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Preparing for catastrophic climate change

by

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Preparing for catastrophic climate change

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Abstract

We study optimal adaptation to climate change when the harmful consequences of global warming are associated with stochastic occurrence of abrupt changes. The adaptation policy entails the accumulation of a particular sort of capital that will eliminate or reduce the catastrophic damage of an abrupt climate change when (and if) it occurs. The occurrence date is uncertain. The policy problem involves balancing the tradeoffs between the (certain) investment cost prior to occurrence and the benefit (in reduced damage) that will be realized after the (uncertain) occurrence date. For stationary economies the optimal adaptation capital converges to a steady state. For growing economies the optimal adaptation capital stock approaches the maximal economic level above which further accumulation is ineffective.

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Keywords: climate change, adaptation, hazard

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1 Introduction

Climate policy measures can be categorized as mitigation or adaptation. The former aims to prevent or reduce anthropogenic processes that (are believed to) affect climate change, e.g., emission of greenhouse gases (GHG), thereby preventing or delaying its harmful consequences. The latter is concerned with reducing or eliminating climate change induced damages once they occur.[1] Examples of adaptive measures include using artificial snow making in the Alps, the construction of levees to prevent flooding of plain areas as a result of rising seawater, or the development of crop varieties immune to pathogens that are likely to flourish with changes in certain climate characteristics.

Since the atmosphere is a global, open-access and common resource, preventive policies, such as reduction of global GHG emission, require concerted and coordinated international effort, in which the scope of a single country to influence policy is limited (Dockner and Long 1993, Barrett 2003). On the other hand, a country can significantly affect climate change-induced damages that may be inflicted upon it by undertaking appropriate adaptive measures well in advance. From the vantage point of countries that are vulnerable to irreversible consequences of climate change, proactive adaptive policies may well be preferred to mitigation policies.[2] In this work we focus on adaptive climate policies.

The situation considered is that of a country under threat of a catastrophic damage that may be induced by abrupt climate change. The climate change

[1] Adaptation policies are defined by Parry et al. (2007, p. 6) as "Adjustment in natural or human systems in response to actual or expected climatic stimuli of their effects, which moderates harm or exploits beneficial opportunities."

[2] "Mitigate we might, adapt we must" argues Nordhaus (1994, p. 189), while Klein et al. (2007) add that adaptation is not enough without mitigation (see discussion in Shalizi and Lecocq 2010).

process is exogenous (to the single country) and the onset of the abrupt catastrophic event is uncertain. An adaptation policy entails investing in a particular sort of capital that will reduce the damage inflicted by the calamity when it occurs. This investment consumes resources and entails real costs but yields benefits only after the catastrophe occurs. The policy design problem involves the investment and buildup of the adaptation capital in light of the delicate tradeoffs between the (certain) investment costs prior to occurrence and the benefits after (the uncertain) occurrence.

The damage inflicted by a catastrophic climate change can assume different forms, shapes and scales, depending on the nature of the catastrophe (rise in seawater, disease outburst, extended drought) and on the afflicted location (see the taxonomy of events-damages in De Zeeuw and Zemel 2011). Following Karp and Tsur (2011), we assume that the event reduces income by a certain share from the occurrence date onwards. The innovation here is to make this reduction a function of the stock of the adaptation capital at the occurrence date. The flow of investment benefits can then be associated with the reduction in the expected income loss vis-à-vis the expected loss that would have been realized without the investment (or under different investment policies). We characterize the optimal investment policy and show how it depends on preferences (time discounting and aversion to intergenerational inequality), the (exogenous) catastrophic hazard, the marginal productivity of preventive capital, and the scale and severity of the damage.

We find that for stationary economies (without exogenous or endogenous technical change), investment in adaptation capital may not always be warranted, depending on time preferences, aversion to intergenerational inequality, the catastrophic hazard (occurrence risk) and the severity of the ensuing damage. When undertaking adaptation measures is warranted, which is always the case for truly catastrophic damages, the optimal adaptation capital process converges monotonically to a unique steady state. In contrast, growing economies should always engage in adaptation and eventually build the corresponding capital stock to the point beyond which it is no longer effective.

The next section lays out the model's components and specifies the policy problem. Sections 3 and 4 characterize the optimal policy for stationary and growing economies, respectively, and provide insights into some salient properties. Section 5 concludes and the appendix contains technical derivations.

2 Adaptive policy specification

Harmful consequences of global warming are often associated with abrupt changes that give rise to catastrophic damages. Each link in the chain leading from anthropogenic change of atmospheric GHG concentration to the occurrence of abrupt climate change and the ensuing catastrophic damage involves uncertain elements (Schelling 2007). Following Clarke and Reed (1994) and Tsur and Zemel (1996, 1998), we account for these considerations by assuming that a catastrophic (abrupt) climate change will occur at an uncertain time T whose distribution depends on atmospheric GHG concentration. The latter is exogenous to a single country. We assume first a constant hazard rate, denoted h, so the distribution and density of T are, respectively, $F(t) = 1 - e^{-ht}$ and $f(t) = he^{-ht}$.[3] The event reduces income by a share $\psi(k(T))$ from the occurrence date onward, where k is damage control capital and $\psi : [0, \infty] \mapsto [0, 1]$

[3]The modifications needed to account for (exogenously) increasing hazard are outlined in 3.1 below.

satisfies

$$1 \geq \psi(0) > \psi(\infty) \geq 0;\ \psi'(k) < 0\, and\, \psi''(k) > 0\, \forall\, k \in [0, \bar{k});\ \psi'(k) = 0\, \forall\, k \geq \bar{k}. \tag{2.1}$$

Thus, the share of income loss is a decreasing and convex function of the stock of adaptive capital. The maximal effective adaptive capital $\bar{k}$ may be finite or infinite.

To allow a sharper focus on adaptation policy, we assume away productive capital. This is consistent with a neoclassical growth model in which capital and income grow at a constant rate and the saving rate is constant. The rate of growth (driven by exogenous technical change) is denoted g. With initial income normalized to unity, the flow of income prior to the occurrence of the event is e^{gt}. Let $x(t)$ represent the share of income invested in (adaptation) capital k at time t, so income is allocated between consumption, $e^{gt}(1-x(t))$, and investment in adaptation capital, $e^{gt}x(t)$. Adaptation capital, then, evolves according to

$$\dot{k}(t) = e^{gt}x(t) - \delta k(t), \tag{2.2}$$

where δ is the depreciation rate. After the occurrence date there is no role for adaptive actions and consumption equals $e^{gt}(1 - \psi(k(T)))$. We assume that there is no depreciation of capital after the event, or that depreciation is irrelevant.[4]

Assuming iso-elastic utility, the pre- and post-event utility flows are $\frac{[e^{gt}(1-x(t))]^{1-\eta}-1}{1-\eta}$ and $\frac{[e^{gt}(1-\psi(k(T))]^{1-\eta}-1}{1-\eta}$, respectively, where $\eta > 0$ is the elasticity parameter.

[4]For example, dykes protect a given area and depending on their height occurrence implies that a certain fraction is flooded and becomes useless for production after the flood. Alternatively, $e^{gt}(1 - \psi(k(T)))$ could represent the maximal welfare that can be realized after the event took place. The important issue is that the event occurrence reduces the productive potential of the economy.

The payoff is

$$\int_0^T \frac{[e^{gt}(1-x(t))]^{1-\eta}-1}{1-\eta}e^{-\rho t}dt + \int_T^\infty \frac{[e^{gt}(1-\psi(k(T))]^{1-\eta}-1}{1-\eta}e^{-\rho t}dt,$$

which can be written as

$$\int_0^T \frac{(1-x(t))^{1-\eta}}{1-\eta}e^{-\tilde{\rho}t}dt + e^{-\tilde{\rho}T}\frac{(1-\psi(k(T))^{1-\eta}}{(1-\eta)\tilde{\rho}} + \frac{1}{(\eta-1)\rho} \tag{2.3}$$

where

$$\tilde{\rho} \equiv \rho + g(\eta - 1) \tag{2.4}$$

is assumed positive. The expected payoff (ignoring the constant term) is[5]

$$\int_0^\infty \frac{1}{(1-\eta)\tilde{\rho}}\left[\tilde{\rho}(1-x(t))^{1-\eta} + h(1-\psi(k(t)))^{1-\eta}\right]e^{-(\tilde{\rho}+h)t}dt. \tag{2.5}$$

The optimal adaptive policy consists of the investment and capital processes, $x^*(t) \in [0,1]$, $k^*(t)$, $t \geq 0$, that maximize (2.5) subject to (2.2), given initial capital $k(0) = k_0 < \bar{k}$. The nonnegativity of $x(t)$ follows from the irreversibility of k (which cannot be used for consumption). The upper bound ($x \leq 1$) reflects the requirement that investment in damage control cannot exceed income.

We proceed to characterize the optimal adaptation policy, considering stationary ($g = 0$) and growing ($g > 0$) economies separately.

[5]Write the first term of (2.3) as $\int_0^\infty \frac{(1-x(t))^{1-\eta}}{1-\eta}e^{-\tilde{\rho}t}I(T > t)dt$, where $I(\cdot)$ assumes the value 1 when its argument is true and 0 otherwise, and take expectation with respect to T to obtain $\int_0^\infty \frac{(1-x(t))^{1-\eta}}{1-\eta}e^{-(\tilde{\rho}+h)t}dt$. The expectated value of the second term is $\int_0^\infty e^{-\tilde{\rho}t}\frac{(1-\psi(k(t))^{1-\eta}}{(1-\eta)\tilde{\rho}}f(t)dt = \int_0^\infty h\frac{(1-\psi(k(t))^{1-\eta}}{(1-\eta)\tilde{\rho}}e^{-(\tilde{\rho}+h)t}dt$, which upon adding to the first term gives (2.5).

3 Optimal policy: stationary economy ($g = 0$)

The current-value Hamiltonian corresponding to the above problem (suppressing the time argument for convenience) is

$$H = \frac{1}{(1-\eta)\rho}\left(\rho(1-x)^{1-\eta} + h(1-\psi(k))^{1-\eta}\right) + m(x - \delta k),$$

where m is the current-value costate variable (shadow price of k). Necessary conditions for an optimum include

$$-(1-x)^{-\eta} + m \leq 0, \text{ equality holds if } x > 0, \tag{3.1}$$

$$\dot{m} - (\rho + h + \delta)m = (h/\rho)(1-\psi(k))^{-\eta}\psi'(k) \tag{3.2}$$

and the transversality condition $He^{-(\tilde{\rho}+h)t} \to 0$.

The first condition says that the marginal utility of consumption should equal the marginal opportunity cost of consuming rather than investing the last income unit. The second condition is an arbitrage condition.[6]

In an optimal steady state (where $\dot{k} = \dot{m} = 0$), (2.2) and (3.1)-(3.2) imply that

$$(1-\delta k)^{-\eta} = \varphi(k) \tag{3.3}$$

must hold, where

$$\varphi(k) \equiv \frac{-\psi'(k)}{(1-\psi(k))^{\eta}}\frac{h}{\rho(\rho+h+\delta)}. \tag{3.4}$$

[6] In discrete time it would read

$$m(t+1) + (h/\rho)(1-\psi(k))^{-\eta}(-\psi'(k)) - \delta.m(t) = m(t) + (\rho + h)m(t)$$

The right-hand side gives tomorrow's revenues of putting an amount m in the bank today. The left-hand side is the return on investing the same amount in one (marginal unit of capital), consisting of the capital gain, the discounted total marginal utility of permanently higher consumption in case the catastrophe occurs minus depreciation of capital.

Since $(1-\delta k)^{-\eta}$ increases in k and (2.1) implies that $\varphi(\cdot)$ is decreasing, (3.3) can have at most one root in $(0, 1/\delta)$. Denote by $\tilde{k}$ the solution of (3.3) if such a solution exists in $(0, \frac{1}{\delta})$. Since $(1-\delta k)^{-\eta}$ equals 1 at $k = 0$ and explodes as k approaches $1/\delta$, the condition

$$\varphi(0) > 1 \tag{3.5}$$

guarantees that $\tilde{k} \in (0, \frac{1}{\delta})$ exists.

We can now characterize the optimal policy as follows:

Proposition 1. *Suppose $g = 0$ and (2.1) holds. (i) If $\varphi(0) > 1$, adaptive investment is warranted and the optimal capital trajectory $k^*(t)$ converges monotonically to a steady state at $\tilde{k} \in (0, \frac{1}{\delta})$. (ii) If $\varphi(0) \leq 1$, no adaptive investment is warranted ($x^*(t) = k^*(t) = 0$ for all $t \geq 0$).*

A formal proof is given in the appendix. Here we provide an intuitive explanation with the aid of a phase diagram. In the diagram (Figure 1), capital k is on the horizontal axis and the consumption share $1-x$ on the vertical axis. k is constant when $1 - x = 1 - \delta k$. Thus along the $\dot{k} = 0$ isocline, $1 - x = 1$ for $k = 0$ and $1 - x \to 0$ as k approaches $1/\delta$. Noting (3.2), the consumption share is constant for $(1-x) = (\varphi(k))^{-1/\eta}$, with $\varphi(k)$ defined in (3.4). The function $\varphi(k)$ is decreasing for $k < \bar{k}$ and constant thereafter. Hence the consumption share increases along the isocline. The figure depicts the case where $\bar{k} > 1/\delta$ and $\varphi(0) > 1$, in which the two isoclines intersect in $(0, 1/\delta)$. It is seen that in this case the steady state (the intersection point) is globally stable, which provides the intuition of the first part of Proposition 3.1. The second part of the Proposition corresponds to the case in which the locus of points where $1 - x$ is constant lies entirely above the $\dot{k} = 0$ isocline and, with small initial capital, the economy is trapped in a situation where the adaptive capital stock necessaritly goes to zero.

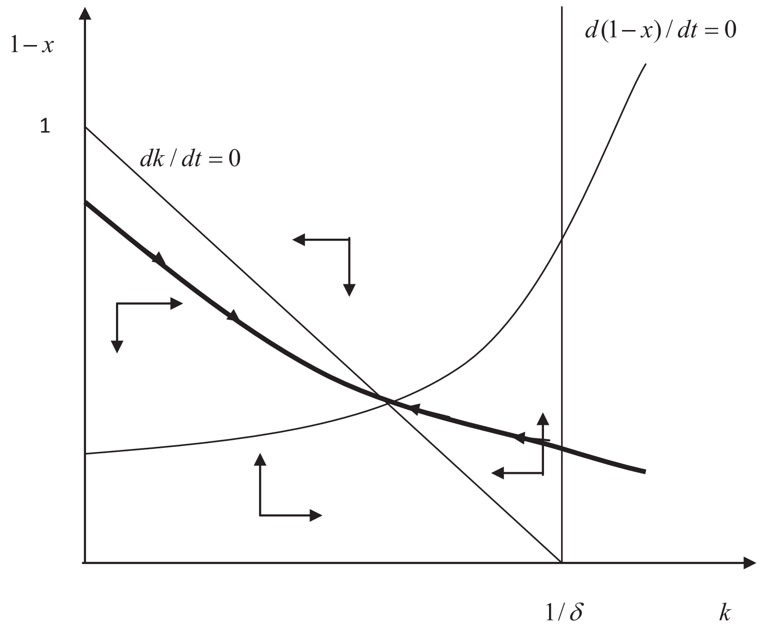

Figure 1: A phase diagram explanation of Proposition 1.

The proposition (and Figure) highlights the key role of

$$\varphi(0) = \frac{-\psi'(0)}{(1-\psi(0))^{\eta}} \frac{h}{\rho(\rho+h+\delta)}$$

in determining whether or not adaptive action is warranted. The effect of the damage function enters via $\frac{-\psi'(0)}{(1-\psi(0))^{\eta}}$. It is seen that both larger $-\psi'(0)$ and $\psi(0)$ closer to one increase $\varphi(0)$, thus also the desirability of adaptive action (in the sense of making condition (3.5) more likely to hold). A larger $-\psi'(0)$ implies that initially (when $k = 0$) adaptive investment is more effective in reducing the damage. A $\psi(0)$ closer to one implies larger damage without adaptive action. The doomsday case corresponds to $\psi(0) = 1$, in which case $\varphi(0)$ explodes, ensuring condition (3.5) and the desirability of adaptive action.

The $\varphi(0)$ expression also illuminates the role of the preference parameters, η and ρ (recall that $\tilde{\rho} = \rho$ when $g = 0$), the hazard rate, h, and the depreciation rate δ. As expected, a larger ρ depresses the desirability of adaptive action, in that it decreases $\varphi(0)$, by discounting more heavily future post-event benefits associated with the damage reduction. The elasticity η, on the other hand, increases the desirability of adaptive action (in that it increases $\varphi(0)$). This can be understood by noting the role of η as a measure of aversion to inter-generational inequality (larger η implies higher aversion to inter-generational inequality): failing to take adaptive action today means increasing the welfare of the present generation at the expense of future generations (that will suffer by the climate-induced catastrophe when it hits), hence it increases inter-generational inequality.

The hazard effect is, as expected, positive (it increases $\varphi(0)$): a larger h (with the ensuing larger occurrence probability) implies a larger risk, thus more scope for adaptive action. Since δ constitutes (part of) the price of adaptive investment, it negatively affects adaptive investment.

3.1 Increasing hazard

Extending the analysis to the case of non-constant hazard is straightforward. Suppose the hazard increases over time (e.g., with atmospheric GHG concentration which is exogenous to the country under consideration) and approaches the upper bound $\bar{h}$ in the long run. The distribution and density of T become $F(t) = 1 - e^{-\int_0^t (\tilde{\rho}+h(s))ds}$ and $f(t) = h(t)e^{-\int_0^t (\tilde{\rho}+h(s))ds}$, respectively, and the expected payoff (equation (2.5)) becomes

$$\int_0^\infty \frac{1}{(1-\eta)\tilde{\rho}} \left[\tilde{\rho}(1-x(t))^{1-\eta} + h(t)(1-\psi(k(t)))^{1-\eta}\right] e^{-\int_0^t(\tilde{\rho}+h(s))ds} dt.$$

The present-value Hamiltonian is

$$H(t) = \frac{1}{(1-\eta)\tilde{\rho}} \left(\tilde{\rho}(1-x(t))^{1-\eta} + h(t)(1-\psi(k(t)))^{1-\eta}\right) e^{-\int_0^t(\tilde{\rho}+h(s))ds} + \lambda(t)(x(t)-\delta k(t)),$$

where $\lambda(t)$ is the present-value costate (shadow price of capital). With $m(t) = \lambda(t)e^{\int_0^t(\tilde{\rho}+h(s))ds}$ the current-value costate, the necessary conditions (3.1)-(3.2) remain valid (with $h = h(t)$). The long-run behavior of the economy is the same as that with a constant hazard $\bar{h}$, but the time profile of $h(t)$ affects the transition dynamics approach to the steady state.

4 Optimal policy: growing economy ($g > 0$)

The Hamiltonian is

$$H = \frac{1}{(1-\eta)\tilde{\rho}} \left(\tilde{\rho}(1-x)^{1-\eta} + h(1-\psi(k))^{1-\eta}\right) + m(xe^{gt} - \delta k),$$

and necessary conditions for (an interior) optimum include

$$-(1-x)^{-\eta} + me^{gt} = 0, \tag{4.1}$$

$$\dot{m} - (\tilde{\rho} + h + \delta)m = (h/\tilde{\rho})(1-\psi(k))^{-\eta}\psi'(k) \tag{4.2}$$

and the transversality condition $He^{-(\tilde{\rho}+h)t} \to 0$.

It turns out that

Lemma 1. *Under the optimal policy, $m(t) \to 0$ as $t \to \infty$.*

The proof is given in the appendix. The optimal policy characterization for a growing economy can now be stated:

Proposition 2. *Suppose $g > 0$ and (2.1) holds. Then, the optimal capital process $k^*(t)$ approaches $\bar{k}$ as $t \to \infty$. If $\bar{k}$ is finite, the investment process $x^*(t)$ evolves in the long run along the $\delta \bar{k} e^{-gt}$ path and vanishes asymptotically.*

Proof. Noting (4.2), Lemma 1 implies

$$\lim_{t \to \infty} \psi'(k^*(t)) = 0, \tag{4.3}$$

ensuring, noting (2.1), $k^*(t) \to \bar{k}$. If $\bar{k}$ is finite, then (2.2) implies that in the long run $x^*(t) = \delta \bar{k} e^{-gt}$. ∎

As time goes by, a growing economy can more easily afford investing in adaptation capital, since the same fraction of income generates increasing investment rates. Moreover, the damage that will be inflicted by the catastrophic climate change is proportional to the size of the economy, hence rises as the economy grows and so is the benefit of damage reduction, i.e., of adaptation capital. Together, these two motives imply that a growing economy should (eventually) invest in adaptive capital to the point where its marginal productivity vanishes.

5 Conclusion

Countries that are vulnerable to potentially catastrophic and irreversible consequences of climate change will often find it beneficial to prepare well in advance for such calamities rather than wait and hope that the international community will take the precautionary actions needed to avert or mitigate (anthropogenic drivers of) climate change. We study how to prepare for catastrophic climate change by means of accumulation of adaptive capital that will reduce the damage inflicted by the calamity when it occurs. The catastrophic damage is triggered by an abrupt climate change that will occur at an uncertain time. The occurrence time distribution (or hazard) depends on the atmospheric concentration of greenhouse gases, which is exogenous to a single country.

For a stationary economy (no technical change), we find that whether or not adaptation actions are warranted depend on the discount rate, the aversion to intergenerational inequality, the catastrophic risk (hazard) and the severity of the catastrophic damage. If adaptation is warranted, which is always the case for truly catastrophic (large damage) threats, we find that the optimal adaptation capital approaches monotonically a unique steady state.

In contrast, a growing economy will always find it beneficial to undertake adaptation actions by investing in adaptation capital up to the point where it is no longer effective. This is so because, as time goes by, a growing economy can more easily afford investing in adaptation capital, since the same fraction of income generates larger investment rates, and moreover the damage that will be inflicted (upon occurrence of the catastrophic climate change) increases as the economy grows and so is the benefit of damage reduction (i.e., of adaptation capital).

These results were obtained in a stylized setting, which can and should be extended in several directions. It would be interesting to have productive capital in addition to adaptive capital and see how their accumulations are interrelated. This will allow analyzing a growth model with savings for two potential purposes. It has also been assumed that the climate change calamity occurs only once. However, after having incurred one catastrophic occurrence another could arrive, and this is not modeled here (see Tsur and Zemel 1998, for a modeling of recurrent event). During the post-event period of a once-and-for-all event, welfare depends upon the existing adaptive capital stock and there is no role for adaptation policy. In a recurrent event setting, adaptation policy continues to be relevant after occurrence as well.

Appendix

A Proof of Proposition 1

We note first that the optimal state process $k^*(t)$ is monotonic. To verify this, consider first the case where the optimal policy is unique and suppose that $k^*(t)$ is not monotonic, i.e., for some $0 \leq t_1 < t_2$, $k^*(t_1) = k^*(t_2)$ while $k^*(t_1)$ increases (resp. decreases) and $k^*(t_2)$ decreases (resp. increases), so $x^*(t_1) > x^*(t_2)$ (resp. $x^*(t_1) < x^*(t_2)$). But for autonomous problems the control can be expressed as a function of the state, implying $x^*(t_1) = x^*(k^*(t_1)) = x^*(k^*(t_2)) = x^*(t_2)$ – a contradiction. If the optimal policy is not unique, at least one optimal state process is monotonic (see Hartl 1987, and Tsur and Zemel 1994).

Since $x(t) \leq 1$, the capital process is bounded above by $1/\delta$. It follows that $k^*(t)$ must converge monotonically to a steady state in $[0, \frac{1}{\delta}]$. Let a $\hat{}$ over a variable indicate steady state. Then, (2.2) implies $\hat{x} = \delta\hat{k}$, (3.1) gives $\hat{m} = (1-\hat{x})^{-\eta}$ and, using $\dot{\hat{m}} = 0$, (3.2) gives $\hat{m} = \varphi(\hat{k})$. Together, these equations imply that the steady state capital stock $\hat{k}$ must satisfy (3.3).

(i) Under (2.1) and (3.5), equation (3.3) admits a unique solution $\tilde{k} \in (0, \frac{1}{\delta})$, thus $\hat{k} = \tilde{k} > 0$, establishing the claim.

(ii) When $\varphi(0) \leq 1$, then $\varphi(k) < 1$ for any $k > 0$ and there exists no positive k that solves (3.3). Undertaking a positive investment implies, by virtue of the monotonicity of the optimal state process, that the optimal capital process must converge to a positive steady state and the latter must satisfy (3.3) – a contradiction. The optimal policy in this case is therefore not to undertake any adaptive investment.

B Proof of Lemma 1

If $m(t)$ does not vanish asymptotically, then, for large enough t, either (i) there exists some τ such that $m(t) \geq \epsilon > 0$ for all $t \geq \tau$, or (ii) $m(t)$ is cyclical. We show that neither case is possible.

Case (ii): Suppose there exists some τ such that $m(t) \geq \epsilon > 0$ for all $t \geq \tau$. For large enough t, $m(t) \geq \epsilon > 0$ implies, noting (4.1), that $x(t)$ is close to 1 and (2.2) implies that $k(t) \approx \frac{1}{g+\delta}e^{gt}$. The transversality condition $He^{-(\rho+h)t} \to 0$ requires $e^{-(\tilde{\rho}+h)t}m(t)[e^{gt}x(t) - \delta k(t)] \to 0$ or $e^{-(\tilde{\rho}+h)t}m(t)(e^{gt} - \delta k(t)) = e^{-(\tilde{\rho}+h)t}m(t)e^{gt}(1 - \frac{\delta}{g+\delta}) \to 0$, hence $e^{-(\tilde{\rho}+h-g)t}m(t) \to 0$.

Now the necessary condition (4.2) can be written as

$$\dot{m} - (\tilde{\rho} + h + \delta)m = (\tilde{\rho} + h + \delta)\varphi(k)$$

where $\varphi(k) \equiv \frac{-\psi'(k)}{(1-\psi(k))^\eta}\frac{h}{\tilde{\rho}(\tilde{\rho}+h+\delta)}$ is defined in (3.4) with $\tilde{\rho}$ instead of ρ. Since $k(t)$ increases indefinitely, (2.1) implies that $\varphi(k(t)) \to 0$ and asymptotically $m(t) \approx e^{(\tilde{\rho}+h+\delta)t}$, in violation of the transversality condition $e^{-(\tilde{\rho}+h-g)t}m(t) \to 0$ and ruling out Case (i).

Case (ii): If $m(t)$ is cyclical, there exist pairs $t_1 < t_2$ such that $m(t_1) = m(t_2) \geq \epsilon > 0$, $\dot{m}(t_1) > 0$ and $\dot{m}(t_2) < 0$, for arbitrarily large t_1. For large enough t_1, $m(t) \geq \epsilon > 0 \, \forall t \in [t_1, t_2]$ and (4.1) imply $x(t) \approx 1 \, \forall t \in [t_1, t_2]$, in which case, noting (2.2), $\dot{k}(t) \geq 0 \, \forall t \in [t_1, t_2]$ so $k(t_1) \leq k(t_2)$ and $\varphi(k(t_1)) \geq \varphi(k(t_2))$. Invoking (4.2) gives

$$\dot{m}(t_1) - \dot{m}(t_2) = (\tilde{\rho} + h + \delta)[\varphi(k(t_2)) - \varphi(k(t_1))] \leq 0,$$

contradicting $\dot{m}(t_1) > 0$ and $\dot{m}(t_2) < 0$ and ruling out this case.

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