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How Might Climate Change Affect Economic Growth in Developing Countries?

A Review of the Growth Literature with a Climate Lens

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Abstract

This paper reviews the empirical and theoretical literature on economic growth to examine how the four components of the climate change bill, namely mitigation, proactive (ex ante) adaptation, reactive (ex post) adaptation, and ultimate damages of climate change affect growth, especially in developing countries. The authors consider successively the Cass-Koopmans growth model and three major strands of the subsequent literature on growth: with multiple sectors, with rigidities, and with increasing returns. The paper finds that although the growth literature rarely addresses climate change per se, some issues discussed in the growth literature are directly relevant for climate change analysis. Notably, destruction of production factors, or decrease in factor productivity may strongly affect long-run equilibrium growth even in one-sector neoclassical growth models; climatic shocks have had large impacts on growth in developing countries because of rigidities; and the introducing increasing returns has a major impact on growth dynamics, in particular through induced technical change, poverty traps, or lock-ins. Among the most important gaps identified in the literature are lack of understanding of the channels by which shocks affect economic growth, lack of understanding of lock-ins, heavy reliance of numerical models assessing climate policies on neoclassical-type growth frameworks, and frequent use of an inappropriate "without climate change" counterfactual.

This paper—a product of the a product of the Sustainable Rural and Urban Development Team, Development Research Group—is part of a larger effort in the group to mainstream climate change research. Policy Research Working Papers are also posted on the Web at http://econ.worldbank.org. The authors may be contacted at lecocq@nancy-engref.inra.fr or zmarakshalizi@yahoo.com.

How Might Climate Change Affect Economic Growth in Developing Countries? A Review of the Growth Literature with a Climate Lens

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1. Introduction

Climate change specialists are alarmed by the acceleration in greenhouse gases emissions associated with the current fossil-fuel dependent economic growth rates, and they recommend strong mitigation action. However, many countries see the need for continued growth now and worry that economic growth will be harmed if they engage in mitigation.

Yet in the absence of any action, climate change will generate damages that will also alter country growth trajectories relative to the case without climate change, possibly even more so than if mitigation measures were adopted. Even when coping behaviors are factored in ('reactive adaptation'), the remaining damages of climate change (i.e., technically or economically irreversible consequences for welfare) may still be very large. Early actions to adapt to a world with a different climate ('anticipative adaptation')—of increasing importance as mitigation is delayed due to collective action problems—may of course reduce potential damages further, but they may also impose a toll on economic growth. Thus all types of action (including 'no action') will imply a set of costs.

The problem that policymakers face is thus to compare the implications for economic growth of several policy trajectories with more (or less) action *ex ante*, in the form of mitigation and proactive adaptation, and thus less (or more) levels of reactive adaptation and damages *ex post*; with a view to finding a portfolio of policy actions that minimizes the impact of the climate change bill—mitigation, proactive adaptation, reactive adaptation and ultimate damages—on economic growth.

In the present paper, we take one step towards achieving this goal by examining how individual components of the climate change bill affect growth, and what are the channels by which they do so. Comparing how policy trajectories that include all four components of the climate bill affect growth, let alone finding the optimal mix between mitigation, proactive adaptation, reactive adaptation and residual damages is beyond the scope of the present paper (Lecocq and Shalizi, 2007, discuss the latter problem from a resource allocation point of view).

The literature on the economic modeling of climate change has addressed only subsets of these issues. Most climate change models estimate the cost of mitigation[1] in a partial equilibrium or static general equilibrium framework (see e.g., Weyant et al., 1999 for a review). As such, they do not analyze the consequences of mitigation for *growth*. A few papers use growth models (e.g., Nordhaus, 1993) and analyze the consequences of mitigation for growth, but they do not examine how the structure of the underlying growth model constrains the results. In addition, since the impacts of climate change are uncertain and difficult to model, most climate change models analyze the problem in a cost-efficiency framework, and hence do not explicitly model damages (e.g., McKibbin and Wilcoxen, 1999, Paltsev et al., 2005). A few climate change models analyze the problem in a cost-benefit framework and explicitly model damages (e.g., Manne and Richels, 1992), but they usually rely on simplified growth models that are insufficient to address the complexity of the relationship between impacts of climate change and economic growth that would be of interest to policymakers.

The theoretical and empirical literature on economic growth addresses many issues that are directly relevant to the climate change problem, such as the relationship between climatic shocks and economic growth. But it rarely discusses climate change explicitly. One exception is Tol and Fankhauser (2005), who consider the 'ultimate impacts' of climate change on growth (but not the consequences of mitigation and adaptation measures) within a one-sector framework.

The objective of this paper is to briefly review the theoretical and empirical literature on economic growth in order to qualitatively assess the consequences for growth of the different components of the climate change bill (defined in section 2.1). Our approach is similar to Tol and Fankhauser's, but we extend their analysis in two directions: first by taking all components of the climate change bill into account, and second by reviewing the implications of a wider range of theoretical and empirical results about economic growth.

The paper is structured as follows. Section 2 sets the stage by detailing the different components of the climate bill and discussing briefly how the channels by which they affect growth might differ. On this basis, section 3 discusses the implications of climate change for economic growth within the theoretical framework of the Cass-Koopmans (CK) growth model.

[1] The cost of mitigation is "the total value that society places on the goods and services forgone as a result of the diversion of resources to climate protection" (Markandya et al., 2001, p.459). In theory, *net* costs should be computed, taking into account avoided damages of climate change. In general, however, 'mitigation costs' refers to *gross* costs, that is without taking avoided damages into account. In cost-benefit settings, benefits of mitigation are usually reported separately.

We start with the CK model because it is the simplest analytical framework with normative content within which the discussion can take place, and because it underpins a large number of the numerical models where the consequences of mitigation (or of ultimate damages) on growth are discussed. The CK model, however, does not adequately capture key stylized facts about growth, particularly in developing countries (section 4). Though no single model to date fully overcomes this limitation, the growth literature has seen major developments since the CK model. Here we review how the components of the climate change bill affect economic growth in three major strands of the recent literature: models that 'open the black box' and consider economies with multiple sectors and regions (Section 5), models that take rigidities into account to better capture transitional growth processes (Section 6), and models that allow for increasing returns to scale (Section 7). The final section summarizes key findings from the review and draws implications for the literature on growth, for numerical modeling of climate change, and for policy.

2. Setting the stage: An informal framework for analyzing the impacts of climate change on economic growth

2.1. The four components of the climate change bill

The causal chain linking economic behavior today to economic consequences tomorrow *via* climate change can be summarized as follows: economic activities → emissions → concentrations → climate change → impacts on (ultimate damages to) physical and ecological systems and, finally → impacts on (ultimate damages to) economies. In this paper, **mitigation** consists of reducing emissions (or removing greenhouse gases (GHGs) out of the atmosphere) at the beginning of the chain to avoid or minimize climate change in the first place, whereas **adaptation** consists of responding to economic damages of climate change at the end of the chain.

In addition, two forms of adaptation are distinguished. **Reactive adaptation** focuses on 'coping' with the adverse impacts of climate change *ex post*, when they occur. **Anticipative adaptation** (or proactive adaptation) focuses on lowering the costs of coping *ex ante*. It encompasses measures taken in advance to limit the ultimate damages of climate change and/or to reduce the extent of reactive adaptation required when climate-change associated events and

trends materialize.[2] In this paper we use the term '**ultimate damages**' for those damages that would be incurred in the absence of any policies, and '**remaining ultimate damages**' for those damages that are technically or economically irreversible, and likely to remain after all mitigation and adaptation expenditures have been incurred.

Thus, the additional effort on economies imposed by the presence of climate change has four components: (i) mitigation efforts (M), (ii) anticipative or proactive adaptation efforts (P), (iii) coping or reactive adaptation efforts (R), and (iv) the ultimate damages/remaining ultimate damages (UD/RUD) of climate change on the economies—the level of which depends of course on the level of mitigation, as well as, on the level of proactive and reactive adaptation.[3]

Mitigation, proactive adaptation and reactive adaptation are policy variables, whereas remaining ultimate damages/ultimate damages are impacts that remain after adopting policies (mitigation, proactive adaptation and reactive adaptation) or in the absence of adopting any policies respectively.

2.2. The different components of the climate bill will have different consequences for growth

The most obvious difference between the components of the climate change bill is in timing: ultimate damages and reactive adaptation expenditures are incurred at the time damages occur, whereas proactive adaptation and mitigation expenditures are incurred before damages occur. As a result, the components of the climate bill are likely to differ by the degree of concentration of efforts in time.[4] Ultimate impacts of climate change and reactive adaptation expenditures may be inescapably concentrated in time (and possibly repeated), for example when an extreme weather event occurs. On the other hand, it is possible to distribute proactive adaptation and mitigation

[2] For repeated events, the reaction of societies may change over time. The first time a crisis occurs, economic agents (societies/households/firms) will spend to cope *ex-post* within their ability to pay (i.e. reactive adaptation), but if repeated crisis are expected, the same agents might adopt anticipative adaptation *ex-ante*.

[3] The ultimate impacts of climate change on economies may sometimes be positive (for some regions and sectors), at least within a tolerable range of climate change. For example, agriculture in temperate and boreal zones is expected to benefit from climate change for mean temperature increase below 3°C relative to the current level (Adger et al., 2007). However, because of uncertainties much of the focus of climate change analysis is on the risks—i.e. the net adverse consequences/damages—accompanying climate change.

[4] Differences in timing also point to two key issues in the comparison across policy trajectories. One is the value of the discount rate. The second is uncertainty, which is highest when action is undertaken early.

efforts over longer periods of time.[5] Whether efforts are concentrated in time or not has implications for growth because rapid transitions are more difficult to adjust to.

The second main difference between components of the climate bill is in nature: the ultimate damages of climate change result from physical changes in the environment within which the economy operates; whereas mitigation, proactive adaptation and reactive adaptation are policy measures aimed at modifying households and firms behaviors, but from within the economic system. The consequences for growth will be different in each case.

The ultimate impacts of climate change are likely to affect factors of production and their productivity directly. For example, climate damages may reduce capital stock—e.g., cyclone destroying factories, farms and houses—, reduce the productivity of capital—e.g., floods reducing the number of days during which factories can produce or the number of months during which a road network is usable—, or reduce the growth rate of factors of production—e.g., climate-change related spread of malaria increasing infant mortality rate or leading to additional out-migration from malaria infected regions. Thus, the ultimate damages of climate change may directly affect the level (and the growth rate) of productivity in climate-sensitive sectors—e.g., increases in temperature eroding agricultural productivity, and indirectly in sectors that may not appear at first glance to be climate sensitive such as, manufacturing or services.

On the other hand, reactive adaptation, anticipative adaptation and mitigation, are likely to translate into additional expenditures to avoid or minimize changes in the stock, productivity or growth rate of production factors, or to avoid or minimize changes in production functions. Additional expenditures might be needed to strengthen infrastructure—for example, to erect a dyke and protect a farm, a factory or a building from sea-surges and keep capital stock intact and productive, or to strengthen institutions—for example, by enforcing zoning measures to avoid occupation of a flood plain.

The distinctions made above are not absolute, as all four components of the climate bill are likely to encompass both concentrated and gradual efforts,[6] and to affect growth via both

[5] Unless of course repeated delays in starting action make gradual increases in mitigation and proactive adaptation impracticable.

[6] The ultimate damages of climate change might span over long periods of time (e.g., gradual increase in temperature), whereas mitigation or proactive adaptation, as noted in the footnote 5, might require large efforts over short periods of time to be effective.

expenditures and direct influence on factors of production or production functions[7]—but with different proportions. Yet the distinctions made above provide a useful guide to reviewing the literature: How do growth models respond when factors are affected by ultimate damages? And how do they respond when additional expenditures are incurred to minimize ultimate damages? What are the implications of gradual efforts for short-term and long-term growth? And what are the implications of shocks?

2.3. Evaluating the consequences of each component of the climate bill for growth

An important methodological point about the appropriate counterfactual must be made here. Initially, when climate change emerged as a policy concern, the focus was on mitigation. But since damages were uncertain, most assessments of mitigation policies adopted a cost-efficiency framework in lieu of a cost-benefit framework. Unfortunately, without an appropriate counterfactual, the baseline used for comparison was usually business-as-usual growth (BAU) *in the absence of climate change*. This made it seem as if all policy actions (mitigation, proactive adaptation and reactive adaptation) would be more costly than the *laisser faire / BAU* (scenario S1 in Figure 1).

However, as mentioned in the introduction, what matters ultimately for policy decisions is the relative impacts on growth of different policy trajectories, where more (less) action is taken and less (more) damage and reactive adaptation is incurred. In the presence of impending climate change, the appropriate counterfactual *laisser faire* scenario is one in which no action whatsoever is taken against climate change; and in which, as a result, the full set of damages associated with climate change are incurred on the whole portfolio of assets (S2). Unless the expected costs of mitigation and adaptation are very high relative to expected damages, it is possible to reduce the total climate bill by adding some degree of reactive adaptation (S3), and that it is possible to reduce the total climate bill *further* by adding well-selected combinations of anticipative measures (proactive adaptation and mitigation) (S4). In other words, an optimal policy combination of mitigation, proactive adaptation and reactive adaptation, should both reduce the *remaining ultimate damages* of climate change and the *total climate bill* relative to the *laisser faire* BAU scenario in the presence of climate change (S2). Our assumptions about growth rates g

[7] For example, the ultimate impacts of climate change may also induce additional expenditures affecting growth such as costs of relocation. Similarly, mitigation or proactive adaptation may directly affect productivity if, e.g., proactive

and per capita outputs y in scenarios (S1) to (S4) are summed up in Table 1. These relationships also underlie the relative positions of the aggregate output curves on Figure 1.

Table 1: Assumptions regarding relative economic performance under scenarios S1 to S4 representing scenarios with vs. without climate change (CC) and the absence vs. presence of policy actions for mitigation (M), proactive adaptation (PA), and reactive adaptation (RA). g refers to growth rate of per capita GDP in the transition (subscript T) or in the steady-state and y to the associated level of per capita GDP

Scenario	Damages	Transition to steady-state growth path		Steady-state growth path	
		Growth rate of output	Level of per capita output	Growth rate of output	Level of per capita output
S1. BAU w/o climate change	no UD	g_T ($g_T > g$)	$y_T < y$	$g > g_{CC}$	$y > y_{CC}$
S2. BAU w/climate change	**w/UD**	$g_{T2} >=< g_T$	$y_{T2} >=< y_T$	$\boldsymbol{g_{CC}}$	$\boldsymbol{y_{CC}}$
S3. w/CC: RA+RUD$_3$	RUD$_3$<UD	$g_{T3} >=< g_{T2}$	$y_{T3} >=< y_{T2}$	$g_3 > g_{CC}$	$y_3 > y_{CC}$
S4.w/CC: M+PA+RA+RUD$_4$	RUD$_4$<RUD$_3$	$g_{T4} >=< g_{T3}$	$y_{T4} >=< y_{T3}$	$g_4 > g_3$	$y_4 > y_3$

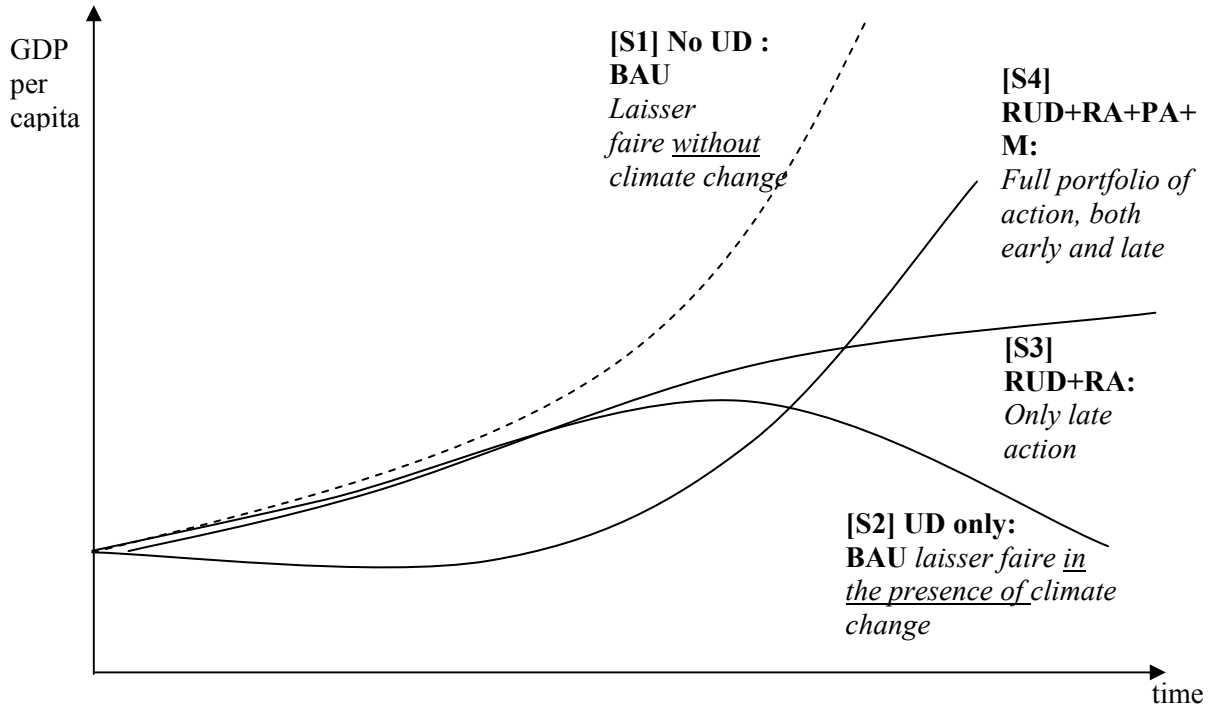
As a result, policy action—if correctly chosen—will bring a benefit relative to the *laisser faire* scenario where full damages are incurred (S3 and S4 versus S2). This point may seem trivial, but is important because climate change models often lack an explicit representation of damages and thus compute *gross* costs of mitigation (i.e., without taking avoided damages into account), as if climate policies were imposed on a World in which climate change *does not exist*.[8] Relative to this BAU scenario, policy action will always result in a high cost, but this reference case (S1) does not relate to any real-world situation anymore, since climate change is occurring. In theory, for the purpose of comparing the (net) costs of climate policies, it should not matter whether net costs are computed directly, or whether gross costs are compared with gross benefits. Yet in practice, the message conveyed is different when negative (net) costs or when positive (gross) costs are reported—even when it is explicitly stated that the latter do not include avoided

adaptation leads to the adoption of new crops that are more capital-intensive to produce.

damages.[9] In addition, and more importantly, there is *a priori* no reason why the implications of mitigation (and proactive adaptation) and the implications of remaining ultimate damages (and reactive adaptation) for economic growth should be separable. For example, the prospects for hydro energy, avoided deforestation or biological sequestration through plantations are very different in a world with climate change and in a world without it. Uncertainties on damages explain why gross costs are often used instead of net costs, but it must be made clear that the 'costs' of policy action on growth that are then reported are (i) *not sufficient to choose the best portfolio of policy actions* if they are **not** also complemented with an estimate of avoided impacts of climate change on economic growth, and (ii) that even this comparison is probably not a good proxy for the combined effects of all policy actions and remaining ultimate damages on growth, since it overlooks the linkages between damages and policy actions.

[8] For example, all but one of the thirteen models in Weyant (1999) report gross costs of mitigation only. When the projection period was only 10-20 yrs into the future—at a time when the current effects of climate change were not measurable—this approach may have been acceptable. But even then, it was not appropriate for projection periods of 50-100 yrs into the future. However, today with the growing evidence that climate change is already underway and causing damages, the policy debate relying on a comparison of the gross costs of different strategies is not tenable.
[9] Mohr (1995) discusses the importance of how the results of climate change policies are framed.

Figure 1: **Growth over time in the *laisser faire* BAU cases w/o CC [S1] and w/ CC [S2], with reactive adaptation only [S3], and with the full portfolio of action (reactive adaptation, anticipative adaptation and mitigation) [S4]**



3. Implications of climate change for economic growth within a Cass-Koopmans optimal growth model

The one-sector Cass-Koopmans optimal growth model is the simplest analytical framework to generate insights into how climate change affects the growth process. It also provides the foundation for a wide range of numerical models attempting to compare the costs and benefits of climate mitigation (e.g., Manne and Richels, 1992; Nordhaus, 1993).

3.1. A short presentation of the Cass-Koopmans model

The Cass-Koopmans model (Cass, 1965, Koopmans, 1965) combines the Ramsey approach of intertemporal welfare maximization (Ramsey, 1928) with the Solow-Swan (or neoclassical) production function and factor dynamics (Solow, 1956, Swan, 1956) to describe the optimal economic growth path in a one-sector closed economy. A discrete-time version of the model is

provided here. Let t denote time periods. Let K_t and L_t be capital stock and labor stock at period t, and let $Y_t = A_t\, F(K_t,L_t)$ be the aggregate output with A_t total factor productivity. A key assumption of the neoclassical Solow-Swan production function $F(.,.)$ is that each factor has decreasing returns when the other is held constant. Output is divided between consumption C and investment I (Eq.1). Investment increases the stock of capital at the next period, while capital depreciation (η) reduces it (Eq.2). Labor stock grows at an exogenous rate g (Eq.3).

$$Y_t = A_t\, F(K_t,L_t) = C_t + I_t \qquad (1)$$

$$K_{t+1} = (1-\eta)K_t + I_t \qquad (2)$$

$$L_{t+1} = L_t\,(1+g)^t \qquad (3)$$

Because the economy in the model is a closed economy without a public sector, investment is assumed equal to savings. Because the marginal productivity of capital stock (K_t) tends to zero for a fixed size labor force (L_t) , growth in an economy modeled by (1-3) can be sustained in the long run only if the labor force grows (i.e., only if the exogenous rate of growth of labor g is strictly positive)—absent technical change. In this case, Solow and Swan show that when the rate of savings (s)—i.e., the investment to output ratio I_t/Y_t is held constant, the economy converges towards a steady-state growth path in which aggregate output, aggregate consumption, and aggregate capital stock all grow at the same rate as the labor force—in other words, in which (k) the capital to labor (capital per worker) and (c) the consumption to labor (consumption per worker)[10] ratios are constant. The only possibility for consumption to labor to keep growing in the long run is if exogenous technical change is assumed (see below).[11]

Cass and Koopmans examine model (1-3) from the perspective of a social planner who maximizes an intertemporal welfare maximization W—assumed utilitarian (Eq.4, with U the

[10] Consumption per worker and consumption per capita (as a proxy for individual welfare) will be equal if the labor force is equal to the population. Otherwise, consumption per capita will be a fraction of the consumption per worker, with the fraction being defined as the ratio of the labor force to the population..

[11] Exogenous technical change is also the only solution for aggregate output to grow in the long run when labor stabilizes or declines. In fact, demographic history suggests that population (and thus labor) grows significantly only in the transition between high-birthrate, high-mortality and low-birthrate, low-mortality states—because the decline in birthrate usually lags the decline in mortality. When the transition is completed, population tends to stabilize.

individual utility functions at each generation—assumed identical—, and δ the pure rate of time preference).

$$\text{Max}_{\{C_t\}} W = \sum_{t=1}^{\infty} \frac{U(C_t)}{(1+\delta)^t} \tag{4}$$

The rationale for looking at optimal growth instead of studying the dynamics of model (1-3) with *ad hoc* savings rule is twofold. First, from an analytical point of view, it allows one to understand how climate change affects the best (i.e., welfare-maximizing) achievable growth path. Second, optimal growth theory provides normative insights on how savings should be adjusted to maximize welfare when climate change is taken into account. This is consistent with the ultimate goal of the research within which this paper takes place, i.e. to provide policy insights for adjusting development strategies in the context of the emerging risk of climate change. However, strong assumptions are required about the welfare function. Since the construction of a welfare function is fraught with uncertainties and controversies, for example on the value of the pure rate of time preference, we try and distinguish between the results presented below which depend on the welfare function and those that do not.[12]

In the Cass-Koopmans model, *regardless of the initial capital and labor endowments*, optimal investment (i.e. optimal savings) decisions make the economy converge[13] towards a unique optimal (i.e., welfare maximizing) steady-state growth path where aggregate output, aggregate capital and aggregate consumption all grow at the same rate as labor g—and thus where capital to labor and consumption to labor ratios are constant.[14] It is only in the transition path from the initial to the optimal capital to labor ratio aggregate output grows at a faster rate than the rate of growth of labor. In the steady-state growth path, aggregate output grows at the same rate as the labor force. If the labor force grows at the same rate as population—i.e., if g is the rate of population growth—then aggregate output per capita is stable in the steady-state growth path. But if labor force grows at a faster rate than population because of changes in *participation rates*—i.e., proportion of the population that is working—i.e., if g is higher than the rate of growth of

[12] In the CK model, as in the other models, we examine here, the planner is assumed to have perfect foresight about the future (or about the distribution of possible futures when uncertainty is introduced). We do not build in actors and individuals' expectations. But this could be a direction for future work.
[13] This property is the basis for subsequent analysis of convergence between economies within and across countries.
[14] The same steady-state already exists in the Solow-Swan model.

population—then aggregate output per capita will continue to grow in the steady-state growth path. A key property of the Cass-Koopmans model is that the optimal savings rate automatically adjusts to compensate for positive or negative shocks, steering the economy back towards the optimal steady-state growth path.

Along the optimal steady-state growth path without technical change, the levels of the capital to labor and consumption to labor ratios vary depending on structural characteristics of the economy. For example, if the production function F is Cobb-Douglas $Y = A\ K^{\alpha}\ L^{1-\alpha}$ with α the elasticity of output with respect to capital and A_t is constant, and if the utility function is logarithmic, the steady-state saving rate s (Eq.5), the steady-state capital to labor ratio k (Eq.6) and the steady-state consumption to labor ratio c (Eq.7) are entirely characterized by parameters (α, g, η, δ, A), as follows:[15]

$$s = \frac{\alpha}{1 + \frac{\delta}{\eta + g}} \tag{5}$$

$$k = \frac{K}{L} = \left(\frac{A\alpha}{\eta + g + \delta} \right)^{\frac{1}{1-\alpha}} \tag{6}$$

$$c = A\ k^{\alpha}\ (1\text{-}s) \tag{7}$$

Technical change can be introduced in the CK model in three ways: as increasing labor productivity only (Harrod neutrality), capital productivity only (Solow neutrality) or as increasing total factor productivity (Hicks neutrality). In the general case, only CK models with Harrod-neutral autonomous technical change exhibit a steady-state growth path (Barro and Sala-i-Martin, 2003), while models with Solow- or Hicks-neutral autonomous technical change do not. When the production function is assumed Cobb-Douglas, however, all three forms of autonomous technical change are equivalent. Let us, for example, assume Harrod-neutral Cobb-Douglas such that the productivity of labor stock increases at a rate h. The model with Harrod-neutral technical change can be solved as the model (1)-(3) by using a measure of labor in efficiency units

[15] See, e.g., Lecocq (2000), Chapter 5 for a demonstration of these classic results.

($\underline{L} = L(1+h)^t$) instead of a measure of labor in number of working days. In the equivalents of equations (5)-(7), where g is replaced with $g+h$, it is now the ratios between capital and labor measured in efficiency unit $K/\underline{L}$ and the ratios between consumption and labor measured in efficiency units $C/\underline{L}$ that are constant. On the other hand, the capital to labor *stock* and the consumption to labor *stock* ratios k and c are no longer constant with technical change, they are growing at rate h along the steady-state growth path.

We now analyze how the components of the climate change bill affect growth *via* the two main routes identified in section 2.3 above, namely factors of production (in section 3.2) and additional expenditures (in section 3.3). When the quality of the environment is added to consumption as a determinant of individual utility, the Cass-Koopmans model also allows one to discuss how ultimate damages may affect utility directly (3.4). In each case, the Cass-Koopmans model allows one to discuss consequences for long-term, steady-state growth—namely steady state capital/labor ratios and savings rates—and the optimal transitional dynamics of the economy towards the steady state.

3.2. The implications of climate-change induced impacts on production factors can be significant in a Cass-Koopmans model

Through both shocks and gradual changes, climate change is likely to cause damages that will affect capital and labor directly. The policy components of the climate bill (mitigation, proactive adaptation and reactive adaptation) may also affect factors and factor productivity at the margin.

Impacts on Stock and Productivity of capital (*K*)

One-off diminutions of the *stock* of capital, resulting from, e.g., destruction of factories, farms and buildings with cyclones or sea-surges, will affect the savings rate and the rate of growth of aggregate output in the short-run, but not in the long-run since the characteristics of the optimal steady-state growth path do not depend on the history of capital stock. Following the sudden capital depletion and resulting decrease in consumption, it is optimal for the economy to increase its savings rate—and thus temporarily increase the growth rate of aggregate output—until the steady-state capital/labor ratio is reached.

Repeated shocks on the stock of capital (e.g., because of an increase in the frequency of extreme weather events) will each generate a short-term transition, the repetition of which can be modeled as an increase in the capital depreciation rate η. As a result, the steady-state savings rate

increases, the steady-state capital to labor ratio decreases, and the steady-state consumption to labor decreases.[16]

Temporary changes in the *productivity* of capital—for example, if climate change temporarily reduces water availability in a dam and thus reduces power generation capacity for the same stock of capital—[17] do not affect the steady-state growth path (same argument as for one-off depletion of capital stock above). Whereas a permanent decline in the productivity of capital leads to a lower steady-state savings rate, a lower capital to labor ratio, and usually a lower consumption to labor ratio—as can be seen from equations (5)-(7) when changes in the productivity of capital are modeled as a diminution of the share of capital in the production function α.[18]

Finally, sustained impacts of climate change may modify the rate of autonomous technical change embedded in capital, either negatively (e.g., because resources are drawn away from R&D expenditures) or positively (e.g., because replacement of damaged capital stock increases penetration of new technologies). Since the rate of growth of the aggregate output along the steady-state growth path is equal to the rate of technical change plus the rate of growth of labor stock, any effect of climate change on the rate of autonomous technical change has a direct effect on the rate of growth along the steady-state growth path.

Stock, productivity and growth rate of labor (*L*)

Temporary changes in the *stock* and/or the growth rate of labor—for example, if deaths caused by the impacts of climate change reduce the amount of workers in the economy (e.g. due to an increase in deadly diseases, such as malaria)—have both a short-term effect on the transitional path towards the optimal steady-state growth path, and a long-term effect on the optimal steady-state growth path, even if the rate of growth of labor g returns to its pre-shock level in the long-run. The rationale is as follows: the optimal steady-state capital to labor ratio is not modified by temporary diminutions in the rate of growth of labor. At any point in time after this temporary diminution, however, the *level* of population is lower relative to what would have happened in the absence of the impact. To keep the capital to labor ratio constant, the aggregate level of capital at

[16] As can be seen easily by taking the derivatives of equations (5), (6) and (7) with regard to η.
[17] This example about the dam implicitly assumes a multi-sector economy. It still applies in the context of the one-sector Cass-Koopmans model, since the single productive sector can be interpreted as the aggregate behavior of a black box consisting of several sectors whose interactions cannot be observed or are not modeled.
[18] The variations of c with regard to α are computed in the Appendix.

steady-state must also be lower than it would have been in the absence of the temporary diminution of the rate of growth of labor.[19]

A permanent decrease in the rate of growth of labor g will result in a higher steady-state capital to labor ratio, a higher steady-state consumption to labor ratio, and a lower steady-state savings rate. It will also lead to a steady-state rate of growth of gross output (precisely equal to g) lower than it would have been otherwise.[20]

Temporary changes in the *productivity* of labor—e.g., if an increase in the prevalence of vector-borne disease reduces the average annual amount of labor that individuals can provide—do not affect the long-run equilibrium growth path. Whereas a permanent decline in the productivity of labor leads to a higher steady-state savings rate, a higher capital to labor ratio, and a higher consumption to labor ratio—as can be seen from equations (5)-(7) when a decline in the productivity of labor is modeled as an increase of the share of capital in the production function α.

Finally, climate change may also induce a permanent decrease in the autonomous rate of technical change of the productivity of labor, for example if repeated impacts on population disrupt education efforts. In this case, the rate of growth of aggregate output along the steady state growth path would also diminish.

3.3. The implications of policy or climate-change induced modifications of expenditures for growth are limited in a Cass-Koopmans model

Mitigation policies will generate expenditures, which are usually modeled by adding a drawdown $\boldsymbol{D_t}$ on the expenditure/consumption side of the output – expenditure balance (Eq.8).[21] Policies favoring reactive adaptation and proactive adaptation will also result in expenditures that can be modeled the same way (though most economic models of climate change do not include adaptation as a policy variable). The fact that we examine here one common channel by which adaptation and mitigation may affect growth (namely, additional expenditures) should not be understood to imply that adaptation and mitigation policies do affect growth the same way. In

[19] In other words, diminution in population cannot generate an increase in consumption per capita in the Cass-Koopmans model because ultimately aggregate consumption diminishes by the same percentage.
[20] As can be seen by taking the derivatives of equations (5) to (7) with regard to g.
[21] As noted in section 2.2, remaining ultimate damages may also have an expenditure component (as in Manne and Richels, 1992) due to, e.g., relocation costs. The brunt of the remaining ultimate damages though are likely to affect factors directly.

fact, policies that promote mitigation and adaptation are different, and they are likely to have different implications for economic growth, if only because their implications for the residual ultimate damages of climate change differ (as modeled in e.g., Lecocq and Shalizi, 2007).

$$Y_t = F(K_t,L_t) = C_t+I_t+\boldsymbol{D_t} \qquad (8)$$

Introducing additional expenditures has the following implications in a Cass-Koopmans model. First, temporary changes in expenditures imply no change in the growth rate of aggregate output g or in the composition of the steady-state growth path. This is because the steady-state growth path depends only on the fundamentals of the economy.

Second, permanent changes in expenditures, *if they are independent of the level of production Y*—e.g., if $\boldsymbol{D}$ converges towards a constant $\boldsymbol{D_\infty}$ strictly positive—do not affect the steady-state growth path either. This is because, in the long-run, output dwarfs drawdowns. The transition path back to the steady state, however, will be much longer than with temporary drawdowns.

Third, permanent changes in expenditures, *if they are dependent on the level of production Y*—i.e., if they amount to a loss of global productivity of the economy—affect both the transition to and the composition of the steady-state growth path. In that case, equation 8 can be rewritten as (9) below, where $\boldsymbol{\Omega_t} = 1- \boldsymbol{D_t}/Y_t$ translates the diminution of total factor productivity of the economy induced by climate change.[22]

$$Y_t = \boldsymbol{\Omega_t}\, F(K_t,L_t) = C_t+I_t \qquad (9)$$

If $\boldsymbol{\Omega}$ converges towards a constant $\boldsymbol{\Omega_\infty}$ lower than unity, the optimal steady-state capital to labor and consumption to labor ratios are reduced—though the optimal steady-state savings rate remains constant.[23]

It is also important that because production in the Cass-Koopmans model is assumed to be at the frontier, and because—in a one-sector model—there is no mechanism whereby decreased production of resources in one part of the economy can be compensated by additional production of resources in another, any positive drawdown $\boldsymbol{D}$ (or any total factor productivity correction $\boldsymbol{\Omega}$

[22] Remaining ultimate damages have also be represented this way as in, e.g., the DICE model (Nordhaus, 1993).
[23] As can be seen by deriving equations (5) – (7) with regard to A.

lower than unity) results in a lower consumption to labor ratio than would have happened in the absence of drawdown or factor productivity correction (this might, of course, be compensated by lower damages in the future). In other words, the Cass-Koopmans model does not allow negative gross costs of mitigation (the so-called 'win-win' mitigation policies).

3.4. A modified version of the Cass-Koopmans model allows one to discuss the consequences of ultimate damages for economic growth *via* individuals' utility functions

Climate change will also have non-market impacts, both through the disappearance or transformation of pure final goods, and through the disappearance or transformation of joint goods (i.e., those that are both inputs into the production of consumer goods and directly factored into individuals' utility functions). One example of climate change's effect on pure final goods is the disappearance of culturally significant sceneries[24], landscapes, or biodiversity. One example of climate change's effect on a joint good is the retreat of glaciers in mountain regions, which simultaneously affects irrigation and/or electricity generation—a production function effect—, and changes vistas—a component of an individual's well-being.

Non-market effects of climate change are usually captured by making individual utility functions dependent on both consumption and the quality of the environment $\boldsymbol{e}$. Technically, utility functions are written as $U = U(c,\boldsymbol{e})$ with U increasing in $\boldsymbol{e}$.

How is the optimal growth path of consumption affected if the quality of the environment decreases with climate change? Adding an exogenously decreasing quality of the environment e in the utility function does not modify the optimal growth path if the marginal utility of consumption is *independent* of the quality of the environment—i.e., if $\frac{\partial^2 U}{\partial c \partial e} = 0$. But if the marginal utility of consumption decreases when the quality of the environment decreases (i.e., when c and e are *complements*, $\frac{\partial^2 U}{\partial c \partial e} > 0$), then introducing $\boldsymbol{e}$ in the utility function is equivalent

[24] See e.g., Laplante et al. (2005), who show how the preservation of Lake Sevan—an iconic place in Armenian history and culture—is highly valued by Armenians, both within the country and abroad.

to increasing the rate of pure time preference.[25] As a result, the faster the environment degrades, the lower the steady-state savings rate, the lower the steady-state capital to labor ratio and the lower the steady-state consumption to labor ratio.[26] Conversely, if the marginal utility of consumption increases as the quality of the environment decreases ($\frac{\partial^2 U}{\partial c \partial e} < 0$, i.e., they are *substitutes*), then the steady-state savings rate needs to increase, as does the steady-state capital to labor ratio.

Another implication of this model is that, because $\boldsymbol{e}$ is assumed to become scarcer over time relative to c, the rate of discount that should apply to projects that drawdown consumption now (c_t) to improve the quality of the environment later (e_{t+1}) (e.g., mitigation) is lower than the rate of discount that should apply to projects that draw on consumption now (c_t) to improve consumption in the future (c_{t+1}) (see Guesnerie, 2004, for an extensive treatment with a constant elasticity of substitution utility function). Substitutability between c and e is a key parameter in determining this wedge (Neumayer, 1999).

Table 2 summarizes the different channels by which components of the climate change bill may affect economic growth (both transitional and long term) within a Cass-Koopmans model. A key finding is that additional expenditures (caused by mitigation, proactive adaptation, reactive adaptation have limited effects on the steady-state growth path, unless those additional expenditures grow with output, in which case the total factor productivity of the economy decreases. On the other hand, permanent changes in the productivity, stock or depreciation rate of capital, as well as both permanent and temporary changes in the stock and growth rate of labor (caused by ultimate damages for the most part) do affect the characteristics of the long-term steady-state growth path.[27]

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[25] In this case, for any given level of consumption, the marginal utility of consumption is decreasing with e. Since e is decreasing over time, the marginal utility of consumption is also decreasing over time. Independently, the same amount of marginal utility of consumption has a decreasing value in the intertemporal welfare function (Eq.1) because of the pure rate of time preference. The decreasing quality of the environment and the pure rate of time preference thus combine to reduce the weight of the marginal utility of consumption in the intertemporal welfare function.

[26] When $\frac{\partial^2 U}{\partial c \partial e} > 0$, a degrading $\boldsymbol{e}$ is equivalent to an increase in the pure rate of time preference. For example, if $U(c,\boldsymbol{e}) = \boldsymbol{e} \ln(c)$, and if $\boldsymbol{e}$ is assumed to degrade at a constant rate h over time with climate change, then it is as if the rate of pure time preference increased from δ to $\delta+h$). The implications for the steady-state growth path follow from equations (6) and (7). Derivations of the derivative of c with regard to δ is provided in the Appendix.

[27] The analysis summarized in table 2 is based on a Cobb-Douglas production function. More work is required to determine the extent to which these results extend to other formulations of the production function as well.

Table 2. Summary of the consequences of the components of the climate change bill for economic growth in a Cass-Koopmans model

Cause	Implications for the transition to steady-state growth	Implications for the optimal steady-state growth path			
		K/L ratio ***k***	*I/Y (savings rate* ***s****)*	*C/L ratio* ***c***	*Growth rate of output*[28]
(1) Effect on production factors (mostly through UD or RUD)					
One off diminution of the stock of capital *K*	Temporary increase in savings and in growth rate of output	=			
Repeated shocks on capital stock *K*	Increase in savings and in growth rate of output	-	+	-	=
Temporary diminution in productivity of capital *K*		=			
Permanent diminution of productivity of capital *K*	Decrease in savings rate and in growth rate of output	-	-	-[29]	=
Climate change induced decrease in autonomous technical change of capital productivity		-	-	+	-
Temporary diminution in productivity of labor *L*		=			
Permanent diminution in productivity of labor *L*		+	+	+	=
Temporary change in the stock or growth rate of labor *L*		= (though *K* is higher)			
Permanent decline in the growth rate of labor *L*		+	-	+	-
Climate change induced decrease in autonomous technical change of labor productivity		-	-	+	-
(2) Effect of additional expenditures (policy components of the climate bill)					
Temporary increase in expenditures *D*		=			
Permanent increase in expenditures *D*—independent of *Y*	Longer transition to steady-state	=			
Permanent increase in expenditures D—dependent on *Y*		-	=	-	=
(3) Direct CC impacts on utility					
Ultimate damages on the environment reduce *e* when utility function is *U*(*c*,*e*)—*e* exogenous		**-**	**-**	**-**[30]	**=**

[28] *g* when there is no technical change, and *g*+*h* when technical change is taken into account.
[29] In most cases.

4. Limitations of the Cass-Koopmans model, and a roadmap for improving analysis of the consequences of the climate change bill for economic growth

The Cass-Koopmans model provides an integrated framework for discussing the implications of climate change for economic growth. However, the Cass-Koopmans model is often at odds with empirics. In fact, empirical studies consistently suggest that factor accumulation explains no more than half of observed growth rates—particularly in developing countries (section 4.1). Variations in total factor productivity (TFP) that cannot be explained within the Cass-Koopmans framework account for the other half.

Empirical studies identify determinants of TFP variations. Though there is no consensus on the relative importance of these determinants, or even on the list of determinants itself, these studies point to important characteristics of the growth process that are intuitively relevant for the impacts of climate change, and that are not taken into account in the Cass-Koopmans model. These findings provide a roadmap for the rest of the paper (section 4.2).

4.1. Empirical studies demonstrate that growth is not just factor accumulation

The Solow Swan production function which underpins the Cass-Koopmans' optimal growth model is the simplest theoretical framework that can be used for empirical growth accounting exercises, as it allows the growth rate of aggregate output to be decomposed into the growth rate of factor inputs and technology. In the formulation in equation (1),

$$Y(t) = A(t)\, F(K(t),L(t)) \qquad (10)$$

The expression $A(t)$ represents the level of technology which in the empirical literature is referred to as **total factor productivity** (TFP). The growth rate of aggregate output can then be expressed as:

$$\frac{\dot{Y}}{Y} = \frac{\dot{A}}{A} + \frac{A\frac{\partial F}{\partial K}\dot{K}}{Y} + \frac{A\frac{\partial F}{\partial L}\dot{L}}{Y} \qquad (11)$$

[30] *ibid*

Assuming competitive factor markets, the marginal product of capital is equal to the rate of return r and the marginal product of labor is equal to the wage rate w. Assuming constant returns to scale, the contribution of the growth rate of capital to the growth rate of output can be expressed as α and that of the growth rate of labor as 1-α. In other words, the growth rate of output can be expressed as the weighted average of the growth rates of the input factors (with the weights representing their relative shares in the aggregate output)[31] and of the growth rate of total factor productivity $\dot{A}/A$.

With data on the quantity of output and factor inputs, as well as on factor prices, it is possible to compute the respective growth rates of output, capital and labor, and factor shares of capital and labor. The only unmeasured term would be total factor productivity. But the growth rate of the latter can be expressed as a residual:

$$\frac{\dot{A}}{A} = \frac{\dot{Y}}{Y} - \alpha(t)\frac{\dot{K}}{K} - (1-\alpha(t))\frac{\dot{L}}{L} \qquad (12)$$

Using the log form of the variables, the residual in equation (12) is estimated in the growth accounting literature. A key finding of this literature is that factor accumulation explains only part, typically half or less than half, of observed economic growth rates. This finding holds both when looking at panel data for a given country, and when comparing growth rates across countries globally (e.g., Easterly and Levine, 2001), or in a region, such as Africa (e.g. O'Connell and Ndulu, 2000).[32] In other words, differences in output levels cannot be explained only by differences in factor input levels. Similarly, differences in output growth rates cannot be explained only by differences in factor input growth rates. Total factor productivity (TFP) matters.

[31] For derivations see Solow (1956) or Barro and Sala-i-Martin (2003). This basic model with a Cobb-Douglas production function with constant returns to scale can easily be augmented to include human capital (H) with share (β) as a separate explanatory variable as has been done by Mankiw, Romer and Weil (1992).

[32] Unlike in Asia, the Middle East or in developed countries, the residual in Sub Saharan Africa is on average negative: i.e. the growth rate as predicted by factor accumulation alone should be significantly higher than observed growth rates (O'Connell and Ndulu, 2000).

Beyond this finding, empirical results are not as robust.[33] Theory-based growth accounting treats the residual or TFP as a measure of our ignorance. Little progress has been made in identifying determinants of TFP growth rates using growth accounting techniques. Instead, growth regressions are used to tease out the determinants of TFP growth using cross-country variations in TFP growth rates over time and space, based on more informal or *ad hoc* models of growth. Unlike growth accounting, growth regressions estimate the parameters of the production function rather than imposing them as is done when constant returns Cobb-Douglas production functions are assumed.

The critique of the growth regression literature has focused primarily on data and methodological shortcomings (Temple, 1999).[34] And no empirical (or for that matter theoretical) consensus has emerged on the determinants of TFP growth. Different studies use different variables and data, and it is not easy to compare results or choose the relative importance of the different variables (Levine and Renelt, 1992). This has led to uncertainty on the choice of model. "Many variables have been found to be significant in growth regressions; nearly as many have been found to be 'fragile', in the sense that their statistical significance disappears when a different group of right-hand side variables selected" (Temple, 1999).

Nonetheless, the empirical findings have highlighted certain stylized facts—particularly for developing countries—that suggest the explanatory power of existing theoretical models (Cass-Koopmans or extended versions) is still limited. The following sets of drivers are recognized as playing an important role in total factor productivity growth:

- Policy and institutional factors: e.g., macroeconomic policy, stabilization policy, property rights, rule of law, etc. (which will translate into, *inter alia*, institutional rigidities)
- Structural factors: e.g., changing shares of the agriculture and industry sectors, degree of openness of the economy, etc. (which will translate into, *inter alia*, economic rigidities)
- Geographical factors: e.g., landlocked vs. non landlocked countries, proximity and agglomeration, etc. (which will translate into, *inter alia*, spatial rigidities)
- Shocks, of whatever nature (terms of trade, financial crises, and natural hazards,…).

[33] Typically, empirical findings emerge from the use of econometric techniques that rely on *ad hoc* models of growth. Some of these are reduced form versions of theoretical models, but many introduce additional variables that are not explicitly grounded in theoretical models. Because these findings are from reduced-form estimates rather than from structural equation estimates, it is more difficult to identify the strength of the different channels through which endogenous variables affect growth and hence the ultimate channels through which climate change affects growth.

Among the four sets of determinants outlined above, policies and institutions such as macroeconomic policies (inflation/price stability, exchange rate overvaluation, cyclical volatility, systemic banking crisis), structural policies (human capital/education, physical capital/public infrastructure,…), openness to trade, government size, implementation of anti-corruption laws, or availability of credit have been identified as having a significant impact on growth (Loyaza and Soto, 2002, Aron, 2000). But it is not clear that climate change will make it easier or on the contrary more difficult to adopt them.[35] In any case, the effect of climate change on policy and institutional factors will be indirect.

On the other hand, climate change is likely to have a direct effect on structural factors, geographical factors and shocks.

4.2. A roadmap for the analysis of the consequences of climate change for economic growth beyond the Cass-Koopmans model

The empirical studies discussed in section 4.1 point to three major characteristics of real-world growth processes that (i) are relevant for explaining variations in TFP, (ii) are intuitively relevant for the impacts of climate change, but (iii) are not taken into account in the Cass-Koopmans framework.

The first element is a **disaggregated representation of the economy**. The Cass-Koopmans model has only one aggregated sector. Yet as noted above, structural factors can explain variations in TFP. It is also clear that the residual damages of climate change will differ across sectors, notably between sectors that are climate-sensitive and those that are less so. Third, one needs a disaggregated representation of the economy to evaluate the growth implications of possible responses to climate change, such as shifts of economic factors from climate sensitive sectors to the other sectors.

Multi-sector growth models (that remain, for the most part, within the neoclassical growth framework) are discussed in section 5, along with the effects climate change may have in this framework.

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[34] Nonetheless, cross-country regressions using aggregate data are likely to continue to complement historical case studies of growth or a micro database estimation of parameters and factor shares.

[35] Other factors such as the level of foreign investment and aid are also recognized as playing a role (Easterly and Levine, 2001) , but again the influence of climate change on these, if any, is less direct.

The second element is a **better representation of rigidities and transitional dynamics**. As noted in Section 2, the ultimate damages of climate change are likely to result in an increase in the frequency and magnitude of shocks which, in turn, have an implication for TFP. In addition, policy efforts that are concentrated in time—most notably reactive adaptation—may also be akin to shocks. Yet the Cass-Koopmans model is not designed to analyze short-term reactions to shocks because it assumes immediate clearing of all markets without rigidities.[36]

Section 6 discusses how taking rigidities into account modifies the dynamics of economic growth—using 'eclectic' models that are no longer within the strict neoclassical growth framework. It then discusses the potential impacts of future climatic shocks on economic growth based on the empirical literature about past occurrences of such shocks.

The third element is to introduce **increasing returns in production functions**. From a theoretical standpoint, the fact that growth can only be sustained through exogenous population growth and exogenous technical change is a fundamental limitation of the Cass-Koopmans model, and it stems from the diminishing returns assumption in the production function. From an empirical perspective, increasing returns are observed locally in many sectors or regions: for example, correlations between geography and growth are rooted in part on increasing returns to agglomeration.

Section 7 discusses how the consequences of the climate change bill for economic growth may differ when increasing returns are introduced into aggregated models, in endogenous growth models and in poverty trap models. It then examines how the presence of increasing returns at the sectoral level may generate lock-ins and affect the costs of shifting from one growth path to the other (e.g., positively if one can take advantage of increasing returns to reduce the costs of mitigation/adaptation, negatively if one has to get away from an existing lock-in to highly carbon-intensive technologies). Finally, section 7 discusses some implications of geographical increasing returns for the effects of climate change on growth.

[36] A possible explanation for observed growth paths deviating from steady-state growth paths could be that we are observing transitional paths in the Cass Koopmans model, not to the permanent steady-state growth path. But King and Rebelo (1993) find that transitions in optimal economic growth models are short in most cases. Thus, sustained growth dynamics observed in the real-world cannot easily be explained by the transition dynamics of neoclassical growth models.

5. Opening the black box: Consequences of the components of the climate bill for growth when more than one sector and region is considered

In this section, we focus on models with a disaggregated representation of the economy. We start with the Uzawa model, a neoclassical growth model similar to Cass-Koopmans', but with an economy with a consumption and an intermediate or investment good, and then discuss the consequences of the components of the climate change bill for economic growth in models with two (or more) consumption goods, and in models where primary energy is introduced as a separate production factor.

The aggregate representation of the economy in the Cass-Koopmans model does not allow one to capture the underlying structure of the economy, notably differences in technology and differences between intermediate and final goods, and their implications for growth. As a result, multi-sector growth models have been developed, starting with the two-sector neoclassical growth model by Uzawa (1961, 1963). It extends the Solow-Swan growth model by considering both **a consumer good and an investment good** that is entirely invested to generate new capital stock. Both goods are produced with capital and labor, which are assumed to be *perfectly mobile* across sectors. The standard neoclassical assumption that production factors have diminishing returns (in both consumer good and investment good production functions) remains.

In the optimal growth version of the model, the central planner allocates capital and labor across sectors at each period of time to maximize an intertemporal welfare function. Uzawa (1964) demonstrates that for any initial capital / labor ratio, the optimal path converges towards a unique steady-state growth path. In this steady-state growth path, aggregate capital grows at the rate of growth of labor, and the capital/labor ratio is constant in each sector. The overall dynamics of the Uzawa model is thus very similar to the dynamics of the Cass-Koopmans model, except that the path towards steady-state differs sharply depending on whether it is the investment good or the consumption goods that is more capital-intensive.

The implications of shocks on production factors and of increases in expenditures on economic growth, thus, have similar implications for long-term aggregate growth in the Uzawa model and in the Cass Koopmans model. A key difference, however, is that impacts or shocks on one sector propagate to the other. Let us assume, for example, that climate change results in a decrease of total factor productivity in the consumption goods sector—for example, if the consumption goods sector is interpreted as agriculture. As a result, more factors (capital and

labor) are required to produce the same amount of the consumer good. Given decreasing returns to production factors in both sectors, the new steady-state growth path will necessarily have a lower consumption per capita than without the decrease in productivity in the consumption goods sector. Full factor mobility, on the other hand, ensures that the transition towards the new optimal growth path is immediate, and that there is no supplemental loss in the transition. A similar result would be obtained for changes in the total factor productivity of the investment sector. Finally, since the relative capital intensity in the two sectors is a major determinant of the transitional path towards the steady state, a climate-change induced modification of the marginal productivity of factors may have significant implications for the transitional growth path if it triggers an inversion of the relative capital intensity in the two sectors.

When **two consumption goods** are introduced in the neoclassical framework—for example to analyze the relationships between economic growth and international trade (e.g., Brecher et al., 2005)—there still exists a steady-state growth path where aggregate capital in both sectors and aggregate consumption increase at the same rate. In such a model, a climate-induced decline in the productivity of one sector necessarily leads to a decrease in global welfare. Because of the diminishing returns assumption to factors in all production functions, the reallocation of capital and labor across sectors—even if instantaneous and frictionless—cannot compensate for the productivity decline. Growth models with more than two sectors exhibit complex dynamics that do not necessarily yield steady-states (e.g., Gale, 1967, Scheinkman, 1976), but as long as decreasing returns and factor mobility remain, shocks on the productivity of one sector cannot be offset or compensated for by the other.[37]

A third class of disaggregated growth models of particular relevance to the present analysis are the models where **energy is explicitly introduced as an intermediate good**. Initially developed after the first oil shock to evaluate how an increase in energy prices might affect growth (e.g., Hudson and Jorgenson, 1974), these models form the basis of most of the numerical analysis of the costs of mitigation policies (Table 3). The modeling framework is usually a multi-sector, computable general equilibrium model with so-called KLEM production functions (capital, labor, energy, manufacturing)—the factor energy being itself a composite good combining the output from several sub-sectors (such as coal, oil, gas, nuclear, etc.)—with an aggregate growth equation

[37] If there are barriers to factor mobility; and if these barriers are reduced because of a climate-change induced shock, there may be positive implications for intertemporal welfare—but these gains are related to the lifting of the barriers, not to the climate induced shocks themselves.

attached to it. Given the large number of sectors involved and the policy oriented application of this research, these models are solved numerically.

A key determinant of the modeling results is the degree of substitutability between energy and capital. Estimating elasticities of substitution is difficult because energy usually represents a small share of total factor costs, and because short-run and long-run elasticities differ. Econometric estimates show both complementarity and substitutability—though there are reasons to believe that there is overall substitutability at the global level (Thompson and Taylor, 1995).

Using these models, the IPCC (Barker et al., 2007) reports relatively modest median reductions in average World Gross Product growth rates over the next decades (0.12 percentage point below baseline each year over the next 50 years for stabilization objectives of 445-535 ppm), though the range of modeling results is large.[38] The treatment of substitution between energy and capital in each model, and thus the underlying assumptions about malleability of capital, along with underlying assumptions about technical change, seem to account for a major part of observed differences in modeling results (Fischer and Morgenstern, 2006, make this point in a meta-analysis of modeling results—though focused on carbon prices, not on growth rates *per se*).

The previous discussion raises a general methodological point of the paper. We assume that the results of numerical models that assess climate policies are driven largely by the structure of the underlying growth model. In fact, by showing how different classes of growth models do or do not capture key empirical features of economic growth (e.g., role of shocks, etc.), the paper partially vindicates this assumption. However, it remains unclear how the dynamics of numerical models depend on specific assumptions within broad model classes. In addition, in the absence of careful 'controlled experiments', it is often unclear to what extent published results of models depend on the values assumed for parameters / scenarios, and to what extent they depend on structural features of the growth engine. In fact, even the best reviews of models report only on costs, without analyzing in depth the structural equations that may underpin differences across models (e.g., Weyant, 1999). The complexity of the numerical models and the difficulty of setting up proper comparisons make these exercises difficult—*yet they are very important for policy purposes*, as illustrated by the following two examples.

[38] These figures are reported against a counterfactual with no damage which, as noted above, is not sufficient to rank policy options and may lead to biased estimates of impacts on economic growth (see discussion in Section 2.3) <<which we have stated is not policy relevant. Should that point be restated here again?>>.

First, Shelby et al. (2006) compare the mitigation costs in the electricity sector in the U.S. for two computable general equilibrium models. They find that different representations of how decisions regarding renewable energy technologies are made lead to major differences in modeling results regarding not only the behavior of fuel markets, but also in the behavior economy-wide variables such as investment and total output. Similarly, the IMACLIM-R model (Crassous et al., 2006) shows that mitigation policies have relatively low effects on GDP growth rates when there are no rigidities in relevant energy markets, but somewhat higher effects when there are rigidities. In both cases, the consequences for growth are minimal compared to other climate change models that do not incorporate 'learning by doing' and the rapid decline in the cost of alternate technologies (Shalizi, 2007). More work is thus required to understand how the structure of the models drives results.

To sum up, growth models with two or more sectors thus provide some insights on the economy-wide implications of impacts of climate change on sub-sectors of the economy. They confirm the intuition that climate change-induced changes in the structure of steady-state growth in one sector will translate into changes in the structure of steady-state growth in the other sector and, in turn, on the structure of steady-state growth in the whole economy.[39] The models also underline the importance of factor mobility (capital and labor) across sectors as a key determinant of the ability of the economy as a whole to adjust to the impacts of climate change (see Section 6 for further discussion on shocks). The Uzawa type theoretical models, however, assume decreasing returns to scale in all sectors. As a result, costs in one sector cannot be fully offset by benefits in another. To allow costs in one sector to be offset by benefits in another, models with increasing returns to scale in some sectors are necessary (see section 7).

[39] This is because the sectors cannot be insulated from each other— a point that is easier to illustrate when direct and indirect linkages between sectors is explicitly modeled in a full input output structure as is often used in multisector simulation models.

Table 3: Sample of numerical climate change models and their theoretical underpinnings in growth theory

Model Name	Type	Theoretical underpinning	Regions	Sectors	Technical change	Mitigation (M)	Anticipative adaptation (PA)	Reactive adaptation (RA)	Damages (UD / RUD)	Note
MERGE[b]	Cost-benefit	Multi-region neoclassical growth model	multi	multi	exogenous	x			x	
DICE[a]	Cost-benefit	Cass-Koopmans	1	1	exogenous	x			x	
RICE[c]	Cost-benefit	Multi-region neoclassical growth model	multi	1	exogenous	x			x	Derived from DICE
ENTICE[d]	Cost-benefit	Endogenous growth model	single	1	endogenous	x			x	Derived from DICE
EPPA[e]	Cost-efficiency	Recursive dynamic CGE model	multi	multi	exogenous	x				
AIM[f]	Cost-efficiency	Recursive dynamic CGE model	multi	multi	exogenous	x				
G-Cubed[i]	Cost-efficiency	Recursive dynamic CGE model	multi	multi	exogenous	x				Explicitly represents exchange rates
IMACLIM-R[g]	Cost-efficiency	Dynamic CGE modeling	multi	multi	endogenous	x				Structure of economy endogenous *via* changes in productivity
NEDyM[h]	Damage analysis	Keynesian short-term dynamics,	1	1	exogenous				x	

Source: (a) Nordhaus (1993), (b) Manne and Richels (1992), (c) Nordhaus and Yang (1996), (d) Popp (2004), (e) Paltsev et al. (2005), (f) Matsuoka et al. (1995), (g) Crassous et al., 2006, (h) Hallegatte et al. (2007), (i) McKibbin and Wilcoxen (1999).

6. Focusing on the transition to steady-state: Consequences of the components of the climate bill for growth when the interaction between shocks and rigidities are taken into account

The models described so far have focused on long-term steady-state growth paths and rested on the assumption that there were no rigidities in prices or in factor allocation across sectors. As a result, readjustments to a new optimal growth path after perturbations are instantaneous and costless. For shorter horizons in terms of the climate change problem (a decade or two), however, growth models need to take into account the significant rigidities in prices and factor allocations observed in practice due to, *inter alia*, non-malleability of capital stock, institutional rigidities/persistence of transaction costs, inability to compensate losers, especially among the Poor, entrenched interests, etc. Even when a few rigidities are introduced in simple growth models, their behavior is significantly altered. For example, Ryder (1969) demonstrates that in a vintage version of the Uzawa model where new capital is assigned once and for all to a sector, the optimal path towards steady-state is much more complex as capital reallocation across sectors can only occur at the margin. In such a model, it is likely that readjustment from one steady-state to another following a climate-change induced shock on capital stock or capital productivity would prove more difficult as well.

The main question for the present paper is to understand how climate-change induced shocks may effect economic growth not just in the long-term, but also in the medium- and short-term. As noted in section 2, ultimate damages and reactive adaptation policies are likely to produce shocks, especially in the case of specific/sudden events associated with climate change. However, mitigation and proactive adaptation may also occasionally involve concentrated efforts akin to shocks. The empirical literature on growth provides findings that are directly applicable to this question. The central message of this literature is that observed costs of shocks for growth are rather high. By implication, the potential costs of climate-change related extreme weather events in the future might also be important.

A large empirical literature demonstrates that shocks—arising from sudden changes in commodity prices/terms of trade shocks, financial crises, and/or natural hazards/climate events—lead to volatility in growth and play a significant role in explaining cross-country economic performances (e.g., Easterly et al., 1993, Collier and Dehn, 2001). The drivers of vulnerability to

shocks include the structure of the economy, presence of rigidities in markets or other institutions. However, there is no consensus on the relative ranking of these drivers.

Developing countries often draw a large share of their GDP from agriculture and tourism, two sectors strongly dependent on climate, and often rely heavily on the export of a handful of primary commodities. These countries are thus particularly vulnerable to natural disasters and to commodity price shocks. For example, the IMF (2003) finds that large-scale natural disasters have occurred on average once every 20 years in LDCs over the 1977-2001 period, with an average impact on GDP ranging from -2.7% to -5.8% in the most recent (1997-2001) period—during which the highest number of disasters also occurred. This study also notes that the impact of shocks on income and growth can be very significant, particularly if part of the infrastructure is destroyed and/or if the shock is long-lasting.[40] Since climate change may increase the frequency and severity of natural disasters, whether through specific events (cyclones) or through gradual changes in local climate, such as core precipitation patterns,[41] the empirical findings above suggest that climate change could strongly affect growth in developing countries, in the absence of policies to mitigate or adapt in anticipation.

Besides dependency on climate-related sectors, technological and institutional **rigidities**—i.e., unemployment, inventories, or institutional barriers to rapid disbursement of emergency funds—are found to significantly increase the costs of shocks (as well as costs of mitigation / anticipative adaptation) in terms of growth in the short to medium-term. First, price and wage rigidities prevent rapid adaptation. Second, there are generally limitations on the speed at which reconstruction expenditures can be absorbed, as demonstrated in recent events such as the Indian Ocean tsunami.[42] Overall, Hallegatte et al. (2007) estimate that when the pre-existing rigidities and limitations on reconstruction expenditures are taken into account, costs of shocks may

[40] Martin and Bargawi (2004) use this data to project that economic growth in Sub-Saharan Africa countries could be reduced by half between 2004 and 2015 because of shocks (both commodity price shocks and natural disasters), compared with an hypothetical 'without shock' projection.

[41] O'Connel and Ndulu (2000) provide an estimate of the impact of climate shocks on economic growth by regressing growth in real GDP per capita over a set of factors including the average proportion of dry years per half decade (an indicator with strong variation across sub-Saharan Africa countries, ranging from 0.057 in Burundi to 0.665 in Guinea). According to the regression, a 1% increase in the proportion of dry years per half decade could reduce growth by about 0.02% per annum.

[42] For example, UNDP (2006) notes that "a major problem in the [post-tsunami] recovery effort is the time it has taken to provide people with decent housing", because of e.g., delays in getting approvals for projects involving multiple actors and stakeholders This problem is not limited to developing countries as evidenced by hurricane Katrina in the U.S. (e.g., Sobel and Leeson, 2006). Similarly in Europe, in the wake of the 1999 Lothar and Martin storms, loggers suddenly found themselves in short supply and their hourly wage increased ten-fold, thereby both slowing down and increasing the costs of clearing forests.

increase 2-4 fold relative to a model where prices adjust immediately, and where reconstruction expenditures are not limited. Third, the costs of climatic shocks may also be magnified by non-economic institutional factors. For example, Rodrick (1999) finds that countries with weak institutions and divided societies (as measured by indicators of inequality or ethnic fragmentation) face the highest costs of damages.

These costs highlight the possible benefits of ex ante policies (both mitigation and proactive adaptation). What differentiates successful countries (in terms of reducing their per capita GDP gap with industrial countries) from unsuccessful ones is their ability to reduce the volatility of growth. Decisive responses to shocks and reduction of vulnerabilities help reduce the cost of shocks. "Developing countries experience a year of negative per capita growth roughly once every three years–whereas in East Asia, the average is one half that rate and, in OECD countries, one third that rate. The East Asia region's ability to avoid shock induced downturns and periods of low growth explains much of the East Asian "miracle" (Zagha et al. 2006).

7. Incorporating non-convexities: Consequences of the components of the climate bill for growth when increasing returns are (locally) possible

7.1. Implications of climate change for growth in aggregated models with increasing returns

One of the major limitations of the standard neoclassical growth theory in representing empirical findings about real-world processes is the assumption of diminishing returns to each factor when the others are held constant, which makes it impossible for the model to generate long-term growth per capita save for assuming an exogenous driver of total factor productivity, such as technological change. This theoretical deficiency of the Solow model, along with its inability to account for empirical 'stylized facts' about economic growth (cf. Section 4) has spurred the development of a large number of models with increasing returns. One set of models introduce zones of locally increasing returns in the production function of neoclassical growth models—thus generating the possibility of poverty trap dynamics when random shocks are taken into account. A second set of models are endogenous growth models, where increasing returns is explicitly represented at the technology or at the human capital level—thereby generating economic growth endogenously.

Adding increasing returns into the production function of a Cass-Koopmans model and random shocks create the possibility of poverty traps

When increasing returns are introduced into the production function of a neoclassical growth model, the model may exhibit several equilibria at various levels of capital to labor ratio for the same exogenously given growth rate of output. Which equilibrium the model will converge to will depend on the initial level of capital to labor ratio. Within an optimal growth setting, the planner can always put the economy on track to reach the best equilibrium by choosing the optimal level of investment. If, on the other hand, the rate of savings is fixed (or, to provide a politically more realistic assumption—upward bounded), not all equilibria may be accessible and the economy might get locked into a poverty trap (see Azariadis and Stachurski, 2004 for a thorough review).

If, in addition, random shocks on the total factor productivity of the economy are introduced, then it is possible that even countries that are at a high equilibrium will fall into a low equilibrium if they are hit by a large shock.[43] Not only the magnitude of shocks. but also their frequency can play an important role in generating poverty traps.

Traditional growth models, with or without rigidities in price adjustments, predict that shocks (such as those arising from climate change) will have temporary impacts on growth, countries eventually moving back to their pre-shock growth path. But 'poverty trap' models suggest that shocks may also have long-lasting consequences because accelerated shocks and/or higher variance (such as the increased frequency of climate shocks in the form of droughts, floods, cyclones, sea surges, etc.) may reduce the chances that developing countries will grow out of poverty traps, and increase the chances that they will get into such traps if not there already (Azariadis and Stachurski, 2004). Thus, climate change can be expected to push more vulnerable countries into poverty traps causing their growth to decelerate or stagnate, and to increase the probability that they will become long-term dependent on international transfers. [44]

[43] Conversely, by analogy, it is theoretically possible for a country at a low-level equilibrium to get out of a poverty trap if the shock is positive and sufficiently large.

[44] Empirical evidence to date is not conclusive on the existence of poverty traps (Kraay and Raddatz, 2007). For that reasons and also on feasibility grounds, the policy recommendation that stems from poverty trap models—namely providing massive aid to lift countries out of poverty traps—is also controversial.

Implications of climate change for economic growth in endogenous growth models

Two main routes have been explored to endogenise the rate of growth. A first approach is ***to broaden the concept of capital to include human and institutional capital,*** in addition to physical capital, and to assume that diminishing returns do not apply to this wider definition of capital. In such models, as pioneered by Lucas (1988), human capital substitutes labor as a factor of production. But unlike labor, human capital can be produced through education. As a result, the rate of growth of both production factors is endogenous, and the model can generate growth per capita without invoking exogenous drivers such as autonomous technical change.

In models with human capital, the impacts of climate change on population (via diseases and premature mortality) have potentially larger consequences for growth, at least in the short- and medium-term, than in models without human capital. This is because a reduction in population (for example working age adults) simultaneously reduces the stock of human capital thereby limiting both the production of physical goods and the production of new human capital. On the other hand, one-off reductions in the stock of human capital may not necessarily have long-lasting impacts on the long-term growth path because these shocks can be offset by higher investment in education in the future.

Thus, the Cass-Koopmans model which does not take into account the role of human capital in economic growth, potentially underestimates the consequences for growth of adverse climate change impacts on population—the latter operating through two different channels concurrently (the reduction of the population in the labor force, as well as, the human capital they embody).

A second route to internalize growth rates is to recognize that technical change is a major driver of economic growth, and ***to model technological change directly***. This approach was pioneered by Romer (1990) and Aghion and Howitt (1992), and it has spurred many developments over the past two decades. In these models, technological change is usually driven by R&D expenditures and/or by learning by doing mechanisms (Arrow, 1962).

Ultimate damages of climate change could affect the drivers of technological change in this framework if climate change impacts adversely affect the availability of physical, human and institutional resources for research and development of new technologies. Endogenous growth models are useful for understanding how *ex ante* policies, such as mitigation (and proactive adaptation) might affect growth. In particular, when ***induced technological change*** is assumed, the high costs of shifting investment from carbon-intensive to less carbon-intensive sectors (or

from climate-sensitive to less climate-sensitive sectors) in the case of mitigation are at least partially offset by the fact that the higher investment in the desired sectors triggers rapid technological change, thereby reducing the costs of the new alternate technologies. The overall effect of mitigation on economic growth becomes ambiguous. Numerical modeling of the implications of induced technical change has yielded conflicting results in the past.[45] But a consensus seems to be emerging around the notion that induced technological change is an important driver of the costs of mitigation policies, especially in the long-run (for the cost of the backstop technology). That effect, however, may not necessarily be sufficient to fully offset high abatement costs in the near-term. Thus, in general, models with induced technical change still conclude that mitigation reduces GDP growth (relative to the without climate change case they use as baseline—see Section 2.3 for a discussion of the inappropriateness of this baseline), but to a lesser extent than in models with exogenous technical change only (Grubb et al., 2006).

A final insight from the economic growth literature with induced technological change is that mitigation policies in the energy sector may affect the production function of the composite good (despite the fact that energy typically represents a small share of factor costs) because of changes in the prices of non-energy goods, changes in labor costs, changes in the costs of capital (through changes in the savings rate and in the cost of equipment).[46] In addition to factor reallocation and price changes, already discussed in Section 5, changes in technology add a third channel through which action in one sector may affect productivity in others.[47]

7.2. Increasing returns also create the possibility of lock-ins in development paths, with major implications for the impacts of climate change on economic growth

Adding increasing returns (including, but not limited to, induced technical change)—to a growth model with two sectors or more creates path dependency and opens up the possibility of lock-ins.

[45] Top-down studies, such as Goulder and Schneider (1999), suggest that the presence of induced technological change do not significantly reduce costs of mitigation because higher technological change in low-carbon intensity sectors crowds out technological change that would have occurred in other sectors, thus averaging out over the whole economy. But bottom-up studies tend to exhibit large cost reductions as a result of adoption of new technologies (e.g., Grubler et al., 1999). Grubb, et al (2006) suggests that bottom-up and top-down approaches are slowly converging.

[46] Ghersi and Hourcade (2006), who make this argument, show numerically that the implications for the evaluation of mitigation policies can be significant.

[47] The same reasoning could apply to proactive adaptation as well, to the extent that mechanisms such as increasing returns to adoption or economies of scale reduce the costs of adaptation technologies.

Lock-ins were initially defined for technologies (Arthur, 1989). When two technologies compete, increasing returns (e.g., network externalities, learning by doing, economies of scale, etc.) may result in a situation in which one technology or format completely dominates the market except for niches. Examples abound, such as between the BETAMAX and VHS standards for videocassettes, between the QWERTY and AZERTY keyboards for typewriters, or between light- and heavy-water nuclear reactors (Cowan, 1990).

Krugman (1995)[48] extended the concept to economic geography showing that lock-ins may also occur in the spatial organization of cities or regions. For example, increasing returns to agglomeration may make new investments very costly to locate in new centers once a productive nucleus is established in an existing center. By analogy, a city with initially low population density may generate higher demand for private car mobility, thereby increasing demand for roads, making it easier for sprawl to develop by cutting transportation costs, and thus keeping density low even as population increases. This eventually leads to a spatial structure that is *locked into* a pattern where public transportation is inefficient and where cars are required—with adverse consequences for the use of fossil fuels and the generation of carbon emissions with current technologies.

The concept may also apply to institutions. For example, cap-and-trade and coordinated taxes were competing instruments on the negotiation table prior to the UN Framework Convention on Climate Change (1992). A series of incremental steps, some of them fortuitous, started to tilt the balance in favor of the cap-and-trade approach. Though no negotiation had taken place, each made it more difficult for negotiators to return back to taxes, and when the negotiation mandate for the Kyoto Protocol was laid out in 1995, the cap-and-trade approach imposed itself as quasi evidence (Hourcade, 2002). Furthermore, the entry into force of the Kyoto Protocol has resulted in the creation of a host of public institutions (e.g., the Executive Board of the Clean Development Mechanism, Designated National Authorities leveling each country) and private institutions (consultants, providers of registries, traders, brokers, exchanges, etc.) with vested interest in the continuation of the approach.[49] Shifting to a coordinated tax regime beyond 2012, as some have suggested (e.g., Nordhaus, 2001), thus faces important hurdles.

[48] And later in Fujita et al. (1999)

[49] The cap-and-trade approach has also been adopted by other regimes in Europe, Australia, Japan or the U.S.

Though it manifests itself in the selection of one particular technology, city structure or institutional arrangement, a lock-in is in fact a systemic effect: part of the economic system adapts to deliver or support one technology to the detriment of the other. In the QWERTY vs. AZERTY competition for example, increasing returns exist both on the supply side, where it is easier to produce one type of typewriter instead of two, and on the demand side, where labor productivity is higher if individuals moving from one firm to another do not have to undertake arduous training in another system.

The discussion above suggests that lock-ins may have significant implications, in some cases positive, and in others negative, for the relationship between the components of the climate bill and economic growth. Self-reinforcing mechanisms facilitating the adoption of carbon-free technologies will be considered good from the point of view of *ex ante* climate policies (such as mitigation and proactive adaptation), whereas similar mechanisms making it more difficult to get out of carbon-intensive technologies will be considered as bad.

Isolated empirical findings suggest that positive lock-ins may go a long way towards offsetting mitigation costs. For example, in an analysis of how France, Germany (and Japan and Italy) responded to the first oil shock, Hourcade and Kostopoulou (1994) show that (i) distinctly different solutions were adopted by each country, with France moving aggressively to develop domestic nuclear supply and a new building code, and Germany supporting industrial exports to compensate its trade balance deficit in the energy sector; (ii) that as a result CO_2 emissions per unit of GDP diminished by half in France and "only" by a quarter in Germany between 1971 and 1990 (IEA, 2004); and yet that (iii) the macroeconomic performances of these countries has been relatively comparable over the period (2.24% annual GDP growth rate in France against 2.42% annual average annual GDP growth rate in Germany), suggesting that widely different environmental outcomes can be obtained at similar welfare costs in the long-run. Part of the difference can be traced to the fact that France has taken advantage of a positive lock-in into nuclear energy (reaping benefits from economies of scale in nuclear capacity, and over time in increasing reliance on electric radiators in buildings).

There is, however, little evidence, either theoretical or empirical, on the implications of lock-ins for growth, and this is an important topic for future research.

7.3. Growth benefits from geographic concentration: as a result, localized impacts of climate change on a growth 'nucleus'/engine of growth center could have disproportionate impacts on economic growth

Empirical analysis shows that economic activity tends to be highly concentrated, at all geographical scales, that production factors, both capital and labor (both skilled and unskilled) tend to accumulate geographically, and that wealth also tends to be increasingly concentrated. This is inconsistent with basic factor accumulation models which predict that capital should flow from developed (rich) to less developed (poor) regions or countries. Complete microeconomic explanations for such concentrations are still missing, but agglomeration economies and economies of scale are clearly playing a role.

Recent work on economic geography provides further insights on how climate change may affect location-dependent growth processes. One strand of the economic geography literature focuses on the location of economic activity (including industry) in terms of the attractiveness of natural characteristics of locations (Sachs et al., 1999) such as climate, prevalence of diseases, natural resources, etc. (its "first advantage" in the expression of Burgess and Venables, 2004). This strand overlaps with the older urban geography tradition which saw cities as locating in areas that could be defended with adequate local water and food resources. Another strand of the economic geography literature, as mentioned above, focuses on the location of economic activity in terms of proximity and increasing returns (Fujita et al., 1999), that provide competitive advantages such as positive agglomeration externalities and the creation of thick markets ("second advantage"). This strand overlaps with the older urban geography tradition which saw cities locating at the crossroads of trade and transportation routes (initially rivers, later roads and ports). However, unlike the earlier tradition the new economic geography's focus on increasing returns provides a theoretical underpinning for path dependency and the observed persistence of primary cities and their continued enlargement.

Climate change may affect this dynamic at two levels. First, climate is one element of the "first advantage". The incidence and spread of diseases like malaria due to climate change may slow the growth of the TFP parameter in countries or regions where those diseases were not prevalent before. Second, growth centers, once established, can become concentrated engines of growth. Severe impacts of climate change on either the growth centers themselves or the

infrastructure that links them to other markets (roads, ports) may have disproportionately large impacts on country-level economic growth, even if the event is very localized.[50]

Concentration of factors and output in climate-vulnerable areas increases potential damages of climate change. For example, if sea transportation remains cheaper than land or air transportation, export industries have an advantage in locating on coasts. But by doing so, they also become more vulnerable to climate change induced sea-level rise, hurricanes, and associated sea surges. Thus, in the longer run climate change might reduce the comparative advantage of being a coastal country relative to a landlocked one if the cost of business increases, because of disruptions associated with flooding and sea surges, or higher infrastructure costs to avoid them.

8. Conclusion

In this paper, we have briefly reviewed the economic growth literature, both theoretical and empirical,[51] as well as the literature on the economic modeling of climate change to examine how the four components of the climate change bill (namely, mitigation, anticipative adaptation, reactive adaptation, and ultimate impacts of climate change) can affect economic growth. The technical results from the review are summarized in Appendix 2, and our main findings are as follows.

(1) A trivial but important **methodological point** is that since climate change is no longer a hypothetical possibility, measuring (gross) costs against a 'without climate change' business-as-usual (BAU) scenario has no policy relevance. The correct counterfactual to rank policies is a BAU scenario *in the presence of climate change*—i.e., one in which *no action* is taken and the full 'ultimate damages' of climate change are incurred. This recommendation is made knowing the difficulty of estimating the size and timing of damages. In addition, even evaluating (gross) costs and (gross) benefits of policy actions separately, as is common practice, may be misleading since the two are not independent (see Lecocq and Shalizi 2007).

[50] Because these centers concentrate the production of GDP, there is a strong incentive for the private sector, as well as, the public sector to protect those centers with anticipative adaptation measures.

[51] In order to keep the length of this paper manageable, the recent growth models and modifications of the CK model are not covered with the same analytical depth as the earlier CK frameworks. However, we believe that our coverage is complete enough so that key insights about economic growth have not been left aside. One area we have covered only in passing (and that may justify further work) is growth in open economies. Another is the literature on short-term growth and business cycles, which is relevant for the more immediate impacts of the different climate change policies.

(2) The ultimate damages (or remaining ultimate damages of climate change) may significantly affect economic growth—particularly when rigidities and increasing returns are taken into account. The ultimate impacts of climate change encompass both gradual changes in climatic averages (precipitation, temperature, etc.) and increases in the frequency and magnitude of shocks. In the theoretical literature, gradual changes in climate can be modeled by gradual losses of productivity (either of selected factors or of aggregate output). In the set of neoclassical models discussed in Sections 3 and 5, productivity losses result in temporary drops of economic growth and/or in a modified composition of the long-term growth path (capital to labor ratio, consumption to labor ratio and savings rate), but **not** in a change in the growth rate of output (used here as a proxy for welfare).

However, extensions of the neo-classical model suggest that climate-induced reductions in the stock of factors of production (both capital and labor) can have significant implications for transitional and long-term growth. Climate change effects on population (via e.g. diseases or outmigration) appear to be particularly important as the rate of growth of the economy might be reduced even in neoclassical models, and as endogenous growth models underscore the critical role of human capital for economic growth.

The empirical literature shows that climatic shocks have already had large impacts on economic growth in some countries—thus suggesting that future climatic shocks, especially if they are larger and more frequent, may affect economic growth further in the same countries as well as in others. Though there is no empirical or theoretical consensus on the key mechanisms through which climate shocks have such large impacts on growth, a number of factors, such as the size of climate sensitive sectors, the indirect impacts on non climate-sensitive sectors, and rigidities in factor allocation and in price adjustments appear to play an important role.

Finally, in heterodox/non-neoclassical models, when the aggregate production function exhibits local increasing returns, economic growth might become *path dependent with multiple equilibria*. And when stochastic shocks are introduced, there is the possibility that countries fall into and remain locked in 'poverty traps'. An increase in the frequency and magnitude of shocks due to climate change would increase the chance of countries falling into poverty traps or reduce their chances of getting out of them. Similarly, increasing returns to agglomeration can magnify the national or global consequences for economic growth of localized impacts of climate change on key localities (i.e. those where engines of growth are located).

(3) We have not identified specific consequences for economic growth arising from **reactive adaptation**. As noted in Section 2, however, reactive adaptation, like damages, may require efforts that are highly concentrated in time. The discussions above about shocks and the role of rigidities thus apply.

(4) The implications of mitigation and proactive adaptation for economic growth are more ambiguous—especially when increasing returns are factored in. Mitigation and proactive adaptation are more likely to result in a reallocation of expenditures towards less carbon-intensive and less climate-sensitive technologies/sectors. In a neoclassical growth model, additional expenditures have limited impact on long-term economic growth, except if the expenditures are proportional to output. Implications for transitional growth, on the other hand, might be significant depending on the size of the output, especially when energy is introduced as a factor of production. In the latter case, the capital/energy substitution rate becomes a critical parameter of the model.

When increasing returns are introduced, the picture becomes more complicated. On the one hand, there is an emerging consensus that induced technical change reduces the costs of mitigation, though not enough to entirely offset them, at least in the short run. (Though this finding is related to mitigation, it is likely that it also applies to anticipative adaptation action since the development of new technologies is also necessary.) More generally, increasing returns creates the potential for lock-ins (technical, geographical, institutional). The consequences of mitigation for economic growth might be less important when 'good' increasing returns mechanisms are harnessed. However, 'bad' lock-ins (for example, if they are a result of investments in carbon-intensive and/or climate sensitive activities) may substantially increase the costs of future action.

(5) Understanding the effects of climate change on economic growth not only requires that climate change models incorporate more up-to-date knowledge already available about growth dynamics, but also that more effort is devoted to closing the gaps in the theoretical and empirical literature on growth. As far as the **theoretical literature on growth** is concerned, two major gaps are identified. The first is on disentangling the channels through which climate shocks affect economies (directly and indirectly). Some recent attempts at capturing the impacts of shocks have been presented in the paper, but more work is required, especially in complex, open economies where markets can both transfer and amplify the

consequences of shocks or smoothen them out. The second gap relates to the relationship between technology, geography, relative prices and long-term patterns of growth to understand how and when lock-ins materialize. To do so, it is necessary to understand how increasing returns at the micro or sectoral scale do affect the growth rate of aggregate output at the macro scale.

Regarding the **empirical literature on economic growth**, we have found (as many before us) that most of the empirical studies on economic growth rely on *ad hoc* models that are not fully grounded in theory, thus making it difficult to decide which model is more relevant, and which variable is more important. Secondly, we find that there is not yet an empirical literature on the effects of the components of the climate change bill on economic growth, probably because concerns about climate change are relatively recent and because the necessary data for empirical modeling are unavailable—not to mention the lack of a solid foundation to attribute effects. Paradoxically, it is the consequences of early action for growth, both mitigation and anticipative adaptation, that have been less studied, whereas there exists a sizeable empirical literature on climatic shocks. However, recent development of large-scale mitigation policies in such places as the EU or some developing countries (through the clean development mechanism) might yield data in the near future.

(6) Because they are usually grounded on the simplest growth models, currently available numerical models that assess climate policies provide limited insights on the effects of the components of the climate change bill on economic growth, and thus on the optimal portfolio of policy actions. In fact, few climate change models analyze the consequences of individual components of the climate bill for economic growth, and no model to our knowledge take them all into account (see e.g., Table 3). Those that do analyze implications for growth usually frame the discussion within a Cass-Koopmans framework or within a multi-sector version of the neoclassical growth framework. As discussed in Sections 3 to 5, the neoclassical growth model lacks key features of real-world growth dynamics—limitations that automatically translate to numerical models based on the neoclassical growth model, and lead to overstating the costs of early action in terms of the impact on growth or welfare.

(7) However, the review also suggests that there is already sufficient material in the growth literature to improve the numerical models significantly, notably by including multi-sectoral approaches, induced technological change and possibly shocks in the next generation of numerical growth models, albeit crudely. On the other hand, as noted above, there is still limited

theoretical and empirical understanding of lock-ins—so for that reason it may be more difficult to incorporate lock-ins into numerical models immediately. But this is likely to be a priority area for future work.

(8) Finally, this review is not aimed at providing policy recommendations at this stage, in part because of the need for more work in theoretical models to incorporate missing features, and the need for specific numerical simulations for different types of cases. Despite that, **the review does provide some insights on how case studies aimed at evaluating the implications of the components of the climate change bill for economic growth in a particular country context should be conducted**.

- First, the review reinforces the idea that climate damage assessments should not be limited to energy and/or climate sensitive sectors because of indirect interactions between these sectors and those non energy sectors that are also not climate sensitive directly.
- Second, the review suggests that particular attention should be paid to shocks, transitions, and geography. Costing shocks correctly increases the total climate bill relative to a case where shocks are not properly taken into account. It also increases the relative benefits of anticipative adaptation/mitigation since the efforts they demand are not as concentrated in time as those required by coping with shocks ex post.
- Finally, the risk of 'bad' lock-ins versus the opportunities for 'good' lock-ins should be analyzed carefully.

To provide better insights on the optimal policy mix between mitigation, proactive adaptation, reactive adaptation (and thus remaining ultimate damages), and to justify more rigorously the ranking of scenarios 1 to 4 that is implicit in Figure 1 (see also Table 1), future work should concentrate on numerical simulations using an extended numerical model of climate change that includes all four components of the climate bill within a framework where rigidities and increasing returns are taken into account.

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Appendix 1 : Variation of steady-state consumption per capita with α and δ in the Cass-Koopmans model

Steady-state consumption to labor ratio can be written as

$$c = Ak^{\alpha}(1-s) = A\left(\frac{A\alpha}{\eta+g+\delta}\right)^{\frac{\alpha}{1-\alpha}}\left(1-\frac{\alpha}{1+\frac{\delta}{\eta+g}}\right)$$

The derivative of c with regard to α is thus:

$$\frac{\partial c}{\partial \alpha} = Ak^{\alpha}(1-s)\left[\ln\left(\frac{A\alpha}{\eta+g+\delta}\right)\frac{1}{(1-\alpha)^2}+\frac{\eta+g+\delta}{A\alpha}\frac{A}{(\eta+g+\delta)}\frac{\alpha}{(1-\alpha)}\right]-Ak^{\alpha}\frac{\partial s}{\partial \alpha}$$

$$= Ak^{\alpha}\left[(1-s)\left(\ln\left(\frac{A\alpha}{\eta+g+\delta}\right)\frac{1}{(1-\alpha)^2}+\frac{1}{1-\alpha}\right)-\frac{s}{\alpha}\right]$$

$$= Ak^{\alpha}\left[(1-s)\ln\left(\frac{A\alpha}{\eta+g+\delta}\right)\frac{1}{(1-\alpha)^2}+\frac{1-s}{1-\alpha}-\frac{s}{\alpha}\right]$$

$$= Ak^{\alpha}\left[(1-s)\ln\left(\frac{A\alpha}{\eta+g+\delta}\right)\frac{1}{(1-\alpha)^2}+\frac{\alpha-s}{\alpha(1-\alpha)}\right]$$

Coefficient α in the Cobb-Douglas production function is typically estimated between 0.3 and 0.4, whereas typical savings rates s are below 0.2 - 0.25, except in fast-growing developing countries where they may reach values above 0.3. The derivative of c with regard to α is thus positive in most cases.

The derivative of c with regard to δ is thus:

$$\frac{\partial c}{\partial \delta} = A\alpha k^{\alpha-1}\frac{\partial k}{\partial \delta}(1-s)-Ak^{\alpha}\frac{\partial s}{\partial \delta}$$

$$= -A\alpha k^{\alpha-1}\frac{k^{\alpha}}{(1-\alpha)}\frac{A\alpha}{(\eta+g+\delta)^2}(1-s)+Ak^{\alpha}\frac{\alpha(\eta+g)}{(\eta+g+\delta)^2}$$

$$= \frac{Ak^{\alpha}}{\eta+g+\delta}\left[-\frac{\alpha}{1-\alpha}(1-s)+s\right]$$

$$= \frac{Ak^{\alpha}}{(\eta+g+\delta)}\frac{s-\alpha}{(1-\alpha)}$$

As per the discussion above, the derivative of c with regard to δ is thus negative in most cases.

Appendix 2. Summary of the consequences of the components of the climate change bill for economic growth in various growth models

Model	Implications for the transition path towards the long-term steady-state growth path		Implications for the long-term steady-state growth path	
	Gradual impacts	**Shocks**	**Gradual impacts**	**Shocks**
Cass-Koopmans (with climate change impacts channeled through the production function early)	*Not analyzed*	*Not analyzed* Loss of capital leads to increased savings and accelerated growth of aggregate output to compensate for lost capital stock	*Temporary* modifications in stock, productivity or growth rate of factors do not affect the long-term steady-state growth path – they only affect the transitional path. *Growth rate of aggregate output* is exogenous in the Cass-Koopmans model, and thus remains unchanged except if the ultimate damages of climate change are assumed to reduce growth rate of labor	
			Permanent diminution of productivity of capital leads to lower steady-state consumption to labor ratio. Permanent increase in expenditures proportional to output leads to lower steady-state consumption to labor ratio	Repeated shocks on capital stock lead to lower steady-state consumption to labor ratio
Cass-Koopmans (with climate change impacts channeled through the utility function only)	*Not analyzed*	*Not analyzed*	Depends on whether degradation of environment impacts marginal utility of consumption. - If c and e are independant, $\frac{\partial^2 U}{\partial c \partial e} = 0$, environmental degradation has no direct impact on growth via the utility function - If c and e are complements, $\frac{\partial^2 U}{\partial c \partial e} > 0$, degradation of *e* leads to lower steady-state consumption to labor ratio - If c and e are substitutes, $\frac{\partial^2 U}{\partial c \partial e} < 0$, degradation of *e* leads to higher steady-state consumption to labor ratio	

Model	Implications for the transition path towards the long-term steady-state growth path		Implications for the long-term steady-state growth path	
	Gradual impacts	**Shocks**	**Gradual impacts**	**Shocks**
Uzawa	In the Uzawa model, impacts on one sector spill over to the other sector via factor allocation. Decreasing returns assumption prevent increased activity in one sector from fully compensating for the loss of activity in another			
	A climate-changed induced modification in the productivity of factors may have non-linear implications for transitional growth path if it triggers an inversion of the relative capital intensity in the two sectors	When rigidities are taken into account (e.g., on capital vintages), transitions are longer than in the Uzawa model without rigidities		
Multi-sector models	Spillovers from climate-sensitive sectors to non-climate sensitive sectors (also from energy-intensive to non-energy-intensive sectors)			
			Multi-sector models do not necessarily generate steady-state growth paths	
Multi-sector models with energy as a production factor	The degree of substitutability between capital and energy is a critical parameter of the model when evaluating the impacts of mitigation policies on economic growth			
Empirical studies of growth with shocks		Empirical studies show that transitions back towards equilibrium after shocks are longer than expected in theoretical models w/o rigidities—rigidities matter		
Endogenous growth models with human capital		Shocks on human capital may have proportionally larger impacts on economic growth than in a Cass-Koopmans model		
Endogenous growth models with induced technological change	Potentially lower costs of mitigation (and proactive adaptation)			

Model	Implications for the transition path towards the long-term steady-state growth path		Implications for the long-term steady-state growth path	
	Gradual impacts	**Shocks**	**Gradual impacts**	**Shocks**
Cass Koopmans growth models with increasing returns in production function		Increased risk of falling or remaining in poverty traps	Possibility of multiple equilibria	Increased risk of falling or remaining in poverty traps
Empirical studies of relationships between growth and agglomerations		Risks of disproportionate impacts on economic growth if key centers for economic growth are hit		
Lock-ins		Mitigation policies may have higher/lower implications for economic growth—relative to a model without lock-ins—depending on whether 'good' lock-ins can be harnessed, or whether 'bad' lock-ins have to be overcome	Possibility of multiple equilibria	