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Adaptation to climate change and economic growth in developing countries

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Abstract

The global climate is changing, and will continue to do so even if greenhouse gas emissions are dramatically curbed. Economies are therefore faced with the challenge of adapting to climate change. This challenge is particularly important in developing countries, which, due to a combination of unfortunate geography and high sensitivity, are most vulnerable to climate change. From a macro-economic point of view, there remains much to learn about the characteristics of optimal adaptation. In particular, it is unclear whether the best way to adapt to climate change is simply to focus on traditional growth and development goals, or to divert significant investment into 'climate-proofing' productive capital. In this paper we conduct analytical and numerical modeling to gain new insights into this question. Our analytical model shows that the task of apportioning investment between productive capital and adaptation to climate change is a subtle one. While it is very unlikely that the optimal strategy involves no investment in adaptation, the scale and composition of productive and adaptive capital investments depend on empirical context. Our numerical application to Sub-Saharan Africa suggests, however, that in most contingencies it will be optimal to invest rapidly in adaptive capital over the coming decades. Our sensitivity analysis goes well beyond the existing literature in evaluating the robustness of this finding.

1 Introduction

The Intergovernmental Panel on Climate Change (IPCC) forecast in its *Fourth Assessment Report* that, in the absence of greenhouse gas emissions abatement, the global average temperature at the end of this century could be up to $6.4°C$ above its 1990 level, or more[1] (IPCC, 2007). To put such

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[1]$6.4°C$ warming is the top end of the IPCC's 'likely' range, which corresponds to the IPCC experts' consensus 66–90% confidence interval.

a change in perspective, the difference in the global average temperature between the present day and the peak of the last Ice Age is about $5°C$. Of course, globally significant emissions abatement may well take place. Nevertheless, even if the atmospheric concentration of greenhouse gases were to have been held at its level in the year 2000 (which has not happened), the earth would 'likely' [2] still be between 0.3 and $0.9°C$ warmer on average by the end of the century, compared with 1990 (IPCC, 2007). Thus the global climate is changing, and even dramatic curbs to emissions will not prevent it from continuing to do so (Solomon et al., 2009). This immediately raises the question of how economies should adapt to changing climatic conditions.

The challenge of adapting to climate change is widely thought to be most important in developing countries (e.g. Tol et al., 2004; Mendelsohn et al., 2006). Terminology varies, but there are in general three reasons for this. The first reason is geography. Many developing countries are located in tropical and sub-tropical regions and as such are already hotter than is optimal for various forms of economic activity. Further increases in temperature will lead to conditions that are less optimal still. As Mendelsohn & Schlesinger (1999) showed, if the relationship between temperature and the output of an economic sector can be approximated with an 'n-shaped' parabola (a so-called 'hill function'), as appears to be the case in a series of important climate-sensitive sectors, then small changes in temperature in hot countries can lead to large losses in that sector's output. Although indexed by temperature, these functional relationships capture the fact that climate change is about much more than just temperature; many of its impacts are expected to stem from changes in the availability of water. Here too, developing countries are often poorly placed, already experiencing especially low or high average rainfall, and/or high intra- and inter-annual variability (e.g. the Indian monsoon). The second reason might be called sensitivity: a relatively large share of the economic output of many developing countries emanates from sectors especially sensitive to climatic conditions, notably agriculture. In some developing countries, agriculture accounts for more than half of GDP. More broadly, the concept of sensitivity can capture the fact that many people in developing countries are already pursuing marginal livelihoods, being for example on the cusp of malnutrition or living in communities with fragile sanitation facilities. The third reason is a lack of adaptive capacity. Developing countries often lack the resources to adapt to climate change, including financial resources (both savings and access to credit), good governance, infrastructure, and information.

It is worth being more specific about what adaptation to climate change is. A definition of adaptation was given by the IPCC (Smit et al., 2001): "any adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities". Within the set of adjustments they refer to, it is often important – including for the purposes of this paper – to distinguish between 'flow' and 'stock' adaptation. Flow adaptation includes the set of adjustments for which both the costs and benefits accrue in a single time period. Examples of flow adaptation include changes in variable agricultural inputs such as crop varieties and fertilizer, and changes in space heating and cooling. In contrast, stock adaptation is a form of investment, in which costs are paid up front, while benefits accrue in several future time periods. Perhaps the easiest stock adaptations to imagine are the construction of dykes to protect against coastal flooding, or dams to store water to cope with droughts. But stock adaptation can take other, more indirect forms, such as investing in health care infrastructure

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[2]As per footnote 1.

in order to cope with a changing burden of disease, and investing in agricultural extension services to support flow adaptations by farmers. In this paper, we focus on adaptation as an investment problem: i.e. in stock adaptation.

This brings us to a second important distinction, which lies at the heart of our paper, between adaptation to climate change and general economic development. Without wishing to oversimplify, one can identify two schools of thought as to the best response to impending climate change in the developing world. The first argues that *'development is the best form of adaptation'*: it is better to prioritize traditional developmental goals – i.e. investing in physical and human capital stocks, and robust institutions – over defensive investments aimed specifically at reducing vulnerability to climate impacts. The rationale for this claim may be traced back to Thomas Schelling (1992), who reasoned that, given developing countries are vulnerable to climate change due in large part to their high sensitivity and low adaptive capacity, both of which are essentially problems of their low level of development, "their best defense against climate change may be their own continued development" (p6). It is important to note that Schelling's attention was primarily focussed on whether adaptation, as opposed to abatement of greenhouse gas emissions, was the best policy response to climate change. Nevertheless, his suggestion has given rise to subsequent work arguing more directly that development is the best form of adaptation (e.g. Mendelsohn (forthcoming); Fankhauser & Burton (2011)). The second school of thought argues that *'development is contingent on adaptation'*: the process of development will be severely compromised by climate impacts, unless specific adaptation takes place. In this view, successful defensive adaptation is a necessary condition for the effective accumulation of capital stocks, and the welfare improvements associated with development. This is most notably the policy position adopted by various multilateral development organizations (e.g. UNDP (2007); World Bank (2010)).

There is a burgeoning literature on adaptation to climate change, as summarized in for example the IPCC's *Fourth Assessment Report*, but a great deal of it is based on local case-studies. However, in recent years, a few studies have emerged to consider adaptation as a macro-economic issue. Their primary purpose has been to quantify the costs of adaptation at the national and regional levels, in support of international political negotiations to agree a package of payments for adaptation from industrialized to developing countries. Fankhauser (2010) divides this literature into a 'first' and 'second' generation. The first-generation studies were very basic indeed. Their approach was simply to estimate the fraction of current investment flows sensitive to climate change, and then to multiply these flows by a mark-up coefficient representing an aggregate estimate of how much it would cost to 'climate-proof' them (Stern, 2007; UNDP, 2007; World Bank, 2006a). This approach was only capable of producing a static estimate of costs, and the mark-up coefficient in particular had almost no empirical basis. The second generation of studies commenced with UNFCCC (2007), which delved into the detail of adaptation costs across the main climate-sensitive sectors, thus enjoying a sounder empirical basis, but remained static. A recent World Bank (2010) study quantified adaptation costs over time, but was critically limited by the assumption that adaptation is undertaken up to the point at which all climate damage has been eliminated. Indeed, this is the main criticism leveled at all of these studies by proponents of the view that development is the best form of adaptation: i.e. that no, or insufficient, attention is paid to the benefits of adaptation, whether those benefits exceed the costs, and whether alternative uses of scarce resources to invest in productive capital would yield greater net benefits

(Mendelsohn, forthcoming).

The latest crop of macro-economic studies has extended so-called 'Integrated Assessment Models' (IAMs) of the coupled climate-economy system to include adaptation as a control variable. This is a very welcome development. For most of the past two decades, IAMs have been developed with either no attention paid to adaptation, or else it was implicit in the function determining climate damages, and thus could not be varied by the planner. Adaptation-IAMs include a dynamic representation of adaptation, and quantify its benefits. They have made an important contribution by showing that optimal adaptation leaves some 'residual' damages from climate change that are not worth adapting to, and that optimal climate policy involves both adaptation and emissions abatement. In addition, they embody a great deal of careful calibration work, which others, like us, can make use of. However, at present the conclusions one can draw from this literature for thinking about the links between adaptation and development are limited. First, the literature has various limitations of scope: some models are, for example, confined to a global aggregation (AD-DICE in Agrawala et al. (2010)), or only consider flow adaptation (de Bruin et al., 2009). Second, the literature is confined to numerical simulation, so it has yet to advance a formal understanding of the analytical foundations of the problem. Third, the numerical simulations have been highly complex, especially in the largest models (AD-RICE and AD-WITCH in Agrawala et al. (2010)), and consequently they have been largely reliant on a single model parameterization. This is a significant shortcoming, because the estimation of the costs and benefits of adaptation, particularly at the level of nations and regions, is well known to be highly uncertain (Agrawala & Fankhauser, 2008).

The aim of this paper is to formalize and improve our understanding of the relationship between adaptation and growth/development in developing countries, using neoclassical growth theory. Is the optimal strategy simply to invest in productive capital, or should investment be diverted into adapting to climate change? Perhaps more importantly given the uncertainties, how robust is the optimal balance to sensitivities in key parameters? In Section 2, we present a tractable analytical model of optimal growth and adaptation. Investments can be made either in productive capital that is vulnerable to climate change, or in adaptive capital, which is not inherently productive, but reduces climate damages. We derive expressions for the optimal controls and show that, even in a simplified model, the task of apportioning investment between the two capital stocks is subtle. We can virtually rule out the possibility that the optimal investment strategy invests nothing in adaptive capital, but beyond that, answers to questions about the dependence of investment in adaptive capital on the level of development – as measured by the stock of vulnerable capital – and about just how much should be invested, depend on empirical circumstances. Therefore we make an empirical application of our model to Sub-Saharan Africa (Section 3), which is widely regarded to be the most vulnerable region of the world to climate change. We show that, in our base-case calibration, the optimal strategy involves rapid initial investment in adaptive capital. More importantly, we show that this finding is relatively robust to changes in the values of key parameters, notably the climate sensitivity and CO_2 stabilization pathway, costs of adjustment, growth rate of total factor productivity, discount rate, and the elasticity of marginal utility. The two parameters that can qualitatively alter the dynamics of capital accumulation, and shift the optimal policy towards more rapid growth in vulnerable capital at early times, are an adaptation effectiveness parameter, and the initial stock of adaptive capital. Section 4 discusses these results

and possible extensions, and concludes.

2   A model of economic growth with investment in adaptation

Our model builds on the standard Ramsey-Cass-Koopmans growth model, which has formed the basis of much related work in climate change economics (e.g. Nordhaus, 2008). The model is designed with regions with small shares of global CO_2 emissions in mind, so that climate change may be treated as exogenous to the region's development choices. This is a mild assumption for almost all developing countries, with the exception of China, which currently accounts for approximately 22% of global CO_2 emissions. The next largest emitter in the developing world, India, accounts for only 5% of CO_2 emissions.

The economy consists of two capital stocks – vulnerable capital K_V, which is productive, but susceptible to climate impacts, and adaptive capital K_A, which is not inherently productive, but reduces the impacts of climate change on output derived from vulnerable capital. Vulnerable capital combines with an exogenous labour time series $L(t)$ to produce output $A(t)F(K_V, L)$, where $A(t)$ is an exogenous total factor productivity time series, and F is the production function. In keeping with much of the literature on modeling climate damages, gross output is modified by a multiplicative damage function $D(K_A, X)$, where $X(t)$ is an exogenous time series of global temperature change. The following conditions on the production function F, as well as the Inada conditions, are assumed to hold (subscripts denote partial derivatives):

$$F_{K_V} > 0, F_{K_V K_V} < 0, F_L > 0, F_{LL} < 0 \tag{1}$$

$$F(mK_V, mL) = mF(K_V, L). \tag{2}$$

Thus there are diminishing returns to each of the factors of production, and the production technology exhibits constant returns to scale. The damage multiplier $D(K_A, X)$ is assumed to satisfy

$$D : \mathbb{R}^+ \times \mathbb{R}^+ \to [0, 1] \tag{3}$$

$$\forall K_A, D(K_A, 0) = 1, D_a(0, 0) = 0, D_a(0, X) > 0 \text{ for } X > 0 \tag{4}$$

$$D_a \geq 0, D_{aa} \leq 0, D_{aX} > 0, D_X < 0 \tag{5}$$

where $D_a = \frac{\partial D}{\partial K_A}, D_{aa} = \frac{\partial^2 D}{\partial K_A^2}, D_X = \frac{\partial D}{\partial X}, D_{aX} = \frac{\partial^2 D}{\partial K_A \partial X}$. Damages are thus modelled as reducing gross output by a factor D, which decreases with the magnitude of climate change X. D is defined so that adaptation has no benefit when there is no climate change. In addition, the marginal unit of adaptation is always beneficial, but exhibits decreasing returns. Finally, the condition $D_{aX} > 0$ implies that an additional unit of adaptive capital is more effective at reducing damages when temperature change is large than when it is small.

The evolution of the two capital stocks is given by

$$\dot{K}_V = A(t)D(K_A, X(t))F(K_V, L(t)) - \delta_V K_V - cL(t) - Q(I) \tag{6}$$

$$\dot{K}_A = I - \delta_A K_A \tag{7}$$

where c is consumption per capita, I is investment in adaptive capital, and $Q(I)$ is the cost of investment in adaptive capital of magnitude I, which satisfies $Q'(I) > 0, Q''(I) > 0$. The convexity of Q determines the magnitude of the adjustment costs the economy faces when transferring output from the vulnerable to the adaptive sector of the economy – these act as a disincentive to rapid adaptation, as large investment flows are penalized more heavily than small ones (Eisner & Strotz, 1963; Lucas, 1967). Adjustment costs arise since stock adaptation will be largely publicly funded (Stern, 2007), and is thus subject to planning costs, policy delays due to the political process, and corruption. Thus the curvature of Q represents the intrinsic inertia in the economy with respect to adaptation – we use it as a coarse measure of the government's efficiency at rolling out adaptation projects. Finally, the parameters δ_V and δ_A are the depreciation rates of vulnerable and adaptive capital respectively.

The social planner chooses the values of c and I so as to maximize the following classical utilitarian objective function:

$$W = \int_0^T L(t)U(c)e^{-\rho t}dt, \tag{8}$$

subject to the constraints (6–7). Under the assumptions specified above the control problem is convex, and thus has a unique solution, with the Pontryagin conditions being necessary and sufficient for an optimum. In our simulation work we will take the time horizon T to be large ($T = 500$ years), and following Nordhaus & Boyer (2000), impose zero terminal conditions on the state variables, i.e. $K_V(T) = K_A(T) = 0$. Then with a moderate discount rate ρ, policy choices for the first several hundred years are relatively insensitive to the terminal conditions. Note that we are uninterested in the properties of any putative steady-state, as the relevant policy issues concern transient adaptation to a dynamically evolving climate – hence our decision to fix the terminal conditions is innocuous.

Applying the Pontryagin conditions to this control problem, the Euler equations for the optimal controls are:

$$\dot{c} = \frac{c}{\eta(c)}\left[A(t)D(K_A, X(t))F_{K_V} - \delta_V - \rho\right]; \tag{9}$$

$$\dot{I} = \frac{Q'(I)}{Q''(I)}\left[A(t)D(K_A, X(t))F_{K_V} - \delta_V + \delta_A\right] - \frac{1}{Q''(I)}A(t)D_a(K_A, X(t))F(K_V, L(t)) \tag{10}$$

where $\eta(c) := -c\frac{U''(c)}{U'(c)}$ is the elasticity of marginal utility.

For the purposes of interpreting this solution, imagine taking a limit in which the adjustment cost function approaches the linear function $Q(I) = I$, i.e. $Q'(I) = 1, Q''(I) = 0$. In this limit the optimal control problem becomes singular, and without imposing constraints on the controls, the solution will instantly adjust the capital stocks so that the algebraic relation

$$A(t)D(K_A, X(t))F_{K_V} - A(t)D_a(K_A, X(t))F(K_V, L(t)) = \delta_V - \delta_A \tag{11}$$

is satisfied at each point in time. That is, the optimal singular control sets the difference between the marginal productivities of vulnerable and adaptive capital stocks equal to the difference between their depreciation rates. This is a familiar result from two-sector growth models (see e.g. Acemoglu (2008, p. 367)). The difference here is the additional exogenous time-series $X(t)$ which moderates the productivity of the economy, and affects the dynamics of investment allocations. If we temporarily simplify even further, and assume that $A(t) = L(t) = 1$ for all time, some additional analytical insights are possible. Defining $f(K_V) := F(K_V, 1)$, and differentiating (11) with respect to time, one can show that optimal investment in adaptive capital is given by

$$I = R_X \dot{X} + R_V \dot{K}_V + \delta_A K_A, \tag{12}$$

where we define the 'response rates' R_X and R_V, which determine the adaptive investment response to changes in the values of X and K_V respectively, through

$$R_X := \frac{D_{aX} - \frac{f'}{f} D_X}{\frac{f'}{f} D_a - D_{aa}} \tag{13}$$

$$R_V := \frac{D_a - \frac{f''}{f'} D}{D_a - \frac{f}{f'} D_{aa}}. \tag{14}$$

The first term in (12) is the most interesting, as it represents the direct effect of the climate dynamics on the investment rule. The second term is an adjustment term which represents an income effect on the optimal combination of adaptive and vulnerable capital. It would be present even if the climate were not changing (i.e. $\dot{X} = 0$), but the economy were growing (or declining), as resources would need to be moved between sectors so that (11) is satisfied. The third term is simply the investment needed to ensure that adaptive capital does not depreciate.

The following two propositions about the investment rule (12), and the response rates R_X, R_V, hold:

Proposition 1. *If $\dot{X} > 0$ and $\dot{K}_V > 0$, then $I > 0$.*

Proof. The definitions (13–14) and the assumptions (5) imply that $R_X > 0$ and $R_V > 0$. The result follows immediately. $\qquad\square$

Proposition 2. *R_X is an increasing (decreasing) function of K_V when $\epsilon_{a,a} < \epsilon_{X,a}$ ($\epsilon_{a,a} > \epsilon_{X,a}$), where $\epsilon_{a,a}$ is the elasticity of D_a with respect to K_A, and $\epsilon_{X,a}$ is the elasticity of D_X with respect to K_A. Moreover, if $f(K_V) = K_V^\alpha$ for $\alpha \in [0,1]$, then R_V is a decreasing function of K_V.*

Proof. See Appendix A. $\qquad\square$

Proposition 1 implies that if we are in a regime in which temperatures are rising, and the economy is developing simultaneously, it is optimal to increase the stock of adaptive capital. This argues against the strong 'adapt through development' hypothesis – positive investment in adaptation (albeit of unknown magnitude at this point) is optimal, even when the economy is accumulating traditional vulnerable capital as well.

Proposition 2 allows us to compare the adaptive investment plans of more and less developed economies, in particular demonstrating how the investment rule changes as the stock of vulnerable

capital increases. All else being equal, more developed economies will respond proportionately less to a change in the capital stock $\dot{K}_V$ than their less developed counterparts, since $\frac{\partial R_V}{\partial K_V} < 0$. However, it is possible that this reduction in the response rate R_V may be offset by an increase in investment due to the change in X. In order for this to be possible, we require $\epsilon_{a,a} < \epsilon_{X,a}$. This condition on the elasticities of the damage function says that in order for wealthier economies to respond proportionately more to climate change $\dot{X}$, the damage reduction effect of the marginal unit of adaptive capital should outweigh its effect on the returns to adaptive investment, which are decreasing in the stock of adaptive capital. Note that the condition depends both on the structure of the damage function $D(K_A, X)$, as well as on the values of K_A, X. It may be satisfied at some points in time over a country's development trajectory, and not at others, as the magnitude of climate change X changes, and the capital stock K_A evolves. Since in general we do not know that $\epsilon_{a,a} > \epsilon_{X,a}$ for all values of X, K_A *a priori*, we cannot conclude that a wealthier economy has less need for adaptation.

Taken together, these propositions suggest that, even in this highly simplified model, the task of apportioning investment between productive and adaptive capital is a subtle one, and certainly not reducible to simplistic prescriptions. While proposition 1 gives us an indication of the sign of adaptive investment over an economy's development pathway, and proposition 2 allows us to determine how the investment rule is affected by different stocks of vulnerable capital, they cannot give us quantitative information about the optimal levels of adaptive and vulnerable capital stocks for a given country over time. In order to investigate this, we now turn to full numerical solutions of the model, and investigate their sensitivity to underlying assumptions about the economy, the effectiveness of adaptation, and the magnitude of climate change.

3   Application to Sub-Saharan Africa

The analytical results discussed above are limited, in that they do not account for the effect of technological change, population growth, or adjustment costs on the investment rule. To address these limitations, and obtain a quantitative understanding of the evolution of the adaptive and vulnerable capital stocks, we now calibrate our model to a specific region – Sub-Saharan Africa. There are two good reasons for focussing our attention on this region. First, it makes a very small contribution to global greenhouse gas emissions (less than 5% of total CO_2-equivalent emissions (EarthTrends, 2009)), and its share in emissions is unlikely to grow substantially over the coming decades. Thus our assumption that climate change is exogenous holds to a good approximation. Second, and more importantly, the region is highly vulnerable to climate impacts (Boko et al., 2007), and thus has a strong incentive to understand how best to protect itself against their effects.

3.1   Model calibration and implementation

To calibrate and simulate the model, it is necessary to make choices for the functions $D(K_A, X)$, $F(K_V, L)$, $Q(I)$, and $U(c)$. We take

$$D(K_A, X) = \frac{1 + g(K_A)}{1 + g(K_A) + f(X)}, \tag{15}$$

Table 1: Model parameters and exogenous time series. Sensitivity analysis is conducted over starred parameters.

Parameter	Interpretation	Base case value
γ	Capital share of production	0.3
α_1, α_2	Gross damage multiplier parameters	$(2.22 \times 10^{-14}, 0.75 \times 10^{-2})$
β_1, β_2^*	Residual damage multiplier parameters (effectiveness of adaptation)	$(0.32 \times 10^{-2}, 0.17)$
δ_A, δ_V	Capital depreciation rates	10%/year
q^*	Cost of adjustment parameter	9.70×10^{-12}
η^*	Elasticity of marginal utility	2
ρ^*	Rate of pure time preference	1.5%/year
$L(t)$	Population	From RICE
$A(t)^*$	Total factor productivity	From RICE
$X(t)^*$	Temperature change	From DICE
$K_V(0)/L(0)$	Initial stock of vulnerable capital per capita	$2796
$K_A(0)/L(0)^*$	Initial stock of adaptive capital per capita	$0.50

where

$$f(X) = \alpha_1 X + \alpha_2 X^2 \tag{16}$$

$$g(K_A) = \beta_1 K_A^{\beta_2}. \tag{17}$$

$\beta_1 > 0$, $\beta_2 \in [0,1]$, ensures that all the derivatives of D have the correct signs. The quadratic dependence of gross damages on temperature change is commonly assumed in the literature, being in agreement with, for example, Nordhaus & Boyer (2000) and Nordhaus (2008) (but see Section 4). We pick the Cobb-Douglas form $F(K_V, L) = K_V^\gamma L^{1-\gamma}$ for $\gamma \in [0,1]$, and choose

$$Q(I) = I + \frac{q}{2} I^2, \tag{18}$$

where q is a parameter which fixes the cost of adjustment from vulnerable to adaptive capital. Finally, our social planner's utility function is assumed to be of the constant relative risk aversion (CRRA) form:

$$U(c) = \frac{c^{1-\eta}}{1-\eta} \tag{19}$$

where $\eta > 0$ is the elasticity of marginal utility (the inverse of the elasticity of inter-temporal substitution), which parameterizes the the planner's desire to smooth consumption over time. A complete specification of the model therefore needs to specify numerical values for the parameters and time series in Table 1.

Data from Agrawala et al.'s (2010) comparison of multiple adaptation-IAMs determine values for the gross damage function $D(0, X)$ and residual damages (i.e. damages as a percentage of GDP, as a function of the adaptive capital stock and temperature change). We performed a nonlinear least-squares fit to this data to determine the values of α_1 and α_2. The parameters β_1 and β_2 were determined so that $D(K_A, X)$ agrees with the calibration values at $(K_A, X) = (\$1.1 \times 10^{11}, 1.25°C)$ and $(K_A, X) = (\$9.7 \times 10^{11}, 2.25°C)$. Note that the reduction in damages from flow adaptation is included directly in the calibration of $D(0, X)$[3], so while flow adaptation is not a control variable

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[3]This approximation is exact if we model the costs and benefits of flow adaptation f as multipliers of gross output Y, e.g. through a function $\tilde{D}(f, X)$, which is a U-shaped function of f for each X. Then the optimal value

in our analysis, its effects are taken into account. Also implicit in our calibration of damages is the relationship between climate impacts and GDP (excluding the effect of flow and stock adaptation), because the underlying IAM studies on which we calibrate control for it. This is clearly critical for the purposes of the present paper, if we are to assess the relative contributions of investments in productive and adaptive capital in optimally reducing climate vulnerability. One example of how this relationship plays out is in agriculture, where the income elasticity of climate damages (as a percentage of GDP) is thought to be negative, for the simple reason that, as GDP per capita rises, the share of agricultural output in GDP per capita falls. However, different income elasticities exist for different sectors (Anthoff & Tol, forthcoming; Nordhaus & Boyer, 2000), and the overall income elasticity of damages is the output-weighted sum across sectors.

The base value of q was calibrated so that 90% of a \$30 per capita per year investment in adaptive capital is realized at $t = 0$. The initial stock of vulnerable capital $K_V(0)$, as well the depreciation rate on K_V, was chosen in agreement with the values in the most recent version of the RICE model (discussed in Nordhaus (2010)), as was the time series of population $L(t)$. The depreciation rate on K_A was taken from Agrawala et al. (2010). We set the initial stock of adaptive capital to a nominal \$0.50/capita, as current adaptive capital stocks specifically designed to combat the impacts of climate change (as opposed to current climate variability) are negligible in Sub-Saharan Africa (see discussion in section 3.3.6). The base case values of the preference parameters ρ and η are in line with much of the literature, although there is a well-known debate about them (Nordhaus, 2008; Stern, 2007), and we explore the implications of alternative settings in our sensitivity analysis.

As we wished to do sensitivity analysis over the two remaining exogenous time series $X(t), A(t)$, they were treated slightly differently. The DICE model (Nordhaus, 2008) was used to generate temperature trajectories $X(t)$ under three scenarios for the global atmospheric stock of CO_2 – Business As Usual (BAU scenario), stabilization of the atmospheric stock of CO_2 at twice its preindustrial level ($2CO_2$ scenario), and stabilization of atmospheric CO_2 at 1.5 times the preindustrial level ($1.5CO_2$ scenario). For each of these scenarios, we obtained temperature trajectories for four different values of the climate sensitivity parameter S. Climate sensitivity measures the equilibrium surface warming that results from a doubling of CO_2 concentrations – it thus quantifies the magnitude of the temperature response to the increase in radiative forcing that arises from increased concentrations of atmospheric CO_2. The value of S is uncertain, due to uncertainties in the instrumental record of temperature changes, and uncertainties about key climatic feedback processes (see Knutti & Hegerl (2008) for a review of climate sensitivity concepts and estimates). We chose $S \in [1.5°C, 3°C, 4.5°C, 6°C]$, which approximates the likely range for its values as determined by the scientific literature. We thus obtained 12 unique temperature trajectories, which were used in our sensitivity analysis. These trajectories are plotted in Figure 18 in Appendix B. It can readily be seen that both the atmospheric stock of CO_2 and the climate sensitivity have a significant effect on the trajectory of X, and consequently that we explore a wide range of values.

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of f in each period is only a function of temperature change X, and may be substituted back into the damage multiplier to define a new gross damage multiplier, which includes optimal flow adaptation, and depends only on the temperature X.

The series for $A(t)$ in RICE may be fitted exactly by a function of the form

$$A(t) = A(0) \exp \left[g_\infty t + \frac{g_0 - g_\infty}{\lambda} (1 - e^{-\lambda t}) \right], \qquad (20)$$

where initial growth in TFP is $g_0 = 2.83\%$/year, the long-run growth in TFP is $g_\infty = 0.23\%$/year, and the rate of adjustment in the TFP growth rate is $\lambda = 0.01$/year for Sub-Saharan Africa. Following Nordhaus (2008), we conduct sensitivity analysis over the initial TFP growth rate g_0. The resulting trajectories for $A(t)$ are illustrated in Figure 19 in Appendix B. Observe that the effect of changes in g_0 on $A(t)$ increases over time.

The model was implemented in MATLAB, and the open-source package GPOPS (Rao et al., 2010) was used to find numerical solutions to the optimal control problem. GPOPS uses a generalized colocation method coupled with a high-performance nonlinear optimization routine. This has the advantage of constraining the search for optimal controls to the subset of functions that satisfy the initial and terminal conditions of the problem. This is particularly useful when the optimum is a saddle path equilibrium (as in our case in the $T \to \infty$ limit), as the boundary conditions are automatically satisfied, and the numerical method is more stable than alternatives such as forward or reverse-shooting (Judd, 1998; Atolia & Buffie, 2009).

3.2   Base case model results

In the first instance, we obtained numerical solutions of the model for our base case calibration, in which climate sensitivity $S = 3°C$, and the model parameters are given by the values in Table 1. Figure 1 plots the optimal controls, per capita consumption c and per capita investment in adaptation I/L, as a function of time. From the left panel of the figure it is clear that climate change has a significant effect on welfare, even admitting the possibility of adaptation, with the consumption path under BAU significantly below that in the 1.5CO$_2$ and 2CO$_2$ scenarios. The right panel demonstrates, unsurprisingly, that the greater the magnitude of climate change, the greater the level of investment in adaptive capital. Although adaptive investment flows are small
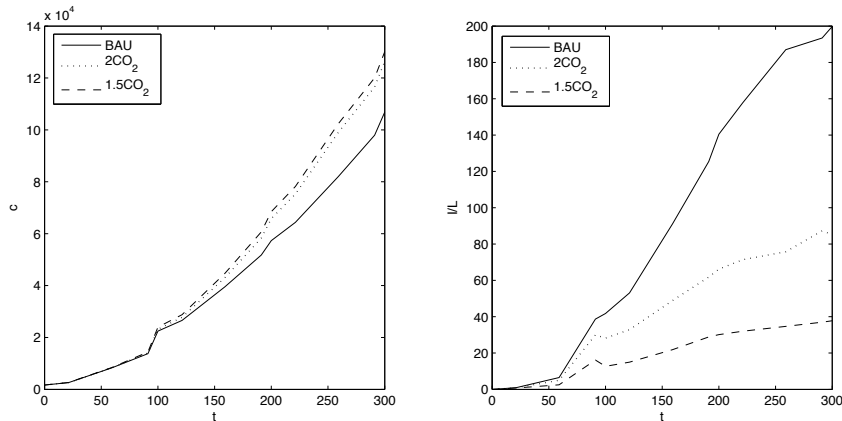

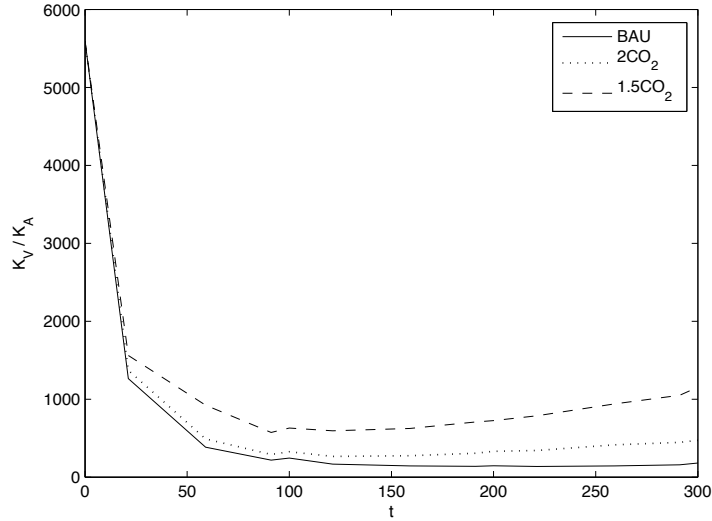Figure 1: Optimal controls for base case model calibration ($S = 3°C$)

Figure 2: Ratio of vulnerable to adaptive capital stocks, base case

relative to consumption, they are not insignificant.

Figure 2, which plots the ratio of vulnerable to adaptive capital stocks over time, demonstrates that adaptive capital is accumulating significantly faster than vulnerable capital under all three climate change scenarios, at least over the first 100 years. In fact, the first 25 years of the model run are characterized by very rapid adaptive investment indeed. It is important to be clear – there is still over 100 times more vulnerable capital than adaptive capital over the entire model horizon, even under the BAU scenario. This is as it should be, since adaptive capital is not productive. To aid the interpretation of this figure, note that

$$\frac{d}{dt}\left(\frac{K_V}{K_A}\right) = \left(\frac{K_V}{K_A}\right)(g_V - g_A),$$ (21)

where g_V, g_A are the growth rates of vulnerable and adaptive capital respectively. Thus when the capital ratio curve is downward sloping, the growth rate of adaptive capital exceeds that of vulnerable capital – this is clearly the case in the first 50 years of the model run. One final qualitative feature of the figure is worth noting – for the first 25 years, the capital ratio curves for the three mitigation scenarios are very close together. This suggests that it is the initial conditions, and not anticipated future climate damages, that dominate the investment rule at early times. The reason for this is that the initial stock of adaptive capital is very low, so that even with climate change of small magnitude at early times, the marginal productivity of adaptive capital is higher than that in the vulnerable sector (due to decreasing returns), leading to a rapid accumulation of adaptive capital stocks. As we shall see in the following section, this result is robust across a large region of the model's parameter space. We perform sensitivity analysis over the initial value of K_A in section 3.3.6. Finally, Figure 3 demonstrates the benefits and costs of adaptation. The left panel demonstrates the reduction in damages obtained by the optimal investment policy in each of the three mitigation scenarios. The benefits are significant, especially so in the BAU scenario.
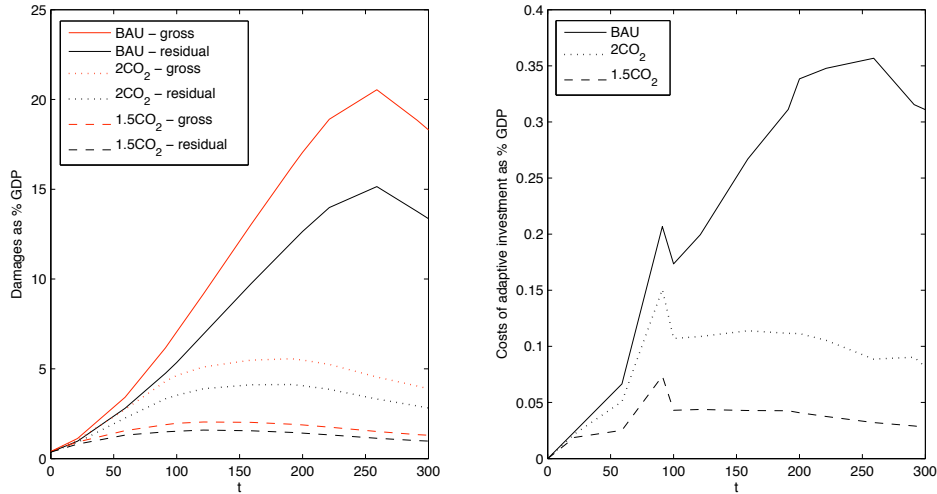
Figure 3: Left panel: Reduction in damages due to optimal accumulation of adaptive capital. Right panel: Flow costs of adaptive investment, as %GDP

The right panel indicates the costs associated with the adaptive investment policy – these are a small fraction of GDP, but through the accumulation of the adaptive capital stock, give rise to a significant amelioration of climate impacts. Thus, in our base case model run, we find that adaptation is an integral part of an optimal development pathway.

3.3 Sensitivity analysis

The analysis of the base case model calibration is suggestive, but should certainly not be read as a definitive finding. Many of the parameters used to generate the results are not at all well pinned down in the existing literature (see e.g. Agrawala & Fankhauser (2008)), thus requiring caution when interpreting the results. In this section we submit our results to a sensitivity analysis, in order to investigate their robustness, and understand the effect of alternative choices for parameters on the model solution. We stress that these results examine only the effect of parametric uncertainty in the model, and not the effect of perturbations to the model structure – we discuss the latter in the conclusions.

To begin, it will be useful to define several summary measures that capture useful information about the effect of a change in parameters on the optimal development policy. We define the stationary equivalent (Weitzman, 1976) of a given policy as the value of consumption per capita which, if held constant, would be equivalent to the welfare achieved by the policy. Formally, if the policy achieves welfare V, the stationary equivalent c^* of the policy is defined implicitly through

$$\int_0^T L(t)U(c^*)e^{-\rho t}dt = V. \tag{22}$$

Thus the stationary equivalent is a welfare measure denominated in the units of consumption per capita, and is evaluated over the same temporal range as V itself. We will find this useful as a

measure of the sensitivity of welfare to model parameters.

Our second set of measures is designed to capture some aspects of the trajectories of the vulnerable and adaptive capital stocks. Clearly, we would like to understand how these trajectories are affected by choices of the model parameters, however it is unilluminating to plot the full set of trajectories over parameter space. Rather, we focus on descriptive statistics of these time series, which aim to summarize the relative importance of adaptive and vulnerable capital over the development pathway. Our measures are the ratio of vulnerable to adaptive capital after 50 and 100 years respectively, and similarly, the difference between the average growth rates of vulnerable and adaptive capital over the first two 50 year periods in the model run. The former measure provides static information about the accumulation of each type of capital, while the later supplies dynamic information about their relative rates of change as the economy evolves. The sensitivities of these scalar measures to model parameters are easily represented in two dimensions.

3.3.1 Climate sensitivity and CO_2 mitigation scenario

Our first sensitivity analysis examines the effect of different assumptions about the value of climate sensitivity and the CO_2 stabilization pathway on welfare in two cases: first assuming optimal investment in vulnerable and adaptive capital, and second assuming no adaptation to climate change. The results are summarized in Figure 4. The figure shows two important things. First, adaptation is significantly welfare enhancing, especially so in the more extreme climate change scenarios, i.e. low mitigation levels, and high climate sensitivity. If one concentrates on the welfare values at the three highest values of S, optimal adaptation is approximately welfare equivalent to a reduction of temperature by $1.5°C$. For example, welfare with optimal adaptation at $S = 6°C$ is approximately equal to welfare without adaptation at $S = 4.5°C$, in each of the 3 mitigation
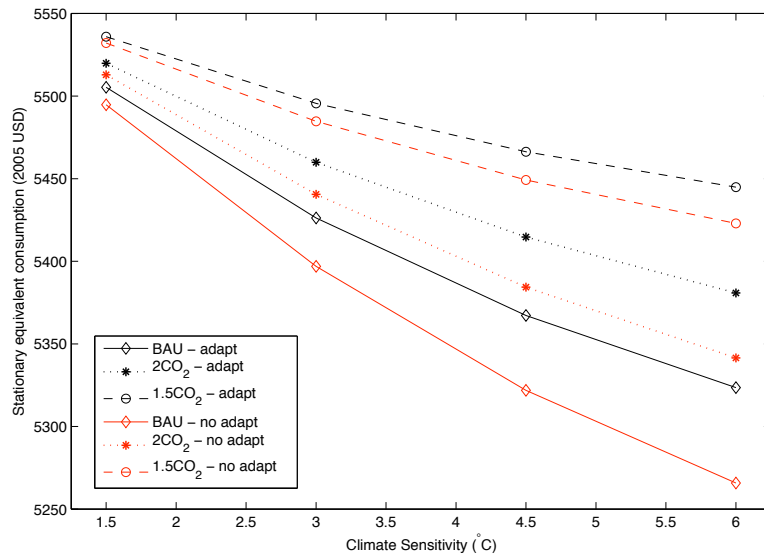

Figure 4: Dependence of welfare on climate sensitivity and global CO_2 mitigation scenario, with and without adaptation

scenarios. This approximation does not hold at $S = 1.5°C$, since welfare has a steep fall-off at low values of S. Second, while adaptation is clearly effective, welfare is still strongly sensitive to the magnitude of climate change. Even with optimal adaptation, global mitigation choices are heavily involved in determining domestic welfare. This argues against the sanguine position adopted by some commentators, who suggest that the impacts of climate change may be simply adapted away (Lomborg, 2007). The figure shows that the difference in welfare between the $1.5CO_2$ and BAU scenarios is larger than the effect of adaptation in either of them. Welfare may be significantly improved by adopting a more ambitious mitigation policy, especially in a high climate sensitivity world.

Figures 5 and 6 demonstrate that our finding that adaptive capital should grow more rapidly than vulnerable capital over the first 100 model years is robust across the range of mitigation scenarios and climate sensitivity values in Figure 18, Appendix B. The ratio of vulnerable to adaptive capital is decreasing in S (Figure 5), since higher S implies greater climate damages, and thus a greater need for adaptive capital. Figure 6 shows that adaptive capital grows substantially faster than vulnerable capital for the first 50 years, with the absolute difference in their growth rates increasing as a function of S. Interestingly, this relationship is inverted over the second 50 model years – although adaptive capital still grows faster than vulnerable capital over this period, the absolute difference in growth rates is smaller the larger is S. Larger S means a greater need for adaptation, and thus a more rapid initial investment in adaptive capital. However, since the stock of adaptive capital is larger for high S, the effects of decreasing returns are felt more for larger S as well. This makes vulnerable capital more competitive after the initial spurt of adaptive capital accumulation, and thus decreases the absolute difference in their growth rates at later times.
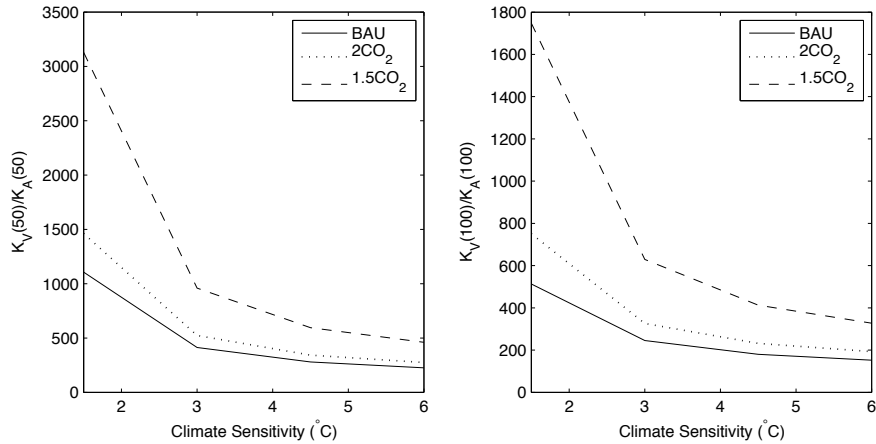

Figure 5: Dependence of capital ratio on climate sensitivity, after 50 and 100 years respectively

3.3.2 Costs of adjustment

The costs of adjustment parameter q is a novel addition to our model. It plays two roles – first it increases the cost of adaptation, and second, it encourages the planner to make anticipatory, cumulative, adaptive investments, since rapid one-off transfers between sectors are penalized heavily.
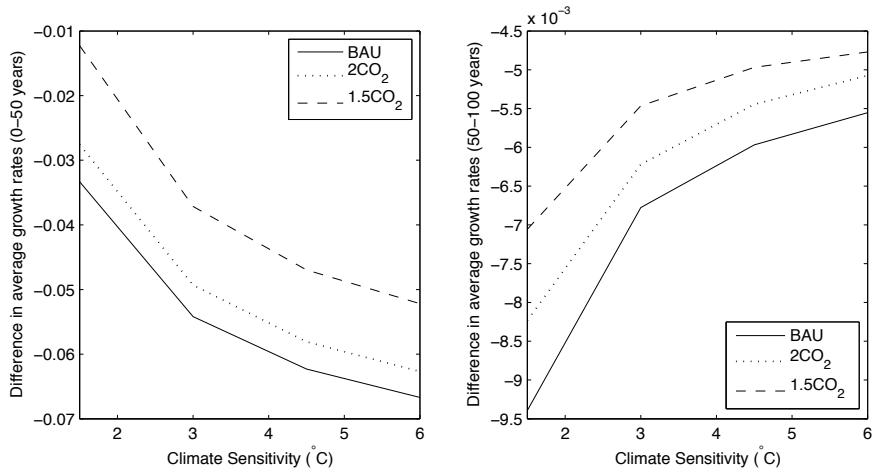
Figure 6: Difference between the average growth rates of vulnerable and adaptive capital, as a function of climate sensitivity, for the first 50 (left panel) and second 50 (right panel) model years.

Figure 20 in Appendix C shows that welfare is relatively insensitive to the value of q. Nevertheless, q does affect the dynamics of capital accumulation. Figure 7 plots the ratio of vulnerable to adaptive capital as a function of q after 50 and 100 years. Increases in the value of q have an increasing effect on the capital ratios, with the ratio after 100 years being significantly more sensitive to q than the ratio after 50 years. This conforms to intuition – high q makes investment in adaptation more costly, thus favouring investment in vulnerable capital, and increasing the capital ratio[4]. It is interesting however that the capital ratio is more sensitive to q after 100 years than after 50 years. This result is driven be the low intial adaptive capital stock, which gives rise to a strong incentive to invest in adaptation early on, regardless of the value of q. Once the initial spurt of adaptive capital accumulation is over however, and decreasing returns to adaptive capital have begun to take effect, an increase in q favours a higher capital ratio.

Figure 8 illustrates that over the range of q values, the average growth rate of adaptive capital is higher than that of vulnerable capital over the first two 50 year periods of the model run, with the growth rates moving closer together as time passes.

3.3.3   Total factor productivity

In order to investigate the sensitivity of the results to assumptions about the time series for TFP, we reran the model over a range of values for its initial growth rate, g_0 in (20). Varying g_0 has a nonlinear effect on the time series for TFP, as demonstrated in Figure 19 in Appendix B, with small changes in its value giving rise to large changes in the resulting time series for $A(t)$ when g_0 is large.

Figure 21 in Appendix C demonstrates that the development pathway of the economy, and associated welfare, is highly sensitive to assumptions about the rate of growth of TFP. Since growth in TFP (along with growth in the population size) drives economic growth in general

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[4]Note that although the absolute magnitude of q is small in this figure, the range of q values corresponds to adjustment costs between 0 and 50% of a \$30 per capita investment at $t = 0$
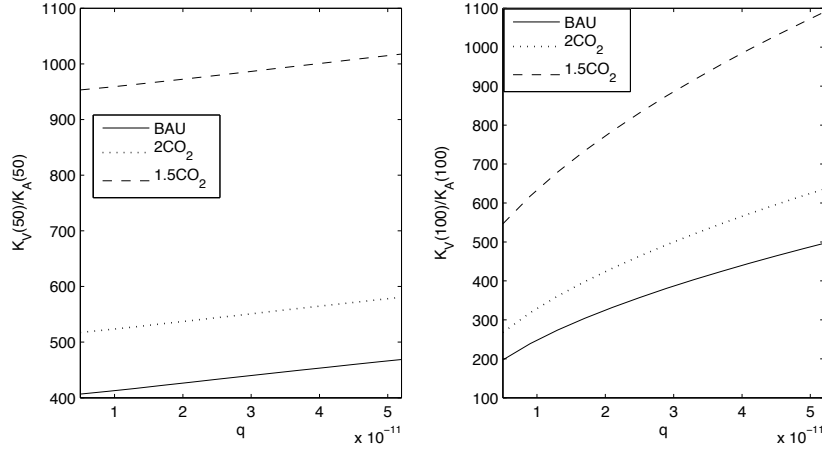
Figure 7: Dependence of capital ratio on cost of adjustment parameter q, after 50 and 100 years respectively
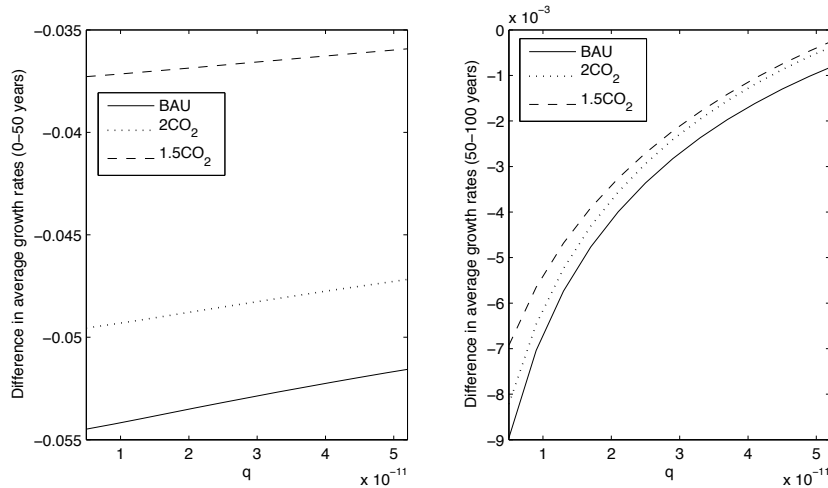

Figure 8: Difference between the average growth rates of vulnerable and adaptive capital, as a function of q, for the first 50 (left panel) and second 50 (right panel) model years.

in the Ramsey model, this is an unsurprising result. Clearly, the value of g_0 is a far greater determinant of welfare than the choice of mitigation policy. This is a feature common to most integrated assessment modeling of climate change – exogenous assumptions about the determinants of aggregate growth drive the results to a large extent (Kelly & Kolstad, 2001).

Figure 9 demonstrates that the capital ratio is largely unaffected by the value of g_0, until one reaches high values of g_0 and at later times, in which case the capital ratio rises with g_0. To understand this, note that when the depreciation rates of adaptive and vulnerable capital are equal (as in our simulations), and the cost of adjustment parameter $q = 0$, equation (11) implies that the capital ratio is independent of $A(t)$ for all time. The fact that $q \neq 0$ in our simulations thus drives the dependence of the capital ratio on g_0. At early times, investment decisions are

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dominated by the initial conditions, and the effects of adjustment costs are largely out-gunned by the difference in productivity in the adaptive and vulnerable sectors. This accounts for the flat curves in the left panel of Figure 9. After 50 years have passed however, adaptive capital has accumulated to a point where the marginal productivities of the two sectors are more equal, and thus the presence of non-zero adjustment costs affects the investment rule and hence the capital stocks. Now increasing g_0 has a symmetric effect on the marginal productivities of adaptive and vulnerable capital, so its effect on the capital ratio must be purely due its influence on total output. Since an increase in g_0 makes future generations more wealthy, and the utility function is concave, increasing g_0 implies that the current capital ratio depends less on the planner's anticipated need to accumulate adaptive capital for the future (which only arises since $q \neq 0$). Thus, the larger is g_0, the lower is the incentive to invest in anticipatory adaptation, and the higher is the capital ratio. Figure 10 shows that our finding that the average growth rate of adaptive capital is higher than that of vulnerable capital is robust across the range of values for g_0. The fact that the difference in average growth rates is more sensitive to g_0 at high values is attributable to the nonlinear effect it has on the TFP time series (see Figure 19).
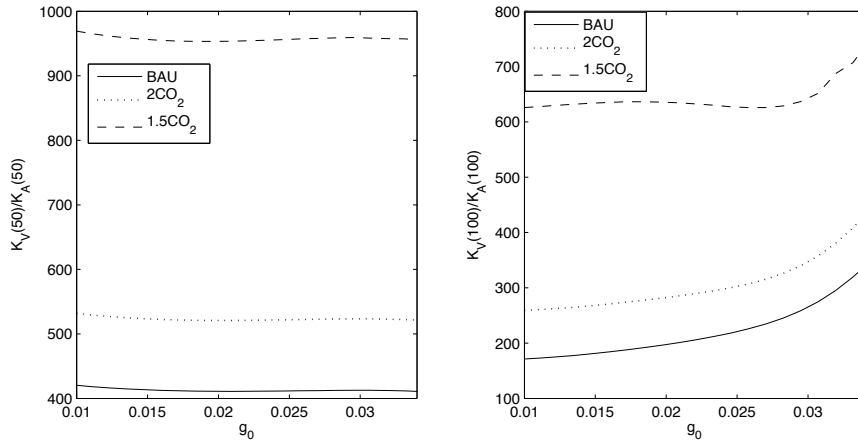

Figure 9: Dependence of capital ratio on initial TFP growth parameter g_0, after 50 and 100 years respectively

3.3.4 Effectiveness of adaptation

Our estimates of the parameters β_1 and β_2 in the residual damage function are based on extrapolations of published literature on adaptation costs and benefits to sub-Saharan Africa. Clearly, these parameters are not well constrained by the literature. In order to investigate how our choices for their values affect our results, we conduct a sensitivity analysis over β_2. We focus on β_2 and not β_1, since the value of β_2 has a larger effect on the returns to adaptation, as it controls the strength of the diminishing returns to adaptive capital. Low values of β_2 imply that high amounts of adaptive capital are required to effectively reduce damages, and that the marginal unit of adaptive capital has a small damage reduction effect. Higher values of β_2 make damages much more responsive to adaptation.
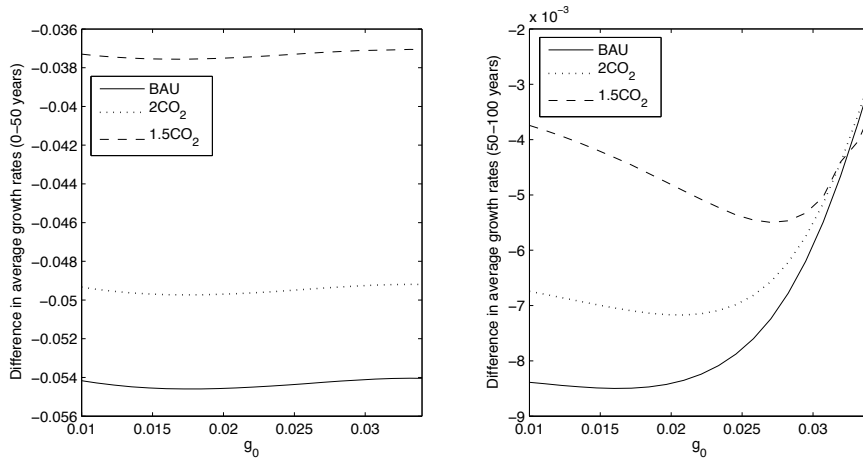
Figure 10: Difference between the average growth rates of vulnerable and adaptive capital, as a function of initial TFP growth g_0, and over the first 50 (left panel) and second 50 (right panel) model years.

Figure 11 demonstrates the dependence of welfare on β_2. The figure's qualitative features are easily explained. As β_2 increases, the welfare differences between the three mitigation scenarios decrease. This is so since high values of β_2 correspond to cases in which adaptation is highly effective at reducing damages. For these values, adaptation is so effective that only small adaptive investments are required to reduce damages substantially (in fact, to near zero for $\beta_2 \approx 0.3$). Hence the higher temperatures that correspond to weaker mitigation scenarios are of little consequence for welfare. For low values of β_2 however, welfare is heavily dependent on the mitigation scenario.
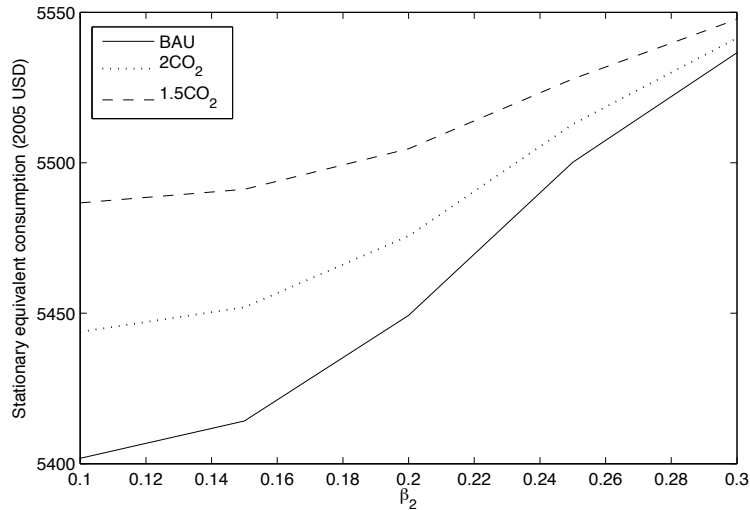

Figure 11: Dependence of welfare on β_2.

The fact that β_2 has such a strong effect on the damage moderating ability of adaptive capital leads to some interesting results for the dynamics of the capital stocks. Figure 12 plots the capital ratio as a function of β_2 – unsurprisingly, these ratios are decreasing in β_2, as an increase in β_2 makes adaptive capital more effective, thus encouraging adaptive investment and decreasing the capital ratio. More interestingly, Figure 13 demostrates that, unlike q and g_0, low values of β_2 can qualitatively alter the dynamics of capital accumulation. The left panel in Figure 13 shows that for low β_2, vulnerable capital grows faster than adaptive capital at early times (the first 5 model years). Figure 14 plots the full time series of the capital ratio for the low value $\beta_2 = 0.1$, showing the early period in which vulnerable capital grows faster than adaptive capital, before declining into the familiar U shape.
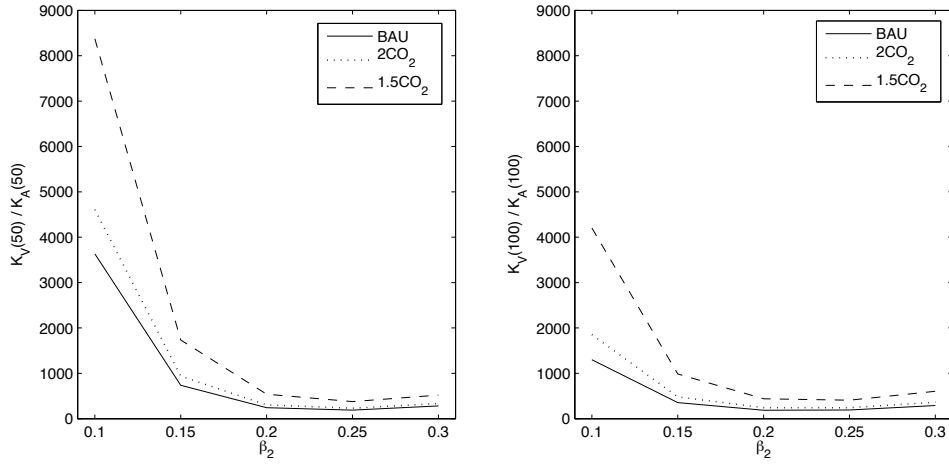

Figure 12: Dependence of capital ratio on effectiveness of adaptation (β_2), after 50 and 100 years respectively
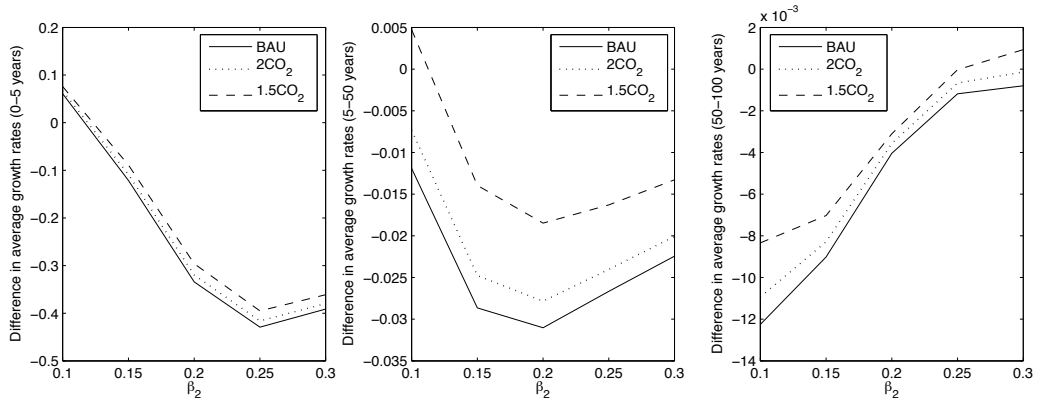

Figure 13: Difference between the average growth rates of vulnerable and adaptive capital, as a function of β_2, for model years 0-5 (left panel), 5-50 (middle panel) and 5-100 (right panel).
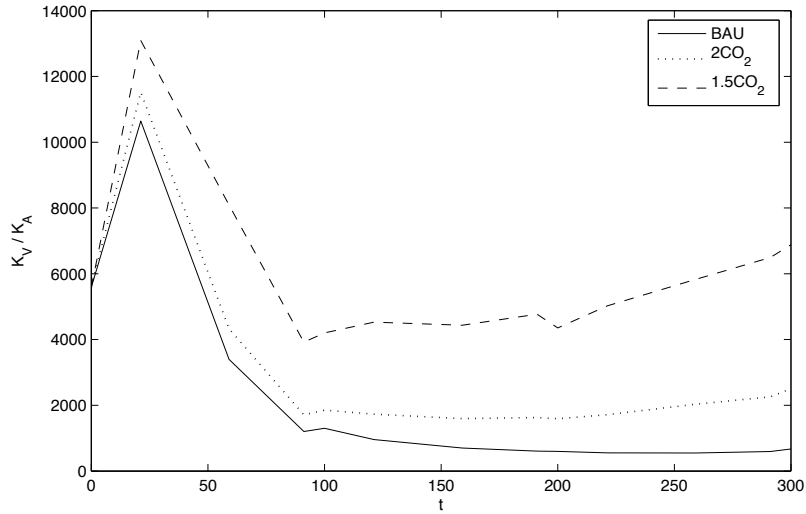
Figure 14: Capital ratio for the low value $\beta_2 = 0.1$. For this value of β_2 it is optimal to engage in a brief period in which 'development' investments are favoured before building up adaptive capital stocks.

3.3.5 Discount rate

The pure rate of time preference ρ represents the degree of impatience amongst the economic agents making investment decisions in the economy. It is well known that its value has a strong effect on the normative evaluation of climate change mitigation policy – indeed differences of opinion about its value largely account for the radically different policy recommendations offered by Stern (2007) and Nordhaus (2008). The effect of ρ on the capita ratio in our model is complex. Increases in ρ tend to favour higher capital ratios in our model (Figure 15). Note however that for the more ambitious 1.5CO$_2$ mitigation scenario, ρ has a non-monotonic effect on the capital ratio. In order to understand this, begin by noting that when the cost of adjustment parameter $q = 0$, the capital ratio should be *independent* of ρ. To see this, simply notice that the singular solution in equation (11) is independent of ρ. Thus the sensitivity of the capital ratio to ρ must be related to the presence of adjustment costs. Adjustment costs give rise to an immediate sunk cost to adaptation – *ceteris paribus*, an increase in ρ will place more emphasis on this cost, giving rise to an increasing capital ratio as a function of ρ. However, an increase in ρ also focusses attention on the immediate damages due to climate change (relative to those in the more distant future), which are of course moderated by the presence of adaptive capital. Note that since adaptive capital is most productive when warming is at its peak, the closer we are to peak warming, the greater the effect of a change in ρ on the optimal value of the adaptive capital stock. Now for the BAU and 2CO$_2$ scenarios, peak warming occurs only in the second or third century of the model run (Figure 18), making the benefits of adaptive capital relatively low at the 50 and 100 year marks considered in Figure (15). Thus, the sunk costs associated with the build up of adaptive capital dominate in the short run, and an increase in ρ leads to an increase in the capital ratio. For the 1.5CO$_2$ scenario however, peak warming occurs after approximately 100 model years, making consideration of the

short run damage reduction effects of adaptive capital more relevant. For low ρ, sunk costs still dominate in this scenario, and the capital ratio is increasing in ρ. However, if ρ increases enough, the benefits of having a high adaptive capital stock to counter peak warming in the short run dominate, and the capital ratio is decreasing in ρ. The effect of the proximity of peak warming on the sensitivity of the capital ratio to ρ is readily seen by comparing the left and right panels of Figure 15. The capital ratio after 100 model years is significantly more sensitive to ρ than after 50 years, since in all cases we are closer to peak warming at this time. Figure 16 tells a similar story for the difference in average growth rates. Appendix C shows that the qualitative dependence of the capital ratio and difference in average growth rates on η, the elasticity of marginal utility, is similar to that of ρ.
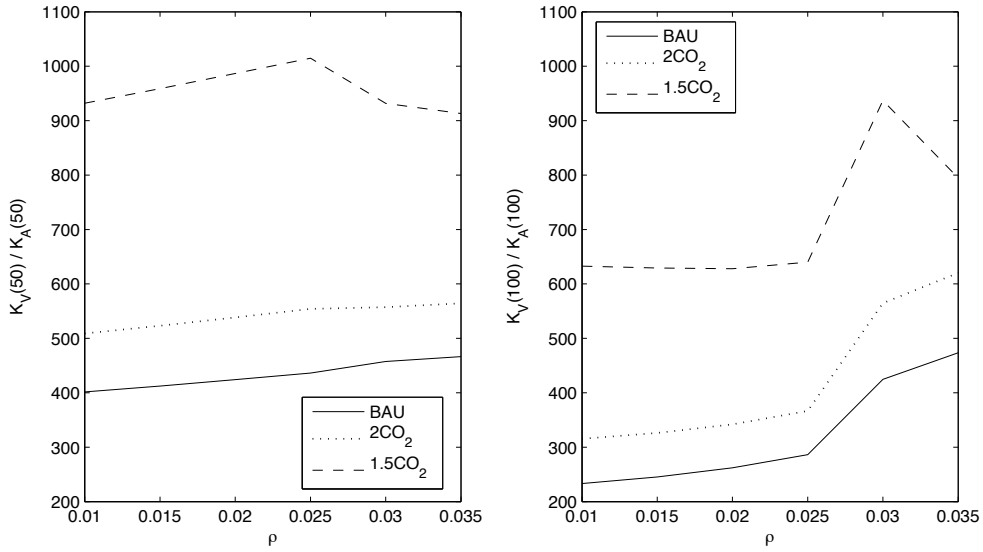

Figure 15: Dependence of capital ratio on discount rate ρ, after 50 and 100 years respectively

3.3.6 Initial stock of adaptive capital

All of our sensitivity analyses thus far have investigated the effects of perturbations to the parameter values assumed in our base case model runs, i.e. they hold the control problem the agent faces fixed, but vary some of its structural parameters. It is also interesting to ask how the results change if we hold the parameters fixed, but vary the control problem by changing the initial conditions. In Figure 17 we plot the dependence of the difference in the average growth rates of vulnerable and adaptive capital as a function of the initial stock of adaptive capital $K_A(0)$[5].

The figure shows that changing the value of $K_A(0)$ can change the qualitative features of capital accumulation, with higher values of $K_A(0)$ tipping the balance of investment towards vulnerable capital in the first 50 years. This result simply reflects the fact that marginal productivity of adaptive capital is decreasing in the capital stock. However, even for large values of $K_A(0)$,

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[5]The dependence of the capital ratios on $K_A(0)$ is not easy to interpret in this case, as changes in $K_A(0)$ have a direct effect on this ratio, and are not only due to the change they induce in the solution to the control problem.
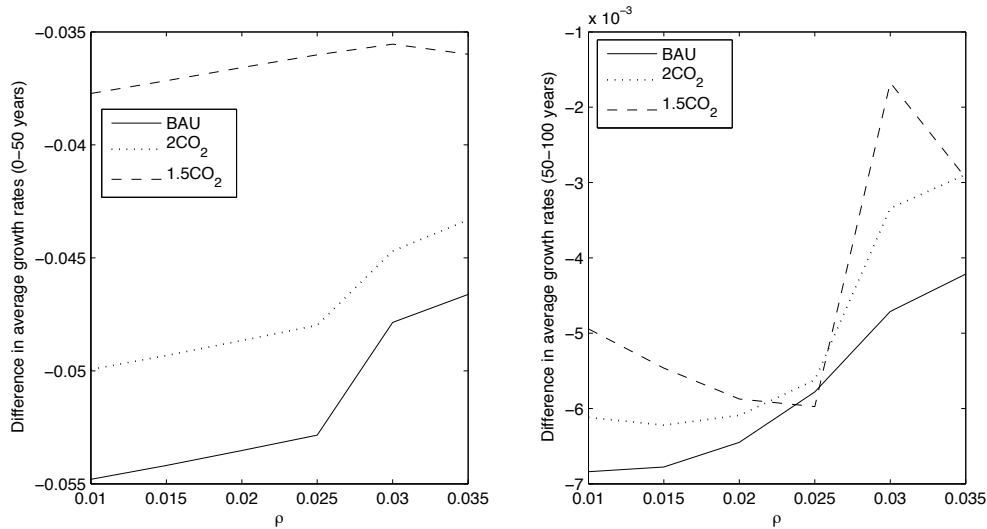
Figure 16: Difference between the growth rates of vulnerable and adaptive capital, as a function of discount rate ρ, after 50 (left panel) and 100 (right panel) years.

adaptive capital grows faster than vulnerable capital over the second 50 years.

We stress that we consider the lowest values of $K_A(0)$ to be the most empirically relevant. Recall that adaptive capital in our model has no productive benefits unless the climate changes, i.e. $X > 0$. With this definition in mind, it seems very unlikely that Sub-Saharan Africa has anything more than a nominal stock of adaptive capital at present. Although there are many capital items currently in place that help reduce vulnerability to current climate variability, these do not count as adaptive capital in our model. Thus, for example, a sea wall designed to protect against storm surge does not contribute to adaptive capital unless it is built higher than it would have been to optimally cope with existing climatic conditions. Only that portion of a wall that is beneficial if the sea level rises counts as adaptive capital. The National Adaptation Programme of Action country database produced by the UNFCCC[6], which collates *proposed* national adaptation projects, shows that, even if we optimistically assume that all the proposed projects are currently in existence, the resulting estimates of current adaptive capital stocks are very low. For example, Zambia proposed adaptation projects valued at approximately \$13 million. Since Zambia's population is also approximately 13 million, this corresponds to \$1 per capita of adaptive capital if all the proposed projects were currently in existence, assuming all the installed capital is exclusively adaptive. The optimism of these assumptions means that lower values are much more likely. Moreover, there is much evidence to suggest that Sub-Saharan African countries lack capital to deal even with current climate variability. For example, a well-known statistic is that Ethiopia has just 1% of the artificial water storage capacity per capita of North America, despite enduring far greater hydrological variability (World Bank, 2006b). Overall then, we believe that very low values of the initial adaptive capital stock are most plausible.

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[6]Available at: http://unfccc.int/cooperation_support/least_developed_countries_portal/napa_priorities_database/items/4583.php
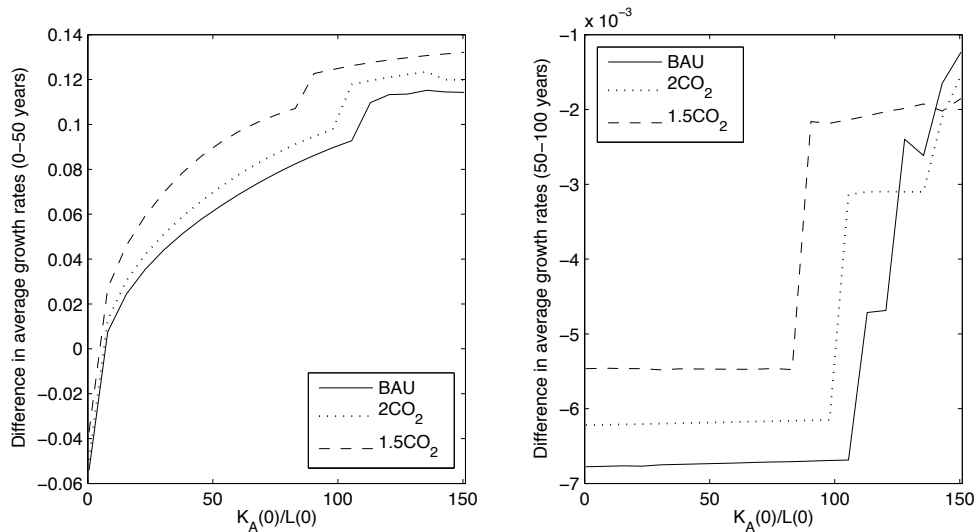
Figure 17: Difference between the growth rates of vulnerable and adaptive capital, as a function of the initial stock of adaptive capital per capita $K_A(0)/L(0)$, after 50 (left panel) and 100 (right panel) years.

4 Discussion

The model we have developed offers a theoretical framework for adjudicating between competing arguments about the level and timing of optimal investment in adaptive capital stocks. Our model has the benefit of making the sensitivity of policy recommendations to key assumptions understandable and transparent. We are thus able to determine which model parameters are most important in determining the qualitative features of the model solutions, and why they affect the results as they do. For a problem as beset by uncertainty as climate change adaptation, we see this kind of analysis as a necessary condition for the useful application of economic models to policy questions. Many of the key parameters of the adaptation problem are highly uncertain, so precise quantitative policy prescriptions are likely to be out of reach, thus heightening the importance of a qualitative understanding of the dynamics of successful adaptation.

Our model is a simple Ramsey-style economic growth model with exogenous technological progress, and two capital stocks – the one productive but vulnerable to exogenous climate impacts, the other reducing the damages the vulnerable sector sustains. By initially simplifying to the special case of constant labour and total factor productivity, we obtained some analytical results about the comparative dynamics of investment in adaptive capital. We showed that adaptive investment is positive when temperatures are increasing, even when the vulnerable sector is growing, thus arguing against a simplistic 'adapt through development' position. We also investigated how the rate of response of the adaptive investment rule to changes in the temperature depends on the wealth of the economy, as measured by its stock of vulnerable capital. We showed that whether or not rich economies have a stronger proportional response to a change in temperature depends on whether the elasticity of the damage multiplier with respect to temperature is higher than its elasticity with respect to adaptive capital. This is a complex condition, which depends on

the parametric form of the damage multiplier, as well as the stock of adaptive capital and magnitude of temperature change. Certainly, the extant empirical literature is not able to determine whether this condition is satisfied for all time, so it is not clear *a priori* that wealthier economies have less need for adaptive investment. Thus, we conclude that the problem of optimally allocating investment between vulnerable and adaptive capital is not a simple matter, and deserving of careful analysis beyond the at times *ad hoc* recommendations in the existing literature.

In order to progress beyond these suggestive analytical results, we proceeded to implement a full version of our model with exogenously evolving technology and labour, and costs of adjustment which limit the ability of the economy to rapidly adjust to changing climatic conditions. Our base case model results show substantial investment in adaptive capital, which brings about large welfare benefits, especially in the more extreme climate change scenarios. We also find that it is optimal to grow the stock of adaptive capital more rapidly than vulnerable capital early on – the ratio of vulnerable to adaptive capital is declining for at least the first 100 model years. This result reflects the fact that returns are greater in the adaptive sector than the vulnerable sector when the adaptive capital stock is low – in part due to the concavity of the production functions in each of these sectors, in part due to the persistent benefits of adaptive capital over time, and in part due to the need to make anticipatory adaptive investments so that the stock of adaptive capital is high when temperatures are at their peak.

In order to investigate the robustness of these results to our parameterization of the model, we conducted sensitivity analysis over key parameters – the climate sensitivity and CO_2 stabilization scenario, the costs of adjustment, the rate of growth of TFP, the effectiveness of adaptation, the discount rate and elasticity of marginal utility, and the initial stock of adaptive capital. We found that in almost all cases, and over plausible ranges for the relevant parameters, our core finding that the rate of growth of adaptive capital exceeds that of vulnerable capital at early times is preserved. We investigated the sensitivity of the capital ratio (which quantifies the relative importance of vulnerable and adaptive capital), and difference in growth rates of the capital stocks (which tells us about differences in the dynamics of capital accumulation), to each of these parameters, and we were able to show that the results follow logically from the model structure. Although our sensitivity analysis was not exhaustive (a practical impossibility given the high dimensionality of the parameter space in even our simple model), we focussed on the most important parameters for the problem at hand. Other parameters, for example the coefficients and exponent of the gross damage multiplier, the capital share of production, and labour time series, clearly affect the model results as well, however their effects on the economic dynamics are partially mimicked by our existing sensitivity analysis. For example, the sensitivity of our results to higher damage estimates associated with higher values for α_1 and α_2 in the damage multiplier, as well as to a functional form including higher-order terms (e.g. Weitzman, 2010), are partially accounted for by our analysis of different values of the climate sensitivity S, different mitigation scenarios, which affect damages as well, and the effectiveness of adaptation β_2. In the same way, changes to the growth rate of labour are similar to changes in TFP growth.

The only parameters that were able to disturb our qualitative finding that it is optimal to grow adaptive capital rapidly initially were β_2, the exponent of adaptive capital in the residual damage function, and the initial stock of adaptive capital. β_2 controls the effectiveness of adaptation, i.e. how the damage-reducing ability of adaptive capital scales with the size of the stock. If β_2 is low, it

is optimal to grow the stock of vulnerable capital rapidly for a brief initial period, before once again investing heavily in adaptive capital. Thus, from the point of view of policy, tying down the value of β_2, or a similar measure of the dynamic effectiveness of adaptation, should be a high empirical priority. Large initial stocks of adaptive capital mean that the effects of decreasing returns are felt more strongly, making adaptation a less attractive investment relative to vulnerable capital. However, we have argued that current stocks of adaptive capital are likely to be very low in most developing countries. Thus, the model results for high initial adaptive capital are of questionable relevance for empirical applications.

Our model could be extended in several directions. Clearly economic modeling of adaptation planning in general would be immeasurably improved by better empirical estimates of the costs and benefits of adaptation. This is always going to be a challenge, as it is in large part an extrapolation exercise: costs depend on irreducible uncertainties about technological progress, and benefits on the scale, composition and climatic vulnerability of future economic activity, none of which is directly estimable from past data. Nevertheless, more empirical studies of all varieties are needed, especially for developing regions like Sub-Saharan Africa. An assumption in our model deserving of further analysis is that adaptive capital is more effective at damage reduction at high temperatures than at low ones. As a first pass at the problem of modeling the effects of adaptation, this is an intuitive assumption to work from. However it may not hold at all temperatures – if climate change is severe enough, the marginal unit of adaptive capital may have little impact on damages. This reasoning suggests that there may be threshold effects which moderate adaptive investment strategies[7], but the nature of such thresholds is very poorly understood and is particularly affected by the problem of extrapolation mentioned above. A further important caveat to our results concerns our neglect of learning effects and optimal policies that account for uncertainty. The learning process, and its associated costs, is an important part of the adaptive process, since economic agents are unlikely to have good predictions of the effects of climate change, and will engage in reactive adaptation and incremental adjustment of their adaptive plans as information is revealed to them over time (Kelly et al., 2005; Schneider et al., 2000). The optimal policies determined by our model are not responsive to this uncertainty – our results are thus analogous to those of Nordhaus (2008) in the mitigation literature (who also solves deterministic control problems, but does sensitivity analysis over the solutions), rather than the stochastic dynamic programming approach in e.g. Kelly & Kolstad (1999) (in which optimal policies account for uncertainty and learning effects). An extension of our model to account for learning is planned in future work.

Finally, there are two further issues that are likely to be important for adaptation, which are not readily amenable to analysis in a model such as ours: short-run climatic shocks, and institutions. The Ramsey growth model and the reduced form damage function approach are unlikely to provide faithful representations of the economic effects of climatic extremes and their associated short-run macroeconomic consequences. Extremes are likely to increase in frequency and magnitude as climate change intensifies, and are important determinants of short-run economic outcomes in developing countries. Similarly, robust institutions are likely to aid in the adaptive process, reducing its cost and improving its effectiveness, in much the same manner as they

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[7]i.e. perhaps $D_{aX} > 0$ for $X < X^*$, $D_{aX} < 0$ for $X \leq X^*$ for some threshold X^*, and $D_a = 0$ for some catastrophic value $X = X^{**} > X^*$ at which adaptation has no effect on damages.

stimulate economic development more generally (Acemoglu et al., 2005). Alternative models which incorporate their effects are likely to play an important role in informing adaptation policy in the future.

A   Proof of Proposition 2

Using the Inada conditions on the production function F, it is easy to show that

$$\lim_{K_V \to 0} \frac{f'(K_V)}{f(K_V)} = \infty \quad \lim_{K_V \to \infty} \frac{f'(K_V)}{f(K_V)} = 0 \tag{23}$$

which, through the definition (13), implies that

$$\lim_{K_V \to 0} R_X = -\frac{D_X}{D_a} \quad \lim_{K_V \to \infty} R_X = -\frac{D_{aX}}{D_{aa}}. \tag{24}$$

Now write $R_X = A/B$, where A, B are the numerator and denominator of the expression in (13) respectively. Then

$$\frac{\partial R_X}{\partial K_V} = \frac{\left[-\frac{d}{dK_V}\left(\frac{f'}{f}\right)D_X\right]B - \left[\frac{d}{dK_V}\left(\frac{f'}{f}\right)D_a\right]A}{B^2} \tag{25}$$

$$= \frac{\frac{d}{dK_V}\left(\frac{f'}{f}\right)D_a\left(-\frac{D_X}{D_a} - \frac{A}{B}\right)}{B} \tag{26}$$

$$= \frac{\frac{d}{dK_V}\left(\frac{f'}{f}\right)D_a(R_X(0) - R_X(K_V))}{B} \tag{27}$$

where $R_X(K_V)$ denotes R_X evaluated at K_V, with the dependence on K_A, X suppressed, and $R_X(0) = \lim_{K_V \to 0} R_X(K_V)$ is given by the limiting value in (24). Now it is easy to show that $\frac{d}{dK_V}\left(\frac{f'}{f}\right) < 0$ (this follows from the concavity of f), and the denominator B and D_a are both positive. Hence we have that

$$\frac{\partial R_X}{\partial K_V} > 0 \iff R_X(K_V) > R_X(0). \tag{28}$$

This condition implies that R_X is a monotonic function of K_V. We can determine whether it is increasing or decreasing, since we know the limiting values of $R_X(K_V)$. If $R_X(0) < R_X(\infty)$, R_X must be increasing, and vice versa. Since the expressions for the limiting values of $R_X(K_V)$ are given in terms of the derivatives of D in (24), we have that $R_X(K_V)$ is increasing if and only if

$$-\frac{D_{aX}}{D_{aa}} > -\frac{D_X}{D_a} \tag{29}$$

$$\iff -K_A\frac{D_{aa}}{D_a} < -K_A\frac{D_{Xa}}{D_X}.$$

To prove that R_V is decreasing in K_V when $f(K_V) = K_V^\alpha$, $\alpha \in [0, 1]$, simply perform the

differentiation of R_V with respect to K_V explicitly to find

$$\text{sgn}\left[\frac{\partial R_V}{\partial K_V}\right] = \text{sgn}\left[\frac{1-\alpha}{K_V}\left(\frac{1}{\alpha} + \frac{2}{K_V}\right)DD_{aa} - 2\alpha(1-\alpha)DD_a + \frac{1}{\alpha}D_aD_{aa}\right]. \qquad (30)$$

Since $D > 0$, $D_a > 0$, $D_{aa} < 0$, the result follows.

B Time series inputs to sensitivity analysis

We parameterized the temperature trajectories $X(t)$ in our model on two axes – global CO_2 concentration and climate sensitivity (S). We ran the global DICE model for Business As Usual (BAU), stabilization at twice the preindustrial CO_2 level ($2CO_2$), and stabilization at 1.5 times the preindustrial CO_2 level ($1.5CO_2$), and for $S \in \{1.5°C, 3°C, 4.5°C, 6°C\}$, generating a global temperature trajectory for each configuration (see Figure 18). Figure 19 displays the time series for the total factor productivity that arise from varying the initial growth rate g_0 in equation (20).
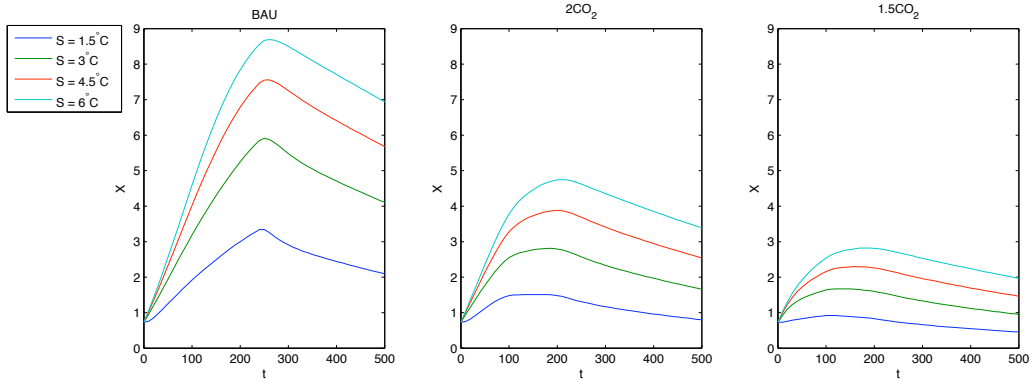
Figure 18: Temperature series corresponding to alternative global CO_2 concentration trajectories, for several values of the climate sensitivity S.
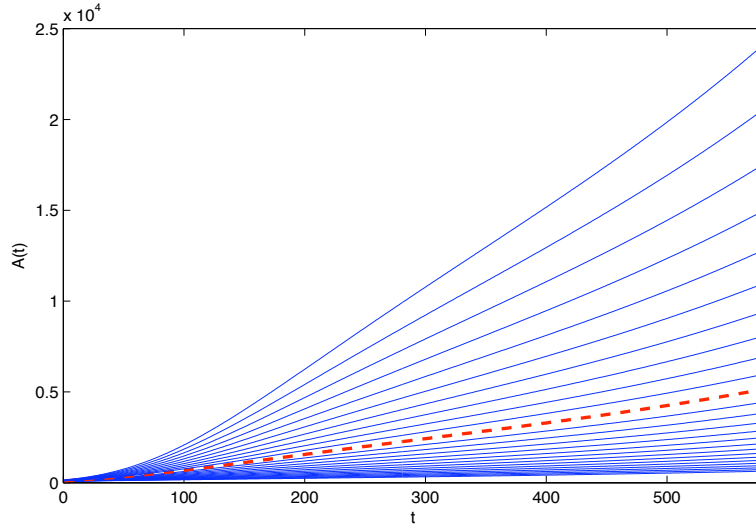

Figure 19: Time series of $A(t)$ used in sensitivity analysis, corresponding to a 1-σ variation of the initial growth rate of TFP, g_0 in (20). The red dashed line is the best guess value for g_0.

29

C   Supplementary sensitivity results

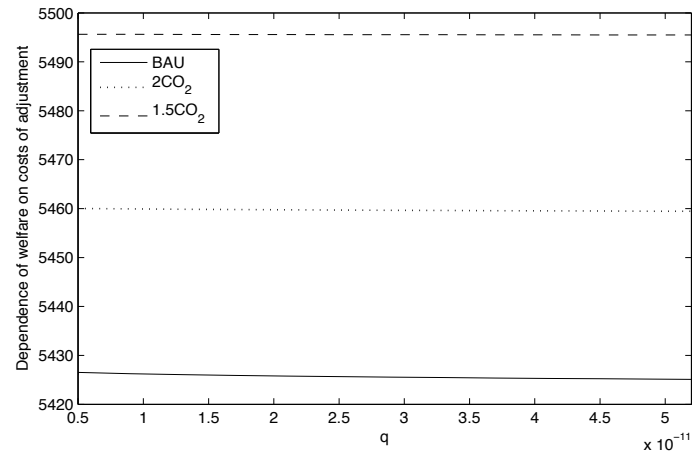## C.1   Welfare sensitivities

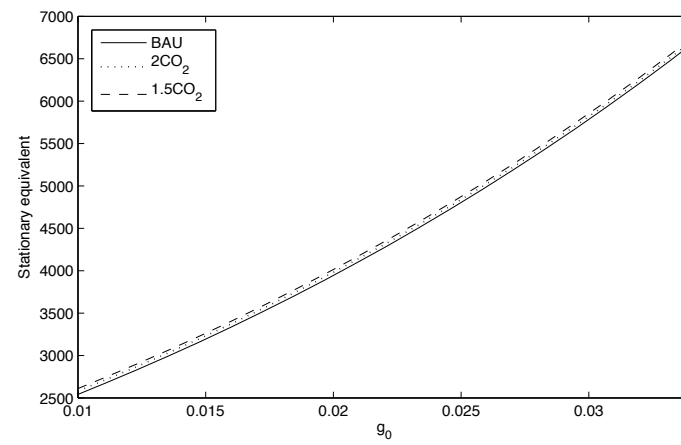Figure 20: Dependence of welfare on cost of adjustment parameter q.

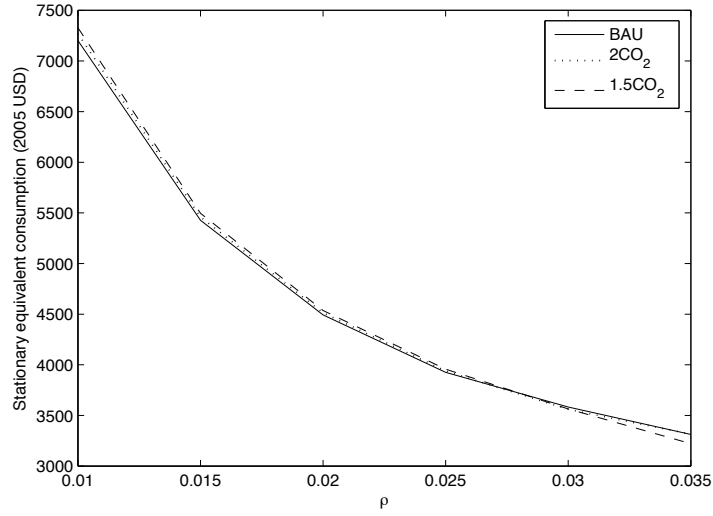Figure 21: Dependence of welfare on initial TFP growth g_0.
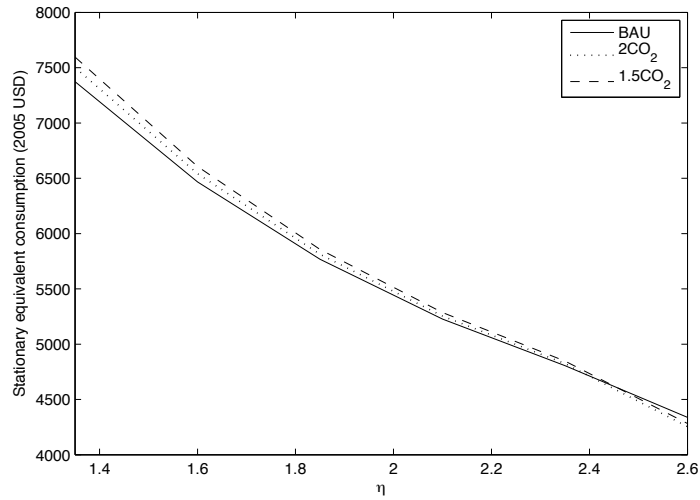
Figure 22: Dependence of welfare on ρ.

Figure 23: Dependence of welfare on η.

C.2 Elasticity of Marginal Utility

The qualitative features of the sensitivity analysis for η, the elasticity of marginal utility, are due to much the same processes as those described above in the case of the discount rate ρ. Since an increase in η increases the desire to smooth consumption over time, and future generations are weathier than present generations, an increase in η is similar to increasing the value of ρ. This can be made precise by noting that, since there is no endogenous uncertainty in our model, the social discount rate δ at time t is given by $\delta(t) = \rho + \eta g_c(t)$, where $g_c(t)$ is the growth rate of consumption at time t. Thus, increasing η places more weight on the short-run, causing the capital

ratio to increase in η when sunk costs due to adjustment dominate the short-run benefits of the adaptive capital stock, and vice versa. Figures 24 and 25 illustrate the qualitative similarity to the sensitivity analysis over ρ.
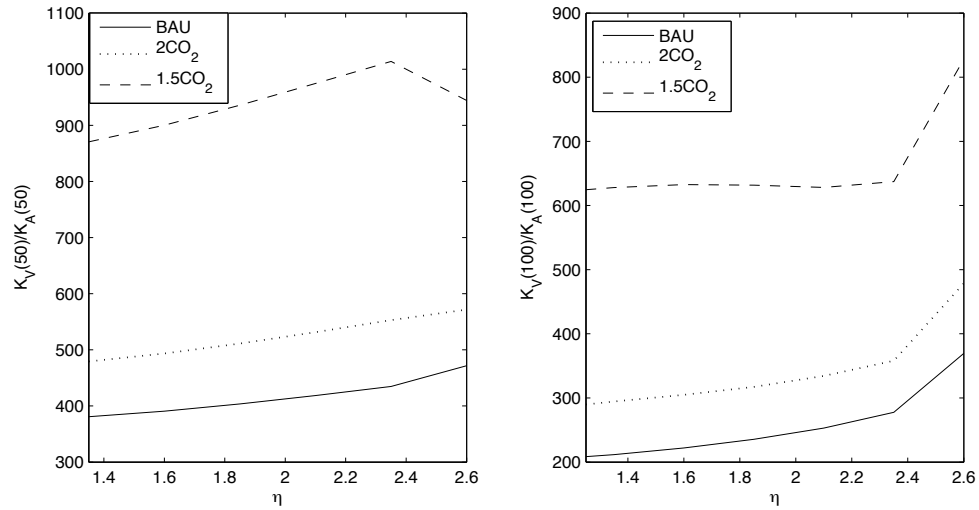

Figure 24: Dependence of capital ratio on elasticity of marginal utility η, after 50 and 100 years respectively
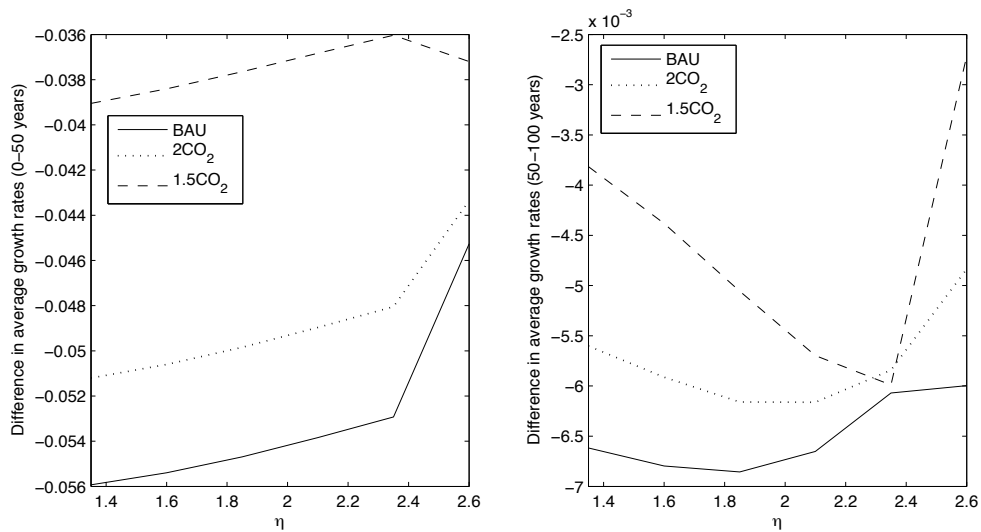

Figure 25: Difference between the average growth rates of vulnerable and adaptive capital, as a function of η, after the first 50 (left panel) and second 50 (right panel) years.

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