c—and decreases at the constant depreciation rate, δ. Climate change thus operates on capital accumulation by destroying a share $[1 - \Theta(S)]$ of production. To make matters simpler, we assume for now that there is no population growth. We remove this assumption when we run our simulations, which demonstrate that the population growth rate is a highly relevant variable. If population (either local or that of the rest of the world) grows even when capital per capita stays constant (as in the steady state), total output and hence total emissions will be higher. For simplicity, we also assume that there is no technological progress.

The second constraint concerns the trend in greenhouse gases from the perspective of the economy under study. We assume that every unit of $F(k)$ generates γ units of emissions.[20] We capture the fact that the environment regenerates itself by introducing a constant regeneration rate, Δ.[21] These two assumptions shape the second constraint:

$$\frac{ds}{dt} = -\Delta S + \gamma F\left(k\right). \tag{3}$$

Equation 3 captures the fact that emissions are an inevitable consequence of the production process, and equation 2 shows their negative influence on future capital. Higher emissions (a flow) indicate higher output. This is the direct effect included in equation 3 through parameter γ, which shows that there is complementarity between emissions and output. Equation 3, meanwhile, shows that the accumulation of emissions (a stock) creates a dynamic negative externality that sooner or later tends to reduce net output.

As shown below (see equation 12), total emissions can be reduced through mitigation. We model those mitigation actions by making the coefficient of emissions a function of a control variable (bm), where m represents the mitigation actions and b their effectiveness. This modeling strategy allows us to incorporate several different cases of mitigation actions, including those aimed at reducing deforestation under the Reducing Emissions from Deforestation and Forest Degradation Program (REDD), which is an important initiative for Brazil. We find that, when considered in the aggregate, mitigation is not a first choice for many countries, but that does not mean that some mitigation programs will not be adopted on a limited scale.

20. This is in line with Copeland and Taylor (1994).
21. See Brock and Taylor (2010).

An important point regarding Δ is that it usually accounts for the fact that the environment is able to reabsorb part of the stock of pollutants, such that $\Delta > 0$. In the case of the model developed by Nordhaus, that role is played by the seas. However, in our simulations, we consider a large (greater than one in magnitude) and negative Δ for small economies, which captures the fact that they face an exogenous positive net rate of growth in the stock of greenhouse gases in the atmosphere that derives from the rest of the world's emissions. In our simulations, δ_s is a function of other variables:

$$\delta_S = \zeta - E_S\left(Y_{RW} * N_{RW} * e_{RW} + Y_C * N_C * e_C\right).$$

That is, Δ may be a function of the natural absorption of the environment, ζ, which is an exogenous negligible rate, less the total emissions of the world, E_S. In this specification, E_S depends on total emissions around the planet, calculated as the sum of the emissions of the rest of the world per unit of output, e_{RW}, times the per capita income of the rest of the world, Y_{RW}, times the population of the rest of the world, N_{RW}, and of those same values for the country concerned, indicated with C. Consequently, the influence exerted by a given country in terms of climate change will be small (compared with the impact of the rest of the world) if its population, its per capita income, or its coefficient of emissions is small. A small country may find that even if it were to reduce its emissions to zero, δ_S would still be negative, which could induce it to consider Δ as a large exogenous negative parameter. As mentioned in the introduction, the country's incentive to reduce its own emissions will be low when the emissions of the rest of the world are disproportionately high and are determined exogenously.

Seen from this perspective, international agreements could give proper incentives for mitigation to small economies if they are matched with a credible reduction of the emissions generated by the rest of the world—that is, reductions in the component that is under their control, e_{RW}, —if they *dramatically* reduce the cost of mitigation or if incentives are provided in the form of economic rewards.

Given all these considerations, the problem faced by the representative consumer is to maximize equation 1 subject to equations 2 and 3. Consumption is the control variable, while emissions and capital are the state variables of the optimization program. The associated Hamiltonian is

$$H = u(c)e^{-rt} + \lambda\left[\Theta(S)F(k) - \delta k - c\right] + \mu\left[-\Delta S + \gamma F(k)\right]. \tag{4}$$

The necessary conditions for a maximum are as follows:[22]

(5)
$$\frac{du}{dc}e^{-rt} - \lambda = 0;$$

(6)
$$\lambda\left[\Theta(S)F'(k) - \delta\right] + \mu\gamma F'(k) = -\frac{d\lambda}{dt};$$

(7)
$$\lambda\Theta'(S)F(k) - \mu\Delta = -\frac{d\mu}{dt}.$$

We now manipulate these expressions to describe the impact of mitigation and adaptation policies on the steady-state level of capital. First, by totally differentiating equation 5, we get

$$\frac{d^2u}{d^2c} * \frac{dc}{dt} * e^{-rt} - r\frac{du}{dc}e^{-rt} - \frac{d\lambda}{dt} = 0.$$

Then, considering the steady state and using equation 5 again, we arrive at

(8)
$$-\frac{d\lambda}{dt} = r\lambda.$$

Replacing this expression in equation 6, we get

$$\lambda\left[\Theta(S)F'(k) - \delta\right] + \mu\gamma F'(k) = r\lambda.$$

Solving for μ yields

(9)
$$\mu = \frac{\lambda\left[r + \delta - \Theta(S)F'(k)\right]}{\gamma F'(k)}.$$

22. It is also necessary for the transversality condition to be satisfied: $\lim_{t\to\infty} \lambda k = 0$.

By taking derivatives with respect to time again, we have

$$(9') \qquad -\frac{d\mu}{dt} = \frac{r\lambda\left[r + \delta - \Theta(S)F'(k)\right]}{\gamma F'(k)}.$$

Finally, by replacing μ and $\frac{d\mu}{dt}$ given by equations 9 and 9′ in equation 7, it can immediately be shown that in the steady state,

$$(10) \qquad \Theta(S)F'(k) - (r + \delta) = -\frac{\Theta'(S)F(k)F'(k)\gamma(k)}{r + \Delta} = \epsilon > 0.$$

must hold. We call k^{***} the level of capital that satisfies this equality. Notice that equation 10 also implies that $\mu < 0$, which is consistent with the fact that emissions S are a stock that the economy wants to reduce.

We now show that k^{***} (the optimal value of the steady-state stock of capital per capita in this setup) is lower than the level of capital corresponding to the emissions-free case. To do this, we consider the ideal case of $\Theta(S) = 1$, which is akin to assuming that the economy is "immunized" from the environment. In this context, it is straightforward to determine the steady-state climate-change-free level of capital, which we denote as k^*:

$$(10') \qquad F'(k^*) - (r + \delta) = 0.$$

A comparison of equations 10 and 10′ shows that in our setting, capital has to be reduced: that is, $k^{***} < k^*$. This occurs as a consequence of two effects that we define separately. The first is an *average effect,* caused by the fact that $\Theta(S) < 1$ (which diminishes the marginal product of capital) and that $F(k)$ is strictly concave. Under our assumptions, it can be readily determined that even if $\Theta'(S)$ were equal to zero, the level of capital satisfying inequality 10, k^{**}, would be lower than k^*. This is simply because

$$F'(k^{**}) = \frac{r + \delta}{\Theta(S)} > F'(k^*) = (r + \delta)$$

implies $k^{**} < k^*$.

The second effect is a *marginal effect* that drives capital to an even lower steady state than k^{**}. To identify this effect, it suffices to note that the representative agent of the economy is aware of the marginal impact of additional capital on production and thus on the total stock S, and that consequently $\Theta'(S)$ becomes relevant (as shown by the right-hand side of equation 10). This implies that we actually need to consider k^{***}, which is the amount of capital that satisfies

$$F'\left(k^{***}\right) = \frac{r+\delta+\epsilon}{\Theta(S)} > \frac{r+\delta}{\Theta(S)} = F'\left(k^{**}\right).$$

This inequality implies that $k^{***} < k^{**}$. The marginal effect stems from assuming $\Theta'(S) < 0$, which simply reflects the (somewhat controversial) idea that increasing emissions monotonically increases the damage suffered by the economy. In turn, this derivative determines the sign of the right-hand side of equation 10, ϵ, and results in the inequality that yields an even lower steady-state level of capital.

Model with Mitigation and Adaptation

We now consider two ways of reducing the harmful impact of emissions: adaptation and mitigation expenditures. In broad terms, mitigation helps to counterbalance the *marginal effect* ($k^{**} - k^{***}$), whereas adaptation helps to reduce the *average effect* ($k^{*} - k^{**}$). This is because mitigation will slow the growth rate of emissions, while adaptation will decrease their impact.

Assume that the economy that we are studying is capable of making expenditures for the purposes of both mitigation and adaptation. The state equations become

$$\frac{dk}{dt} = \left[\Theta\left(S - za\right)F\left(k\right)\right] - \delta k - c - \eta m^2 - \rho a^2 \tag{11}$$

and

$$\frac{dS}{dt} = -\Delta S + \left[\gamma\left(bm\right)F\left(k\right)\right]. \tag{12}$$

While adaptation a reduces the effect of pollution on output by increasing theta through a parameter z (thus softening the average effect), mitigation lowers the amount of pollution generated per unit of output (which means it acts upon the marginal effect, since $(\partial\gamma)/(\partial m) < 0$).

As said earlier, parameter b stands for the effectiveness of mitigation expenses, and m is the mitigation action. Mitigation costs are assumed to be quadratic to represent increasing marginal costs. Mitigation encompasses several possible actions, including the adoption of new technologies, but the adoption of new methods is assumed to be costly. If they were free, they would be adopted immediately, but that does not seem to be the case. In fact, Chisari and Miller develop computable general equilibrium (CGE) models for several Latin American and Caribbean economies (including Brazil and Chile) and find that new clean technologies (which are thus not subject to carbon taxes) are not adopted by these economies when they are too intensive in foreign capital.[23] This shows that when capital has to be remunerated at the opportunity cost, these economies do not adopt the new technologies (which are modeled as latent and therefore not mandatory, so their level of use is determined by relative prices).

However, expenditure in either case is not decreasing, as equation 11 shows that the marginal expenditure on mitigation is $2\eta m \geq 0$ and that of adaptation is $2\rho a \geq 0$. The Hamiltonian then becomes

$$H = u(c)e^{-rt} + \lambda\left[\Theta(S - za)F(k) - \delta k - c - \eta m^2 - \rho a^2\right] + \mu\left[\gamma(bm)F(k) - \Delta S\right]. \tag{13}$$

Although the optimality conditions are the same as in the basic model, we now need to state the Kuhn-Tucker conditions for both m and a:

$$-2\lambda\eta m - b\mu\gamma'(bm)F(k) \leq 0; \tag{14}$$

$$\left[-2\lambda\eta m - b\mu\gamma'(bm)F(k)\right]m = 0; \tag{14'}$$

$$\lambda\left[-z\Theta'(S - za)F(k) - 2\rho a\right] \leq 0; \tag{15}$$

$$\lambda a\left[-z\Theta'(S - za)F(k) - 2\rho a\right] = 0. \tag{15'}$$

23. Chisari and Miller (2015).

Equations 14 and 14′ imply that if the expenditure on mitigation is positive, its optimal level would be

$$m = -\frac{b\mu\gamma'(bm)F(k)}{2\lambda\eta}.$$

Thus, expenditure on mitigation will be larger if the shadow price of pollution μ (in absolute values) is higher or if the marginal productivity of mitigation (measured by b) increases. However, we can expect this parameter to be small in an environmentally small economy.

On the other hand, if the marginal cost of mitigation (measured by 2η) or the marginal utility of present consumption (λ) increases or if output per capita $F(k)$ is not high enough, then there will be few incentives for the economy to spend on mitigation. In developed economies, output per capita is larger and λ is smaller, so our simulations for that type of country reflect a higher propensity to spend on mitigation.

In the case of adaptation expenditures, equations 15 and 15′ indicate that their optimal level, if different from zero, will be

$$a = -\frac{z\Theta'(S - za)F(k)}{2\rho}.$$

This means that in a steady state, adaptation expenditures will increase in step with increases in their marginal productivity, their effect on the palliation of the decrease in output (for $\Theta'_a > 0$), and output itself. Again, this explains why adaptation expenditures are higher in developed economies. On the other hand, a country will spend less and less on adaptation as its marginal cost rises.

Even if $\gamma = 0$ (which means the economy is not the source of significant greenhouse gas emissions), it may be an optimal choice for the economy to spend money on adaptation. This is not the case, however, for mitigation expenditures, since equation 14 would be negative and the optimal level of m would be zero.

Our simulations include cases in which either mitigation or adaptation (or both) is absent until some point in the future. Equations 14 to 15′ show that these courses of action may remain unused, but the level of these expenditures may become positive when economies become richer, because either consumption rises (which induces an increase in mitigation) or capital per capita increases (thus prompting expenditure on adaptation).

Also, if, over time, there is an increase in the stock of pollution S that is exogenous to the economy that we are studying (because the net value of δ_S is negative when we consider the difference between global emissions and local absorption), this will have a negative impact on the economy's actual output and capital accumulation (for $\Theta_S' < 0$). In this case, it is plausible that the economy will become poorer and will either spend less on both mitigation and adaptation or at least postpone these expenditures.

Now that we have introduced the relevant parameters for expenditure on mitigation and adaptation, we are able to define our criteria for classifying a given economy as being environmentally small. In our simulations, an environmentally small economy will have parameters that satisfy all of the following three informal conditions:

(1) $\Delta < 0$: the environmentally small country has no regeneration capacity. The stock of emissions rises over time due to the emissions of the rest of the world, even if the small economy were to produce no emissions at all. Thus, Δ is determined almost entirely by the rest of the world's GDP growth, population, and emissions coefficients.

(2) $b \cong 0$ and $\gamma \cong 0$: the effectiveness of the economy's own mitigation actions is almost nil, and the relevance of its own emissions relative to the world stock is also negligible.

(3) $\Theta_{Sk} > 0$: the marginal impact of S is smaller, the higher the stock of capital. That is, the more capital that an economy possesses, the better able it is to withstand the effects of climate change, but the per capita stock of capital k is small.[24]

Calibration of the Model and Simulations

To illustrate some of the expected results of our model, we calibrated it and ran a series of simulations for three countries: Brazil, Chile, and the United States. Since these countries may not necessarily be making investments in mitigation or adaptation at the present time, the calibration was based on estimated costs of mitigation and adaptation drawn from the literature and adapted to each country.[25]

24. Evidence of this can be found in Schumacher and Strobl (2008) and can be a useful structural property of an economy.

25. We take special care to factor in the prevailing exchange rates to arrive at an accurate figure for the percentage of GDP that those expenditures represent.

Brazil cannot be categorized as an environmentally small economy on the basis of its GDP, and it is the world's seventeenth largest polluter, with CO_2 emissions accounting for 1.3 percent of the world's total emissions. However, this level of emissions may not be high enough to warrant classifying Brazil as an environmentally large economy either, since its expenditures will initially be focused on adaptation. Chile qualifies as an environmentally small economy in any classification that we may consider, so it comes as no surprise that most of the results of our simulations fit in with the findings predicted by the model for this country. Finally, the United States is one of the planet's biggest economies in terms of both production and pollution, and its capital stock and GDP are among the largest in the world in per capita terms. Consequently, it internalizes many of the consequences of pollution and thus uses resources to both reduce and alleviate its impact.

Calibration

This model can easily be written in the general algebraic modeling system (GAMS) to run simulations of different scenarios. In these simulations, utility takes the constant relative risk aversion (CRRA) form with constant elasticity σ. The expected reduction in productivity is modeled as a function of the increase in average world temperatures. Most projections indicate that the increase in the average temperature over the next fifty years will be 3° Celsius. Using a geometric progression, the annual average temperature increase (ΔT) is therefore 0.0037 degrees. We then estimated the damage function, taking the inverse of the atmospheric temperature and the expected estimates of damage to the world economy for the next fifty years. Next, we appraised the relative contribution of each of the three economies to total emissions and estimated how much each of them could contribute to a reduction in the rate of increase in temperature via mitigation.

The law of motion for total greenhouse gases in the atmosphere states that the average temperature will be determined by per capita emissions production (*betp*) and the size of the population both of the country under study and of the rest of the world (*betrow*), parameterized with a constant φ calibrated to transform emissions into temperature increases. Thus, under usual conditions, we obtain a 3° Celsius increase in the earth's average temperature over a fifty-year period.

Since we do not use a natural absorption rate (Δ) for the simulations, this model does not have a steady state (unlike the model discussed earlier in this

TABLE 1. Calibrated Parameters for the Countries Studied[a]

Parameter	*Brazil*	*United States*	*Chile*
Economy			
Initial per capita capital stock: k_0 (in local currency)	22.023	121.257	10.460
Initial per capita income: y_0 (in local currency)	14.022	46.406	5.161
Initial per capita capital stock: k_0 (in U.S. dollars)	11.303	121.257	20.022
Initial per capita income: y_0 (in U.S. dollars)	7.197	46.406	9.879
I (TFP)	2.301	5.762	1.211
Share of capital remuneration: α (percent)	58.45	43.48	61.74
Population growth rate: *n* (percent)	2.02	0.87	1.26
Country population/World population: *np* (percent)	2.87	4.51	0.25
World population growth rate: *nw* (percent)	1.17	1.17	1.17
World GDP growth rate: *gw* (percent)	2.10	2.10	2.10
Environment			
Average temperature (Tm) (degrees Celsius)	14.45	14.45	14.45
CO_2 per capita (ER_{PC}) (tons)	1.94	18.50	4.21
Model			
φ (parameters of conversion of greenhouse gases into temperature) (degrees Celsius)	0.002823	0.002823	0.002823
Per capita emissions: *betp* (degrees Celsius)	0.000013	0.000694	0.000001
Rest-of-world per capita emissions: *betrow* (degrees Celsius)	0.001011	0.003203	0.000316
η (local currency units per unit of the mitigation index)	0.391490	0.021070	0.048340
b (metric tons)	0.515240	0.054030	0.237280
ρ (local currency units per unit of the adaptation index)	0.035050	0.116010	0.012900
Z (degrees Celsius)	0.000260	0.000260	0.000260

a. The initial capital stock in local currency is measured in thousands of Brazilian reales, Chilean pesos, or U.S. dollars, as applicable. The initial stock in U.S. dollars is also measured in thousands.

paper). Even if this might be a strong assumption for physical capital, it is not strong for an autonomous, slowly evolving stock of natural capital.

Unlike Nordhaus and Boyer, who use a multiple regression model in which the impact on average temperatures is computed through successive iterations, or Lyssenko and Shiell, who present an alternative method for considering noncooperative *N*-agent games, our approach corresponds to the case in which a small country has to determine the best approach to follow given the rest of the world's behavior.[26]

The calibrated parameters for the three countries we study are presented in table 1.

26. Nordhaus and Boyer (2000); Lyssenko and Shiell (2008).

Simulations

We ran simulations for the trajectories of the per capita stock of capital, income, consumption and investment, GDP growth and world GDP, the share of output that is lost ($1/\Theta$), the mean temperature, and adaptation and mitigation expenditures in both absolute terms and in terms of GDP, for Brazil, Chile, and the United States. This section presents the results of five of our simulations, taking a fifty-year time horizon. The figures included for each simulation show the mitigation and adaptation expenses as percentages of GDP; the rest of the series and figures have been omitted for the sake of clarity, but they are available on request from the authors. In the figures, the solid lines correspond to the trajectories of adaptation and mitigation expenses in the baseline scenario, while the dotted lines depict the same variables under the alternative simulation scenario.

SIMULATION 1: AN INCREASE IN TOTAL FACTOR PRODUCTIVITY. Figure 1 presents the results for the first simulation scenario, which incorporates an increase in total factor productivity (TFP). As the figure shows, Chile does not spend on mitigation measures at any point in the entire period under consideration. In contrast, Brazil begins to spend money on mitigation after about ten years into the period under study (approximated to 2008), because its per capita income and population growth rates are such that its contribution to total emissions would become more significant. However, these expenditures are very small as a percentage of GDP. For both these countries, adaptation expenditures are positive for the entire time horizon.

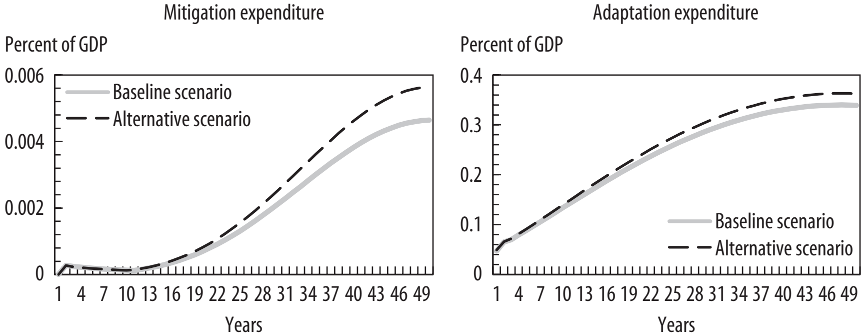
The United States spends on both mitigation and adaptation throughout the period, as its economy is big enough to reap the benefits of the former. In fact, its mitigation expenditures are higher than its adaptation expenditures as a percentage of GDP.

To evaluate possible growth convergence, we increase TFP by 1.5 percent for the United States and by 3 percent for Chile and Brazil. In the case of Chile, mitigation expenditures do not change, even though per capita GDP, consumption, investment, and capital per capita all increase. For Brazil, there is an increase in expenditures on mitigation, although the amount is still very small in terms of GDP. The United States increases its mitigation expenditures more than its adaptation expenditures. In fact, expenditure on adaptation increases in all three countries, which shows that it is considered to be a normal good.

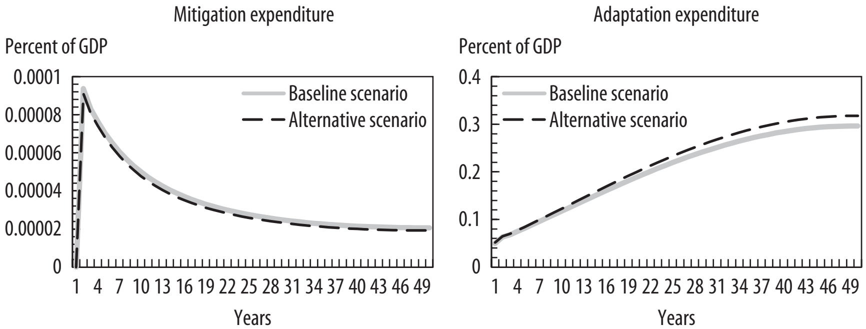
All this leaves the average temperature trajectory and theta almost unchanged for all the countries because nothing is done to reduce emissions,

FIGURE 1. Baseline Scenario and TFP Increase Scenario

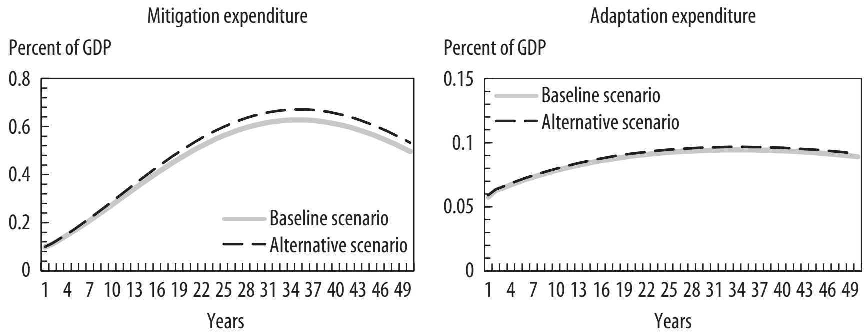
A. Brazil



B. Chile



C. United States



as all efforts are concentrated on reducing the impact of emissions on production.

SIMULATION 2: ADAPTATION IS NO LONGER AVAILABLE ($a = 0$). In the second scenario, we assume that countries cannot spend money on adaptation, so the only control variable that they can use is mitigation to lower the planet's temperature (see figure 2). Thus, we are adding a restriction to the model. Interestingly, this produces no effect whatsoever on the other outcome variables. The economies do not replace adaptation with additional expenditures on mitigation. They instead show a preference for using their resources to increase consumption.[27] Except for theta (which worsens slightly because the variable that counterbalances its trajectory is eliminated), the values for all the variables are almost the same as in the baseline scenario. Because the emissions of Brazil and Chile are relatively small relative to those of the rest of the world, the gains of additional individual efforts to reduce emissions are not meaningful when compared to the bulk of the damage due to the climate change generated by the rest of the world. Given the parameters of the cost functions, the Kuhn-Tucker conditions imply that individual mitigation efforts are not worth undertaking because the marginal cost of mitigation is high. In terms of the model presented earlier, b is too small compared to $2\eta m$.

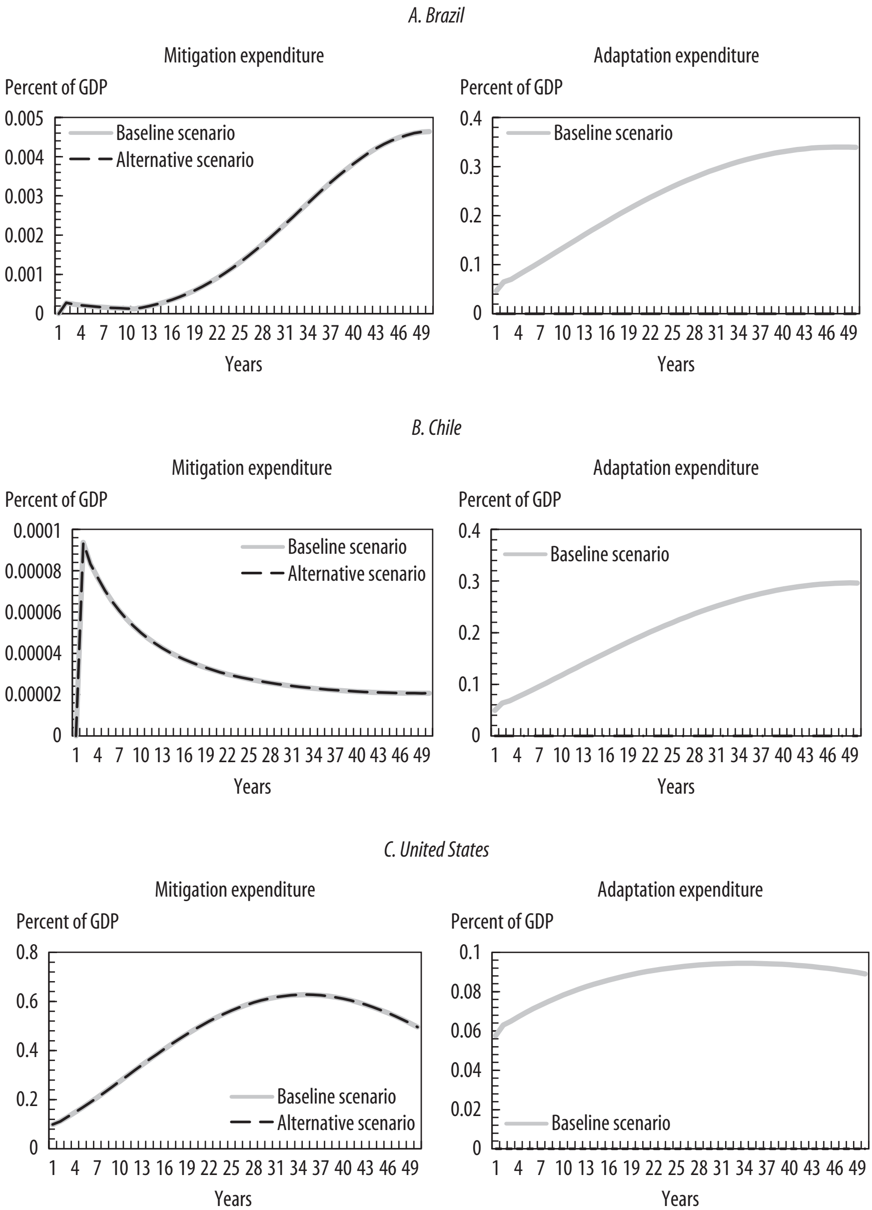
SIMULATION 3: LOWER LEVELS OF POLLUTION GENERATED BY THE REST OF THE WORLD. In this third alternative scenario, we reduce the emissions generated by the rest of the world by half (figure 3). This could be the result of tight restrictions on emissions or technological progress that makes production cleaner. This, in turn, generates a smaller increase in the average temperature (implicit in the trajectory of $1/\Theta$), which leads to an increase in productivity and, therefore, in per capita GDP. The results differ dramatically across countries.

In Chile, only adaptation expenditures increase, even in terms of GDP, despite the expansion of per capita income. This once again illustrates Chile's status as an environmentally small economy, which implies that it has no incentives to devote resources to mitigation.

In Brazil, there is a disproportionate increase in mitigation expenditures relative to adaptation expenditures, but only in the final years of the simulation (presumably because of the prior growth in income). However, mitigation expenditure remains below adaptation expenditure as a percentage of GDP. Per capita consumption increases, but investment rises slightly only in the last ten years, and then only after a slight decrease.

27. This result is not very clear in the figure, however, since the effects on consumption are negligible.

FIGURE 2. Baseline Scenario and No Adaptation Scenario



Finally, the United States raises its adaptation expenditures but postpones spending on mitigation, meaning that, for now, the impact of climate change has also been pushed forward in time. This is a worrisome result, as environmentally large economies could have incentives to defer their mitigation efforts when the rest of the world has made a commitment to reduce its emissions. Also, this increase is smaller than it is in Brazil, presumably because rest-of-world emissions for the former account for three-fourths of total emissions, while for the latter they represent around 98 percent of total emissions.

SIMULATION 4: MITIGATION AND ADAPTATION COSTS DECREASE BY 50 PERCENT. In this fourth alternative scenario, the parameters that reflect the cost of mitigation (η) and adaptation (ρ) are halved (figure 4). This generates significant changes in the variables under study. There is no change in the mitigation expenditures of Chile, which remain null, but Brazil and the United States increase their mitigation expenditures sharply, which shows just how sensitive the decisions made by large economies are to cost-effectiveness ratios. There is also a considerable increase in adaptation expenditures in all three countries and in mitigation expenditure in the United States, even when measured as a share of GDP.

A comparison of Chile and the United States based on this simulation indicates that the problem with mitigation expenditures in environmentally small economies goes beyond cost. Indeed, it is a cost-benefit problem: the effectiveness of mitigation instruments is so limited for these economies (since they would be mitigating a negligible fraction of the emissions that affect them) that any positive cost deters these economies from spending money on mitigation. Brazil seems to be a threshold case, which suggests that fast-growing economies that account for a more significant percentage of total emissions may adopt more mitigation measures if the cost of cleaner technologies is reduced.

SIMULATION 5: REDUCTION OF THE DISCOUNT RATE FROM 3.0 TO 1.5 PERCENT. Finally in this last alternative scenario, we assume a reduction in the discount factor (figure 5). Thus, future consumption carries greater weight in the intertemporal utility function. This means that investment is enhanced (as well as capital per capita), which raises GDP growth. It has been argued that this kind of analysis should be included in the evaluation of investment projects relating to climate change because it would demonstrate that a larger number of environmentally friendly projects are worth carrying out. The simulations address a generalized reduction in the discount rate, and they show that all three economies would grow faster.

FIGURE 3. Baseline Scenario and Lower Rest-of-World Emissions Scenario

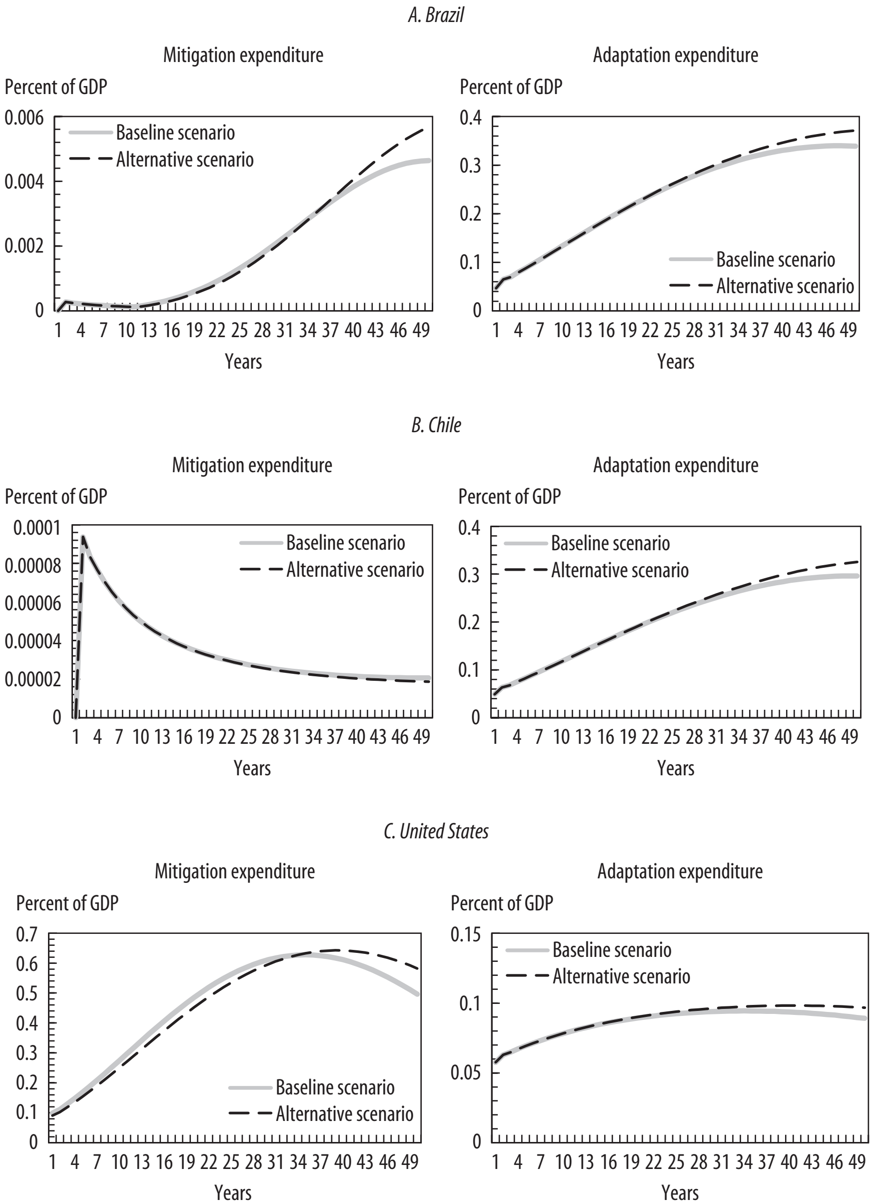
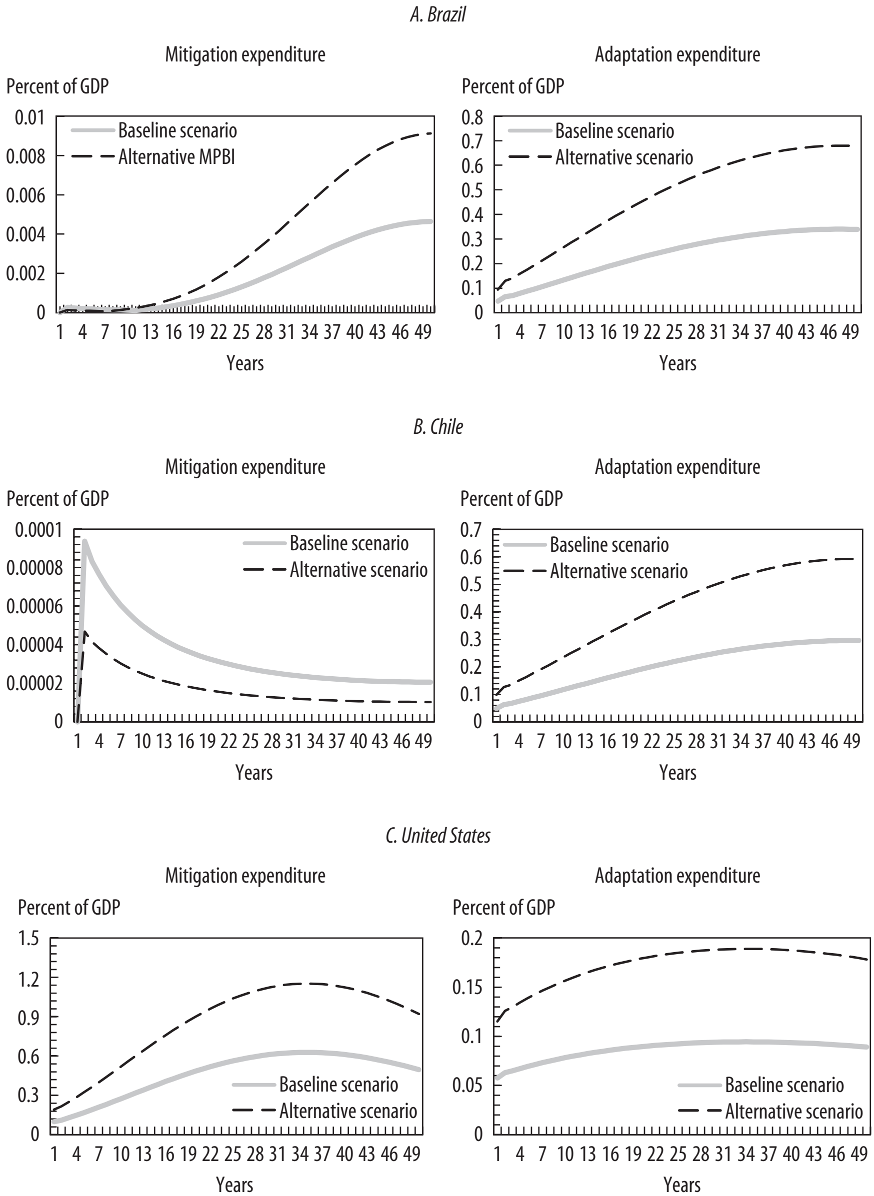


FIGURE 4. Baseline Scenario and Lower Mitigation and Adaptation Costs Scenario



The results do not provide as much of a basis for optimism as expected, however. The generalized reduction of the discount rate may increase the long-run capital stock even more than the average temperature. This means that the reduction of discount rates should be limited to those projects that make a real reduction in emissions. Although the United States is making additional expenditures on mitigation, the mean temperature increase remains constant, and the economy makes the necessary efforts to avert an increase in emissions beyond the initial pattern—but no more than that. Brazil also engages in more mitigation, but Chile does not.

Adaptation rises in all three countries. This is due to the greater affluence of their economies, which allows them to devote more resources to protecting production. The fact that any given percentage reduction in total production will be more significant in absolute terms under the new scenario is an additional factor.

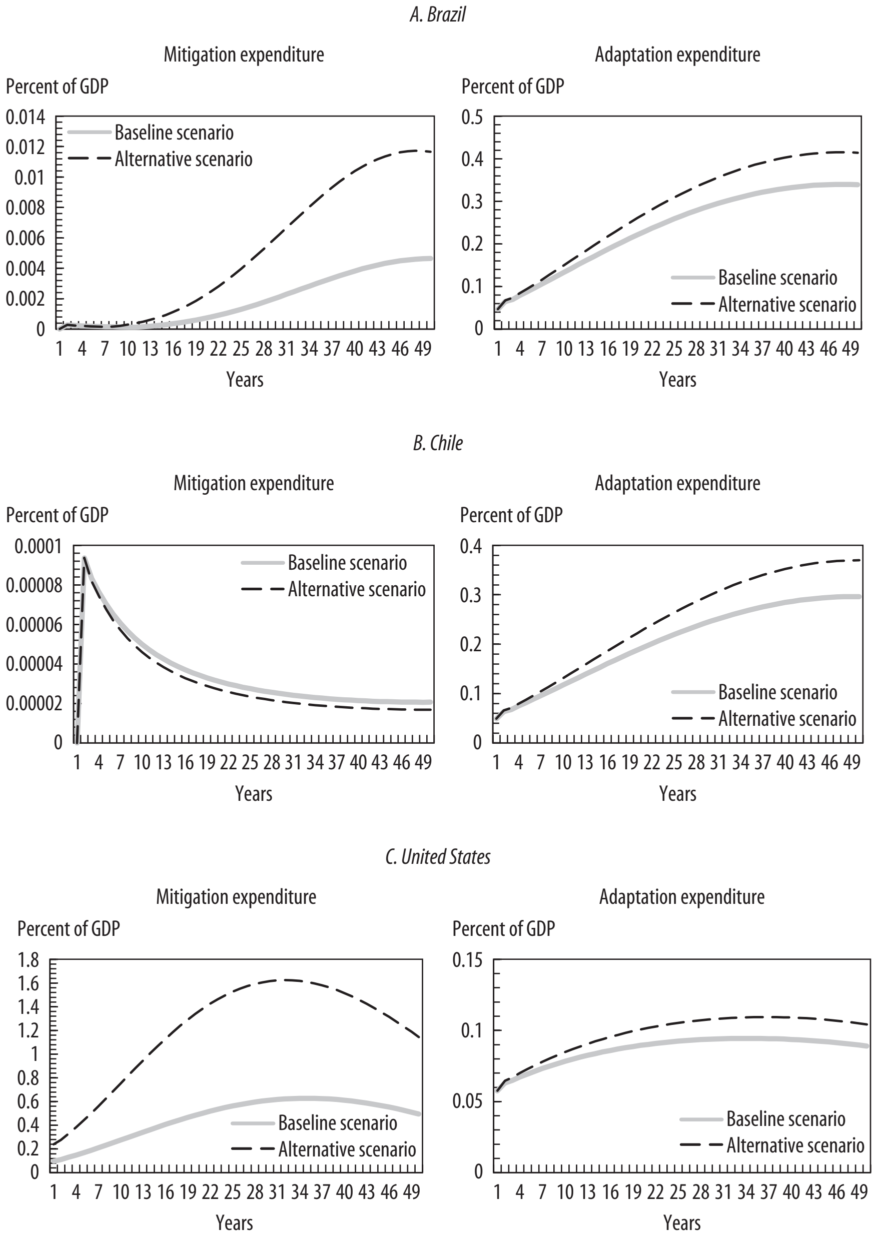
Conclusions

In this paper, we have developed an optimal growth model that incorporates economies' responses to climate change. The model draws inspiration from the DICE model, but allows for the existence of a steady state. The idea was to explore the impact of climate change on the steady-state properties and thus to gain insight into the incentives for the implementation of mitigation and adaptation policies. Accordingly, the model allows for a country's use of mitigation and adaptation measures in an effort to reduce the impact of climate change. We also allow for the possibility that the effects of these policies will differ from country to country depending on the size of each country's contribution to total emissions relative to the rest of the world.

We used this model to conduct several dynamic comparative exercises that shed light on different economies' possible reactions in terms of adaptation and mitigation measures under different scenarios when a steady state does not necessarily exist. The relevance of these exercises can be illustrated by the case of an absence of technical progress in climate change mitigation. In such a case, even if per capita consumption were constant, total emissions would increase because of the growth of the total population; in the case of climate change, what matters are total emissions, not per capita emissions.

The simulations confirm the findings yielded by our analytical model, which looks to structural features of a given country for the reasons underlying its stance on mitigation and adaptation. Based on the model, we expected

FIGURE 5. Baseline Scenario and Lower Discount Rate Scenario



economies that do not account for a significant percentage of total emissions to spend much less on such measures than countries that account for a significant percentage of global pollution. This is the case of Chile and Brazil, relative to the United States. The case of Brazil is particularly interesting because it is an economy in transition: the model shows that because the country will likely become a more significant source of pollution in the coming years, it should begin to undertake some mitigation expenditures.

Reducing mitigation costs or the discount factor—or even boosting growth—has no significant effect on mitigation expenditures for environmentally small economies. This shows that the problem does not lie on the cost side of the equation, but rather on the effectiveness side. The problems related to climate change stem from total emissions produced worldwide. Because environmentally small economies cannot do much to reduce total emissions, they have no choice but to concentrate their efforts on adaptation to conditions over which they have no control.

Three main conclusions emerge from our study. First, while most countries incur adaptation expenses because they need to reduce the negative impact of emissions-driven climate change, mitigation expenses are incurred only when the economy is responsible for a significant share of total greenhouse gas emissions. This is not necessarily a consequence of the cost of implementing such measures, but is rather a cost-effectiveness issue: economies that account for a small fraction of total emissions can do little to reduce them, so their expenditures would be futile.

The second conclusion relates to the first: when adaptation is not possible, small economies will spend less, not more, on mitigation. This is because they are unable to reduce the impact of the existing stock of greenhouse gases and are thus doomed to slower growth. This provides a powerful argument for subsidizing adaptation expenditures in the least developed economies. Furthermore, the only way to ensure that countries will spend on mitigation measures is through credible (that is, enforceable) international agreements under which countries make joint commitments to reduce emissions. One of our simulations shows, however, that if the rest of world were to reduce emissions unilaterally, the large economies would have an incentive to reduce their mitigation expenditures.

Third, the model also shows that rapidly growing transition economies that account for a fairly significant percentage of total emissions may engage in mitigation activities if the cost is affordable. Richer countries can thus provide incentives for developing economies to increase their mitigation expenditures. However, the equilibrium effort level for each country will have to be determined on the basis of further research.

We have argued that in the absence of binding international agreements to limit carbon emissions, Latin American countries should mainly focus on adaptation to cope with the consequences of climate change. Their choice of which adaptation policies to implement will depend on how the uncertainties about climate change resolve over time and on the results of thorough cost-benefit analyses of competing projects. Such cost-benefit analyses have yet to be carried out, however.[28] Nonetheless, the world as a whole must make a more determined effort to reach binding greenhouse gas mitigation agreements. Technological change in developed countries should play a key role in generating viable climate change mitigation measures.

28. See Feld and Galiani (2015) for an in-depth exploration of this issue.

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