Adaptation to climate change and economic growth in developing countries: Online Appendix

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A Proof of Proposition 1

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

$$\lim_{k_V \to 0} \frac{f'(k_V)}{f(k_V)} = \infty \quad \lim_{k_V \to \infty} \frac{f'(k_V)}{f(k_V)} = 0 \tag{1}$$

which, through the definition (14), implies that

$$\lim_{k_V \to 0} R_X = -\frac{D_X}{D_a} \quad \lim_{k_V \to \infty} R_X = -\frac{D_{aX}}{D_{aa}}. \tag{2}$$

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Now write $R_X = A/B$, where A, B are the numerator and denominator of the expression in (14) respectively. Then

$$\frac{\partial R_X}{\partial k_V} = \frac{\left[-\frac{d}{dk_V}\left(\frac{f'}{f}\right) D_X\right] B - \left[\frac{d}{dk_V}\left(\frac{f'}{f}\right) D_a\right] A}{B^2} \tag{3}$$

$$= \frac{\frac{d}{dk_V}\left(\frac{f'}{f}\right) D_a(-\frac{D_X}{D_a} - \frac{A}{B})}{B} \tag{4}$$

$$= \frac{\frac{d}{dk_V}\left(\frac{f'}{f}\right) D_a(R_X(0) - R_X(k_V))}{B} \tag{5}$$

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 (2). 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

$$\frac{\partial R_X}{\partial k_V} > 0 \iff R_X(k_V) > R_X(0). \tag{6}$$

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 (2), we have that $R_X(k_V)$ is increasing if and only if

$$\begin{aligned} -\frac{D_{aX}}{D_{aa}} &> -\frac{D_X}{D_a} \\ \iff -K_A\frac{D_{aa}}{D_a} &< -K_A\frac{D_{Xa}}{D_X}. \end{aligned} \tag{7}$$

This is the condition in the proposition.

To prove that R_V is decreasing in k_V, perform the differentiation of R_V with respect to

k_V explicitly to find

$$\operatorname{sgn}\left[\frac{\partial R_V}{\partial k_V}\right] = \operatorname{sgn}\left[\left(f'''f - f''f'\right) DD_{aa} - \left(f'''f' - f''^2\right) DD_a + \left(f'^2 - ff''\right) D_a D_{aa}\right]. \quad (8)$$

Since $D > 0$, $D_a > 0$, $D_{aa} < 0$, all the factors that depend on f and its derivatives above must be positive if R_V is decreasing in k_V. We now show that this is the case. By manipulating the three f dependent factors (using the fact that $f > 0, f' > 0, f'' < 0$), we can see that they are all positive iff:

$$f'''/f'' < f''/f' < f'/f \quad (9)$$

Now recall that f is a homogeneous function, i.e. $f(mx) = m^\alpha f(x)$ for some α. Differentiate this identity with respect to m, and evaluate the resulting expression at $m = 1$ to find

$$xf'(x) = \alpha f(x) \quad (10)$$

$$\Rightarrow f'/f = \alpha/x \quad (11)$$

Now when f is homogenous of degree α, f' is homogenous of degree $\alpha - 1$, and f'' is homogenous of degree $\alpha - 2$. Thus we have

$$f''/f' = \frac{\alpha - 1}{x} \quad (12)$$

$$f'''/f'' = \frac{\alpha - 2}{x} \quad (13)$$

Thus, we have that $f'''/f'' < f''/f' < f'/f$. Hence $\frac{\partial R_V}{\partial k_V}$ is negative.

Finally, differentiating the expession (16) with respect to k_V shows that

$$\operatorname{sgn}\left[\frac{\partial R_H}{\partial k_V}\right] = \operatorname{sgn}\left[D_{aa} f' - D_a f''\right] \tag{14}$$

from which 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 A1). Figure A2 displays the time series for the total factor productivity that arise from varying the initial growth rate g_0 in equation (22).

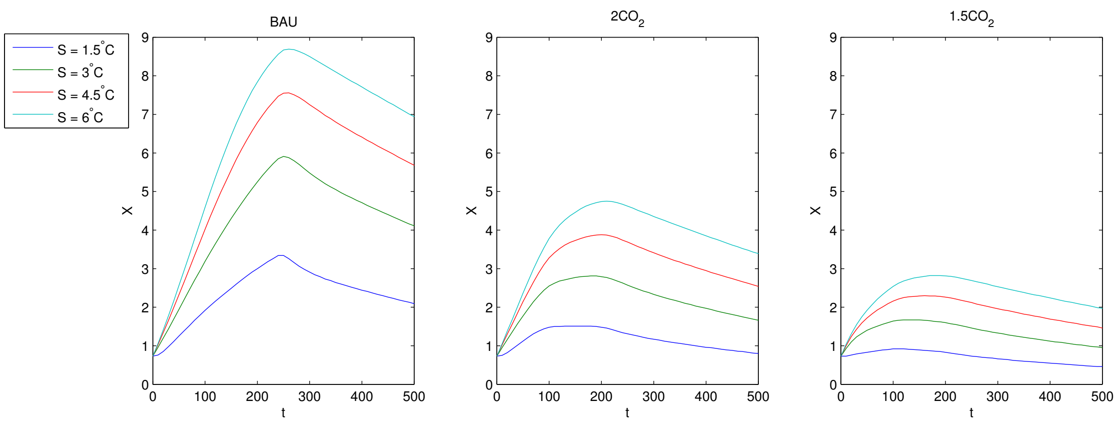


Figure A1: Temperature series corresponding to alternative global CO_2 concentration trajectories, for several values of the climate sensitivity S.

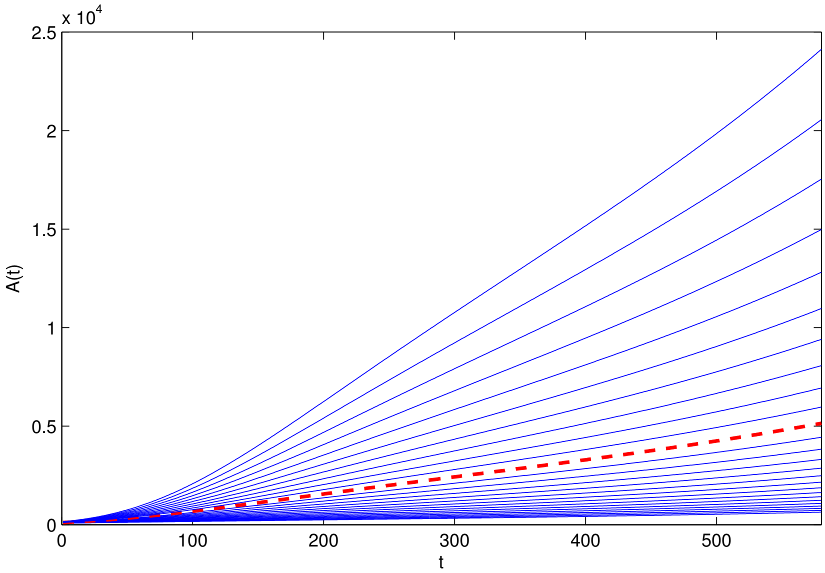


Figure A2: Time series of $A(t)$ used in sensitivity analysis, corresponding to a 1-σ variation of the initial growth rate of TFP, g_0 in (22). The red dashed line is the best guess value for g_0.

C Further sensitivity analysis

C.1 Costs of adjustment

The costs of adjustment parameter q plays two roles in our model – 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 A3 shows that welfare is relatively insensitive to the value of q. Nevertheless, q does affect the dynamics of capital accumulation. Figure A4(a) 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 optimal 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[1]. The fact that the capital ratio is more sensitive to q after 100 years than after 50 years is due to the fact that I is increasing on the optimal path, and $\frac{\partial^2 Q}{\partial I \partial q} > 0$. Since I is larger for later times, a change in q has a bigger effect on the costs of adaptation at later times too.

Figure A4(b) 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.

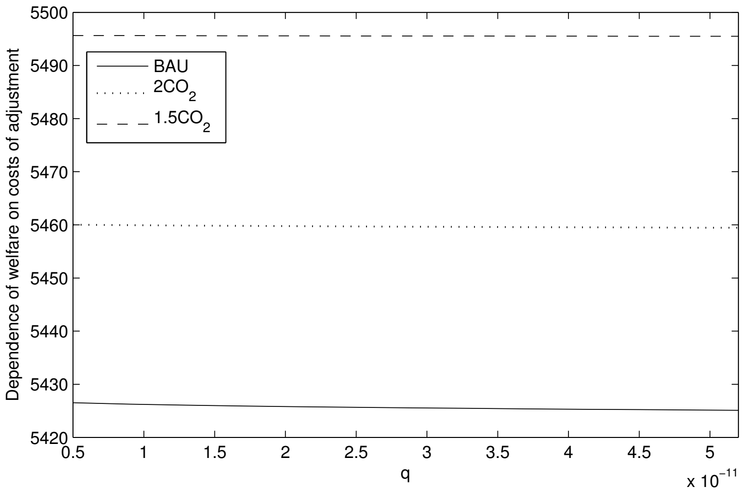
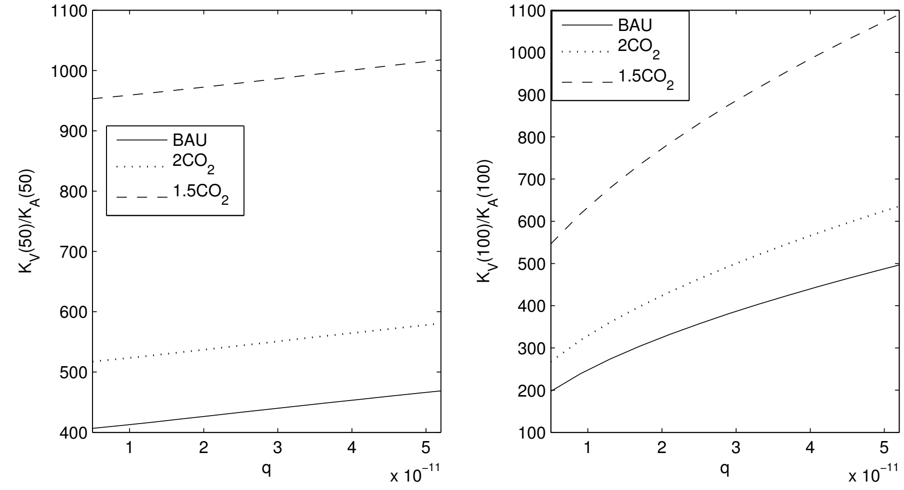


Figure A3: Dependence of welfare on cost of adjustment parameter q.

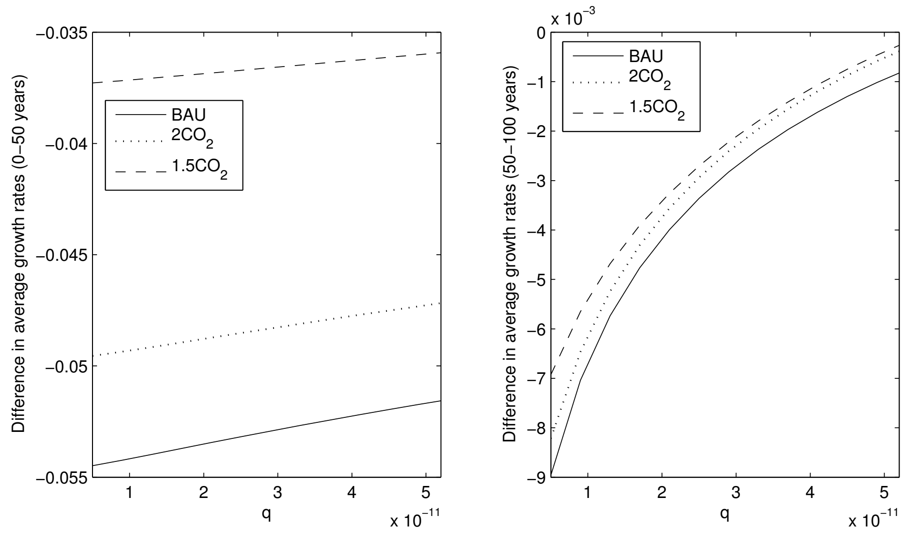
C.2 Total factor productivity

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 (22). Varying g_0 has a nonlinear effect on the time series for TFP, as demonstrated in Figure A2 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.

[1] 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 $t = 0$



(a) Dependence of capital ratio on cost of adjustment parameter q, after 50 (left panel) and 100 (right panel) years.



(b) 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.

Figure A4: Dependence of optimal capital trajectories on adjustment costs (q)

Figure A5 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 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).

Figures A6(a) and A6(b) demonstrate that the capital ratio and difference in growth rates are largely unaffected by the value of g_0 in the first 50 year period. In the second 50 year period the capital ratio rises with g_0. To understand this finding note that TFP affects the marginal returns to investment in the adaptive and vulnerable sectors symmetrically. Thus the consequences of an increase in the the TFP growth rate are mediated through the consumption discount rate, $r(t) = \rho + \eta g_c(t)$, where $g_c(t)$ is the growth rate of consumption at time t ($g_c(t)$ is increasing in g_0), rather than through changes in the relative productivity of the two sectors. At early times, investment decisions are dominated by the initial conditions, with the marginal product of adaptive investment far exceeding that of investment in vulnerable capital. This explains the relative insensitivity of the capital ratio to g_0 over the first 50 years. At later times however adaptive capital has already accumulated, reducing the difference in productivity between the two sectors. In this case increasing the consumption discount rate (via an increase in g_0) places more emphasis on the present, thus decreasing the incentive to anticipate future climate damages by building up the stock of adaptive capital. This explains the upward sloping curves in the second 50 year period. 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 A2).

C.3 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

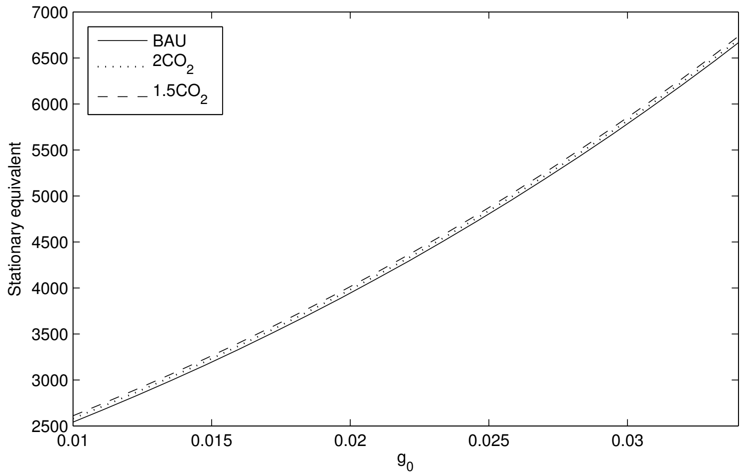
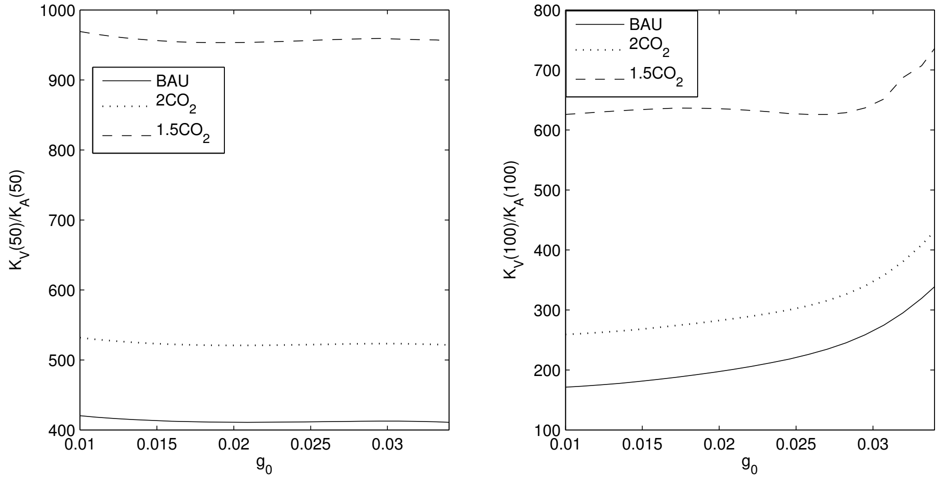


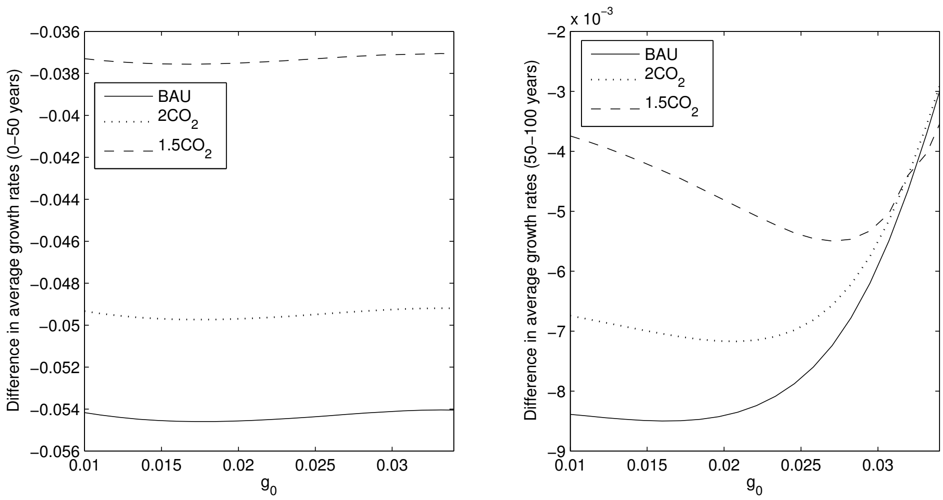
Figure A5: Dependence of welfare on initial TFP growth g_0.

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 capital ratio in our model is complex. Increases in ρ tend to favour higher capital ratios in our model (Figure A8(a)).Note however that for the more ambitious $1.5CO_2$ mitigation scenario, ρ has a non-monotonic effect on the capital ratio.

The sensitivity of the capital ratio to ρ is 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 A1), making the benefits of adaptive capital relatively low at



(a) Dependence of capital ratio on initial TFP growth parameter g_0, after 50 (left panel) and 100 (right panel) years respectively.



(b) 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 A6: Dependence of optimal capital trajectories on the initial growth rate of TFP (g_0).

the 50 and 100 year marks considered in Figure A8(a). 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 A8(a). 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 A8(b) tells a similar story for the difference in average growth rates.

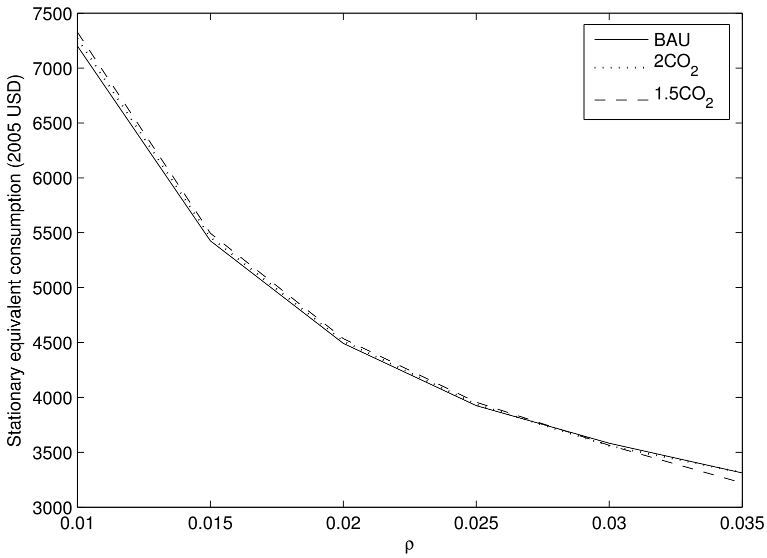
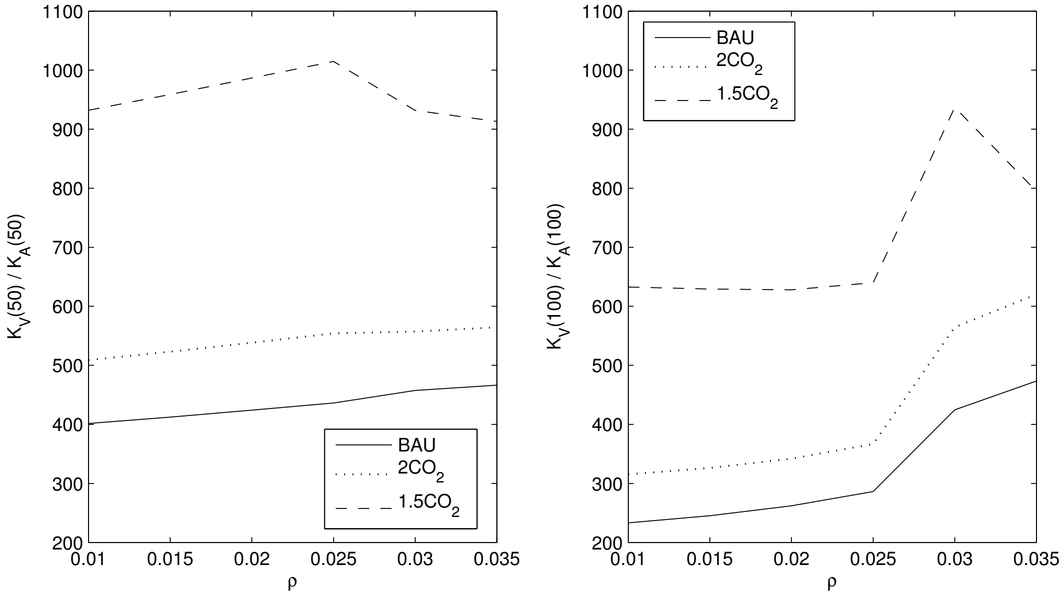


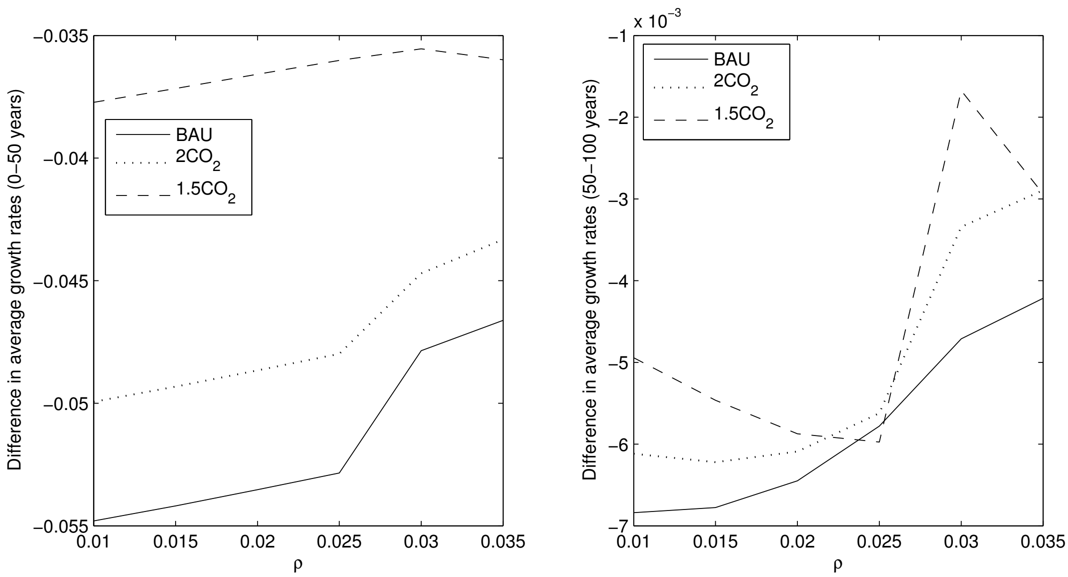
Figure A7: Dependence of welfare on ρ.

C.4 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 wealthier than present generations, an increase in η is similar to increasing



(a) Dependence of capital ratio on discount rate ρ, after 50 (left panel) and 100 (right panel) years.



(b) 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.

Figure A8: Dependence of optimal capital accumulation trajectories on the utility discount rate (ρ).

the value of ρ – they both increase the social discount rate $r(t)$. 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 A10 and A11 illustrate the qualitative similarity to the sensitivity analysis over ρ.

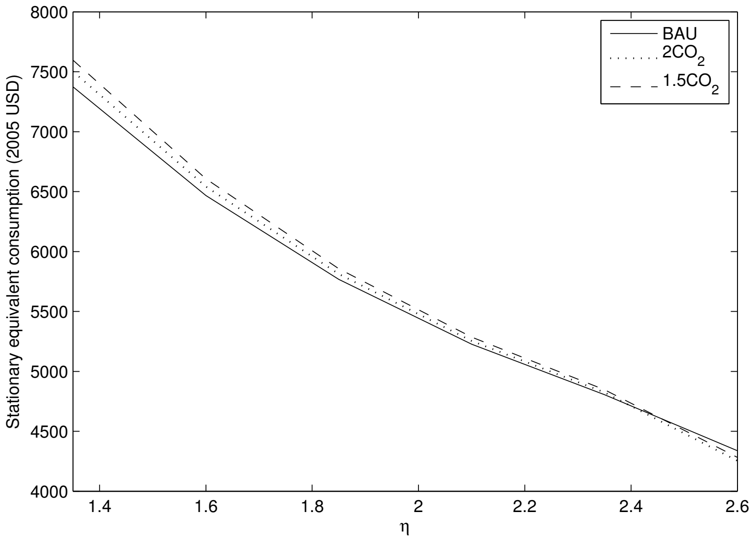


Figure A9: Dependence of welfare on η.

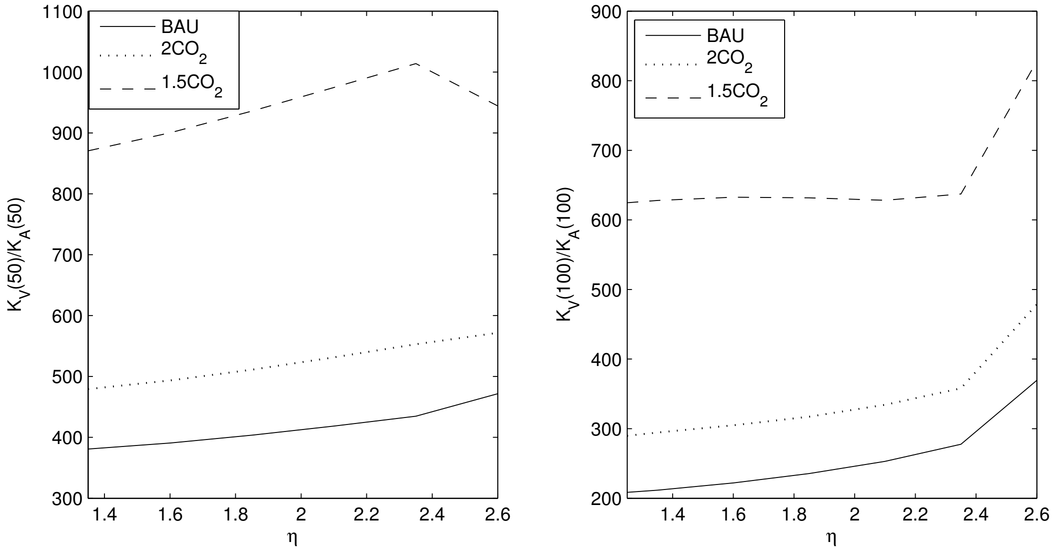


Figure A10: Dependence of capital ratio on elasticity of marginal utility η, after 50 and 100 years respectively

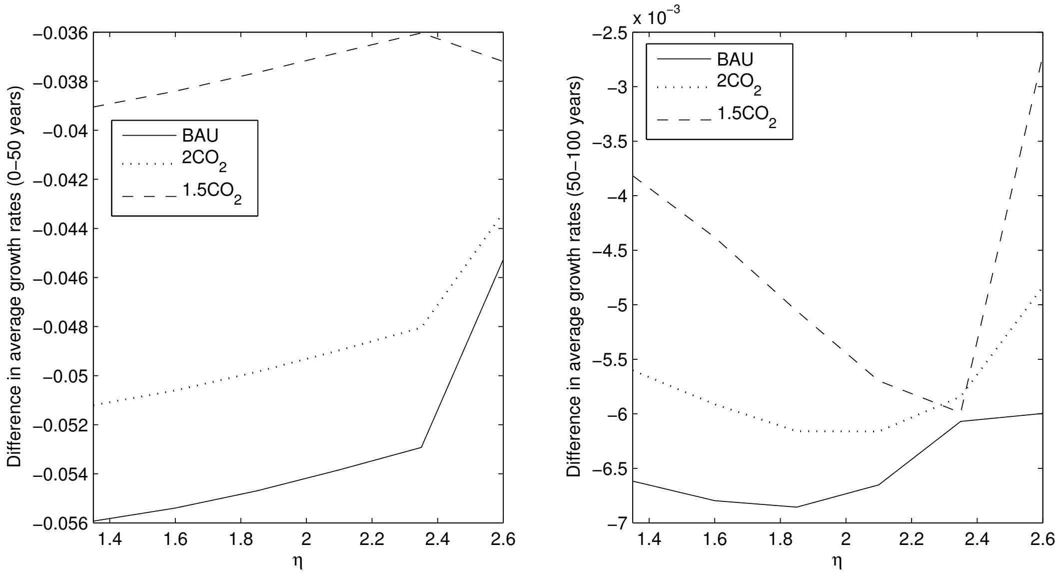


Figure A11: Difference between the average growth rates of vulnerable and adaptive capital, as a function of η, after the first 50 (left panel) and second 50 (right panel) years.

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