Life expectancy and the environment[*]

Fabio Mariani[†]
PSE, Paris 1 and IZA

Agustín Pérez-Barahona
Paris 1 and Ecole Polytechnique

Natacha Raffin
PSE and Paris 1

January 14, 2009

Abstract

We present an OLG model in which life expectancy and environmental quality dynamics are jointly determined. Agents may invest in environmental quality, depending on how much they expect to live. In turn, environmental conditions affects life expectancy. The model produces multiple steady-states (development regimes) and initial conditions do matter. In particular, some countries may be trapped in a low life expectancy / low environmental quality trap. This outcome is consistent with stylized facts relating life expectancy and environmental performance measures. Possible strategies to escape from this kind of trap are also discussed. Finally, we show that our results are robust to the introduction of human capital dynamics, driven by parentally funded education.

JEL classification: D62; J24; O11; Q56.

Keywords: Environmental quality; life expectancy; poverty traps; human capital.

1 Introduction

Environmental care betrays some concern for the future, be it one's own or that of forthcoming generations. Yet, the way people value future is crucially affected, among others, by their life expectancy: a higher longevity makes people more sympathetic to future generations and/or their future selves. Therefore, if someone expects to live longer, she should be willing to invest more in environmental quality.

Of course, the causal link between life expectancy and environmental quality may also go the other way around. Several studies in medicine and epidemiology, like Elo and Preston (1992)

and Evans and Smith (2005), show that environmental quality is a very important factor affecting health and morbidity: air and water pollution, depletion of natural resources, soils deterioration and the like, are all susceptible of increasing human mortality (thus reducing longevity).

Consequently, it should not come as a surprise that, as we will show extensively later on, life expectancy is correlated across countries with environmental quality. In addition, the data suggest the existence of "convergence clubs" in terms of both environmental performance and longevity, with countries being concentrated around *two* levels of environmental quality and life expectancy, respectively.

This paper provides a theoretical framework that allows us to reproduce the two stylized facts highlighted above. To do that, we model explicitly the *two-way causality* between the environment and longevity. If the causal relationship between environmental quality and life expectancy involves *threshold effects*, the resulting dynamic interaction can in turn justify the existence of an *environmental poverty trap*, characterized by both bad environmental conditions and short life expectancy.

In the benchmark version of our model, we consider overlapping generations of three-period lived agents, who get utility from consumption and environmental quality. During adulthood, when all relevant decisions are taken, they can work and allocate their income between consumption and investment in environmental maintenance: consumption involves deterioration of the future quality of the environment (through pollution and/or resource depletion), while maintenance helps to improve it. The dynamics of environmental quality may also be affected by external factors (that are exogenous from our agents' viewpoint). A key ingredient of our setting is that survival until the last period is probabilistic, and depends on the inherited quality of the environment. In turn, this survival probability affects the weight of future environmental quality in the agents' utility function. The idea that agents take utility from the future state of the environment is compatible with both self-interest and altruism towards future generations.

It can be shown that optimal choices depend crucially on life expectancy: in particular, a higher probability to be alive in the third period boosts investment in the environment and reduces consumption (the latter translating into less environmental deterioration). Since longevity is endogenous, if it is affected by environmental quality through a convex-concave function, our model allows for multiple equilibria and may explain the existence of poverty traps. Let us point out that such a convex-concave function is backed up by some well-established scientific literature, and can be justified by the existence of threshold effects in the causal relationship

going from environmental quality to life expectancy (see, for instance, Cakmak et al. (1999) on the air pollution-mortality link, and Scheffer et al. (2001) on applications to ecosystems in general). In this framework, initial conditions do matter: a given country may be caught in a high-mortality/poor-environment trap if low income is associated with a deteriorated environment. Possible strategies to escape from the trap will be also identified and discussed, as well as welfare implications of our model.

We also show that introducing human capital accumulation in the benchmark dynamic model does not alter its main results. If parents can use their income to also educate their children, and if survival probabilities are affected by both environmental quality and human capital, we may eventually end up with multiple development regimes. The only difference is that the low-life-expectancy/poor-environment trap would be characterized by low human capital as well.

Our model is primarily related to those papers that have analysed environmental issues in a dynamic OLG framework. Among them, John and Pecchenino (1994) were the first to introduce the possibility of multiple equilibria, identifying a case for a poverty trap characterized by poor economic performance and environmental degradation; however, life expectancy is assumed to be exogenous and plays no role in their model, since there is no room for uncertainty. The idea of explaining environmental care with an uncertain lifetime is instead present in Ono and Maeda (2001), although in their model environmental quality does not affect longevity. On the contrary, Jouvet et al. (2007) consider the impact of environmental quality on mortality, but neglect completely the role of mortality in defining environmental choices and leave no room for maintenance. Furthermore, our model is also somewhat related to Jouvet et al. (2000), in which the degree of inter-generational altruism is used to explain environmental choices.

A link can be also established between our paper and the literature on poverty traps, which has been comprehensively surveyed by Azariadis (1996) and Azariadis and Stachurski (2005). Differently from the existing papers, we deal with an environmental kind of trap: instead of being defined in terms of GDP per capita, capital accumulation, etc., poverty is now related to environmental quality. It should be clear, however, that we focus only on one specific mechanism lying behind environmental traps. Just as underdevelopment traps may be related to a wide variety of factors, ranging from financial to technological ones, including human capital accumulation and life expectancy (see, for instance, Blackburn and Cipriani (2002), or Chakraborty (2004)), we are perfectly aware that life expectancy is only one of the possible causes of environmental traps.

The remainder of our paper is organized as follows. Section 2 presents some stylized facts on environmental quality and life expectancy that provide the motivation of our the paper. Section 3 introduces and solves the basic model, discussing the existence of an environmental poverty trap and the possible strategies to escape from it. An extended version of the model, allowing for human capital accumulation, is analysed in Section 4. Section 5 concludes.

2 Stylized facts

Here we want to present some stylized facts that motivate our analysis and will be matched by the main results of our theoretical model.

As a proxy for environmental quality, we use a newly available indicator: the Environmental Performance Index (henceforth EPI). This "synthetic" indicator (YCELP, 2006) takes into account both "environmental health", as defined by child mortality, indoor air pollution, drinking water, adequate sanitation and urban particulates, and "ecosystem vitality", that includes factors like air quality, water and productive natural resources, biodiversity and sustainable energy. In the end, the EPI is computed as a weighted average of 16 sub-indicators, each one converted to a proximity-to-target measure with a theoretical range of zero to 100. Therefore, the EPI itself can ideally take values in the 0-100 range and, clearly enough, reducing pollution or preserving natural resources may both contribute to improve environmental quality.[1] Notice that, since child mortality is, obviously, strongly correlated with life expectancy, in the rest of the paper we employ an "amended" version of the original EPI, that is obtained removing the child mortality factor.[2]

Life expectancy is measured using "life expectancy at birth" (2005), from United Nations (2007) data.

Data on environmental quality and life expectancy are simultaneously available for a sample of 132 countries; they allow us to observe a couple of stylized facts.

Stylized fact 1 *Across countries, environmental quality is positively correlated with life expectancy.*

---

[1]Countries with a comparable EPI level may exhibit very different sub-indicators scores. Take for instance United States, Russia and Brazil, that are ranked 28, 32 and 34 respectively, with an EPI ranging from 78.5 to 77. The United States rank very high in environmental health, but very low in the management of natural resources. Russia displays excellent resource indicators, while failing to achieve decent scores in sustainable energy. Finally, Brazil does well in water quality, but is characterized by extremely low biodiversity indicators. See YCELP (2006) for further examples.

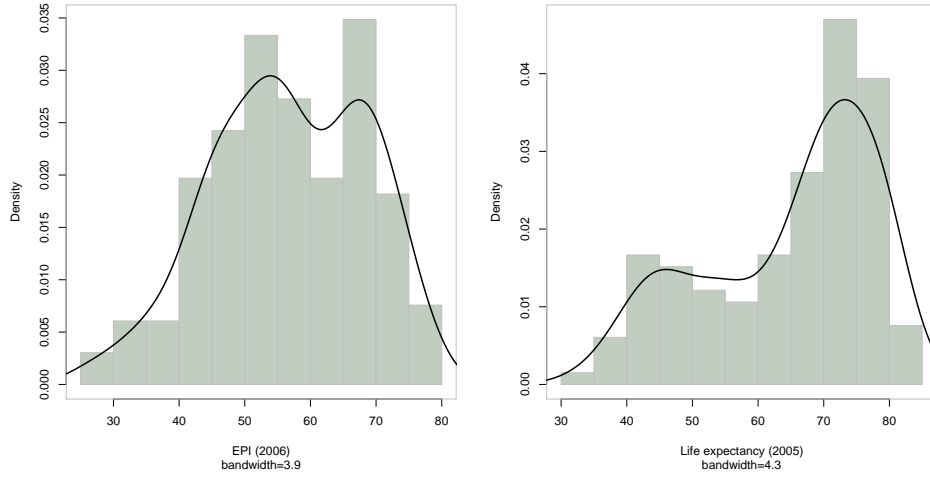[2]Child mortality accounted for 10.5% of the total EPI.

As reported in Figure 1, for our cross-section of 132 countries there is strong evidence supporting the idea that longevity and environmental quality are linked; in particular, the correlation coefficient is equal to 0.66 and statistically significant at the 1% level. The graph below is compatible with the hypothesis of a two-way causality between the two variables.

Figure 1: Environmental quality and life expectancy
Sources: YCELP (2006), UN (2007)

In addition, a second kind of stylized fact is particularly interesting.

Stylized fact 2 *Environmental quality and life expectancy are bimodally distributed across countries.*

Therefore, the data suggest the possibility of an *environmental* poverty trap, characterized also by short life expectancy. This concept points to the existence of "convergence clubs" in terms of environmental performance and longevity: countries are concentrated around *two* levels of the EPI and life expectancy. In fact, Figure 2, depicting both histograms and kernel density estimates (with optimal bandwidth), displays bimodal distributions of both variables across countries.

Moreover, in both cases, the null hypothesis of unimodality is rejected by the Hartigan's *dip* test (Hartigan and Hartigan, 1985). This test measures the maximum difference, over all sample points, between the empirical distribution function, and the unimodal distribution function that minimizes the maximum difference. Accordingly, we calculate the *dip* test statistic (*d*). For our EPI data, the computed value of *d* is 0.0385. As it can be inferred from Hartigan and Hartigan (1985), in the case of our sample size (132 observations), the null hypothesis of unimodality is

Figure 2: Bimodal distribution of environmental quality and life expectancy
Sources: YCELP (2006), UN (2007)

rejected because $d > 0.0370$ (at the 5% significance level). Therefore, we can think the World distribution of environmental quality to be bimodal. The same applies to life expectancy: on the basis of our data, since $d = 0.036$, the Hartigan's dip test allows us to reject the null hypothesis of unimodality at the 10% significance level.

3 The benchmark model

We start by setting up a simple model where agents allocate their resources between current consumption and environmental maintenance. Consumption, generating pollution and/or increasing pressure on natural resources, determines some degradation of environmental quality. No growth mechanism is considered.

3.1 Structure of the model

We consider an infinite-horizon economy that is populated by overlapping generations of agents living for three periods: childhood, adulthood, and old age. Time is discrete and indexed by $t = 0, 1, 2, ..., \infty$. All decisions are taken in the adult period of life. Individuals live safely through the first two periods, while survival to the third period is subject to uncertainty. We assume no population growth. Furthermore, agents are considered to be identical within each generation, whose size is normalized to one (in the first two periods). Preferences are represented by the

6

following utility function, that we assume to be logarithmic to get closed-form solutions:

$$U(c_t, e_{t+1}) = \ln c_t + \pi_t \gamma \ln e_{t+1}; \tag{1}$$

people care about adult consumption (c_t) and environmental quality when old (e_{t+1}); γ (> 0) represents the weight agents give to the future environment (green preferences), while π_t denotes the survival probability (that is taken as given since it depends on inherited environmental quality). Here, for the sake of simplicity, we abstract from time discounting so that the subjective preference for the future is entirely determined by $\pi_t \gamma$. Notice also that in our framework an increase (decrease) in the survival probability translates into a higher (lower) life expectancy, so that hereafter we will use the two concepts interchangeably.

Let us underline that e_t may encompass both environmental conditions (quality of water, air and soils, etc.) and resources availability (biodiversity, forestry, fisheries, etc.).[3] Broadly speaking, e_t can be seen as an index of the amenity (use and non-use) value of the environment. The introduction of e_{t+1} in the individual utility function is consistent with what Popp (2001) defines as "weak altruism": agents decide to provide environmental quality for a combination of both self-interest and the interest of future generations. In other words, people may be willing to engage in environmental maintenance and improvement because they want themselves to enjoy a better environment, and/or because they want to leave a better environment to their offspring.

Adult individuals face the following budget constraint:

$$w_t = c_t + m_t; \tag{2}$$

they allocate their income (w_t) between consumption and environmental maintenance (m_t). In this benchmark version of our model, w_t is assumed to be exogenous.[4] Environmental maintenance summarizes all the actions that agents can take in order to preserve and improve environmental conditions.

Following John and Pecchenino (1994) and Ono (2002), the law of motion of environmental quality is given by the following expression:

$$e_{t+1} = (1 - \eta)e_t + \sigma m_t - \beta c_t - \lambda Q_t, \tag{3}$$

with $\beta, \sigma, \lambda > 0$ and $0 < \eta < 1$.

---

[3]All these issues are taken into account by the EPI, that we have consistently used as a proxy of environmental quality in Figures 1 and 2.

[4]This assumption will be relaxed in Section 3, where we allow for human capital accumulation and consequent income dynamics.

The parameter η is the natural rate of deterioration of the environment, σ represents the effectiveness of maintenance, whereas β accounts for the degradation of the environment, or pollution, due to each unit of consumption. The above formulation also allows for the possibility of external effects (coming from outside economies) on our environment: $\lambda Q_t > 0$ (< 0) represents the total impact of a harmful (beneficial) activity.[5]

Notice that a reduction in c_t has a double effect on the environment: it directly affects environmental quality through the parameter β (alleviating the pressure on natural resources and/or reducing pollution), and frees resources for maintenance (relaxing the budget constraint). Moreover, equation (3) implies that agents cannot, through their actions, modify the current state of the environment (e_t). The latter is thus "inherited", depending only on the past generation's choices.[6]

3.2   Optimal choices

Taking as given w_t, e_t and π_t, agents choose c_t and m_t so as to maximize (1) subject to (2), (3), $c_t > 0$, $m_t > 0$ and $e_t > 0$. Optimal choices are then given by:

$$m_t = \frac{\lambda Q_t - (1-\eta)e_t + [\beta + \gamma(\beta+\sigma)\pi_t]w_t}{(\beta+\sigma)(1+\gamma\pi_t)}, \tag{4}$$

and

$$c_t = \frac{(1-\eta)e_t + \sigma w_t - \lambda Q_t}{(\beta+\sigma)(1+\gamma\pi_t)}. \tag{5}$$

Notice that here, given that agents are identical and the population is normalized to one, aggregate variables (choices) are completely equivalent to individual ones. Therefore, all variables in our model can be also easily interpreted as "country" variables.

From (4) and (5), we can observe that both consumption and environmental maintenance are positively affected by income: richer economies are more likely to invest in environmental care. In addition, current environmental quality has a positive effect on consumption, but a negative one on maintenance: investments in maintenance are less needed if the inherited environment is less degraded. These two results have already been established by existing papers like John and Pecchenino (1994) and Ono (2002).

---

[5]Episodes of acute pollution, like oil slicks or the Chernobyl disaster, can be typical examples of $Q_t > 0$, while the implementation of an international agreement that promotes a worldwide reduction of pollutants (i.e. the Kyoto Protocol) or the preservation of the Amazonian forest could be regarded as a negative Q_t in our model.

[6]Therefore, our results would not change if we introduce current environmental quality (e_t) in the utility function.

The novelty of our model is that we can identify a specific effect of life expectancy (as determined by the survival probability π_t) on environmental maintenance. As it can be easily seen from the following derivative:

$$\frac{\partial m_t}{\partial \pi_t} = \frac{\gamma[(1-\eta)e_t + \sigma w_t - \lambda Q_t]}{(\beta+\sigma)(1+\gamma\pi_t)^2},$$ (6)

that is positive as soon as we have interior solutions, a higher survival probability raises stronger concerns for the future state of the environment, thus inducing more maintenance.

In addition, a relatively larger value of Q_t requires more investment in maintenance. Notice that the term $(1-\eta)e_t - \lambda Q_t$ represents the net effect of *past* and *external* environmental conditions on optimal choices.

3.3 Dynamics

Once we substitute (4) and (5) into (3), we get the following dynamic difference equation, describing the evolution of environmental quality over time:

$$e_{t+1} = \frac{\gamma\pi_t}{1+\gamma\pi_t}[(1-\eta)e_t + \sigma w_t - \lambda Q_t].$$ (7)

Until now we have considered π_t as exogenous, although we have pointed out that life expectancy may depend on (bequeathed) environmental quality. Now, we introduce explicitly a function $\pi_t = \pi(e_t)$, such that $\pi'(\cdot) > 0$, $\lim_{e \to 0} \pi(e) = \underline{\pi}$ and $\lim_{e \to \infty} \pi(e) = \overline{\pi} \leq 1$. This formulation is consistent with a large body of medical and epidemiological literature showing clear effects of environmental conditions on adult mortality, like for instance Elo and Preston (1992), Pope et al. (1995) and Evans and Smith (2005). The shape of $\pi(e_t)$ may reflect "technological" factors affecting the transformation of environmental quality into survival probability such as, for instance, medicine effectiveness.

Notice that agents cannot improve their survival probability by investing in maintenance. This is consistent with equation (3), where *current* environmental choices (especially m_t) affect the *future* state on the environment.[7] Any investment in maintenance will be rewarded, in terms of environmental quality and life expectancy, only in the future period. This introduces, in terms of longevity, an inter-generational externality.

The dynamics of our model are now described by:

$$e_{t+1} = \frac{\gamma\pi(e_t)}{1+\gamma\pi(e_t)}[(1-\eta)e_t + \sigma w_t - \lambda Q_t] \equiv \phi(e_t).$$ (8)

---

[7]Since m_t determines e_{t+1} (and not e_t), it looks sensible to have $\pi(e_t)$, rather than $\pi(m_t)$, for instance.

In this framework, a steady-state equilibrium is defined as a fixed point e^* such that $\phi(e^*) = e^*$, which is stable (unstable) if $\phi'(e^*) < 1$ (> 1).

Depending on the shape of the transition function $\phi(e_t)$, we may have different scenarios. For the sake of simplicity, we assume that w_t and Q_t are not only exogenous but also constant, so that $w_t = w$ and $Q_t = Q$. Figure 3 shows that we have only one stable steady-state as long as $\phi(\cdot)$ is concave for all possible values of e_t. Non-ergodicity and multiple steady-states may instead occur if $\phi(\cdot)$ is first convex and then concave, displaying an inflection point. In this case, depending on initial conditions, an economy may end up with either high or low environmental quality (e_H^* and e_L^*, respectively).
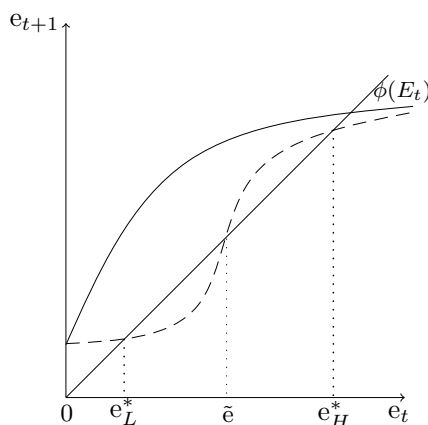

Figure 3: Dynamics

Let us underline that a convex-concave transition function $\phi(e_t)$ might be generated by a convex-concave survival probability $\pi(e_t)$: under low environmental conditions, an improvement of the environmental quality drives a small rise on the survival probability. However, beyond an environmental threshold, this will translate into a much higher life expectancy. Assuming such a functional form for $\pi(e_t)$ is consistent with the idea that, for instance, the function describing the effects of environmental degradation (be it increased pollution or exploitation of resources) on a given ecosystem, or on human health, is itself convex-concave. Dasgupta and Mäler (2003) explain that nature's non-convexities are frequently the manifestation of feedback effects, which might in turn imply the existence of ecological thresholds and therefore of multiple equilibria. Threshold-effects, sigmoid dose-response functions, non-smooth dynamics and

regime shifts in ecosystems are commonly assumed in natural sciences (see Scheffer et al. (2001), for a comprehensive study).[8] Finally, Baland and Platteau (1996) state that, in the case of natural resources involving ecological processes, there might well be threshold levels of exploitation beyond which the whole system moves in a discontinuous way from one equilibrium to another.

3.4 Poverty trap: an analytical illustration

The possibility of multiple equilibria implies the existence of an environmental poverty trap. To give an analytical illustration of such a case, we introduce now the following specific functional form relating the survival probability to inherited environmental quality:

$$\pi(e_t) = \begin{cases} \underline{\pi} & \text{if} \quad e_t < \tilde{e} \\ \overline{\pi} & \text{if} \quad e_t \geq \tilde{e} \end{cases}, \tag{9}$$

where $\tilde{e}$ is an exogenous threshold value of the environmental quality, above (below) which the value of the survival probability is high (low). Obviously, we also assume that $\overline{\pi} > \underline{\pi}$. The value of $\tilde{e}$ may depend on factors such as medicine effectiveness, health care quality, etc. For instance, a low $\tilde{e}$ can be explained by a very efficient medical technology that makes long life expectancy possible even under bad environmental conditions. On the contrary, a high $\tilde{e}$ may represent the case of a developing country where health services are so poorly performing that any deterioration of the environment translates easily into higher mortality.

Given equation (9), the transition function $\phi(e_t)$ becomes:

$$\phi(e_t) = \begin{cases} \frac{\gamma\underline{\pi}}{1+\gamma\underline{\pi}}[(1-\eta)e_t + \sigma w - \lambda Q] & \text{if} \quad e_t < \tilde{e} \\ \frac{\gamma\overline{\pi}}{1+\gamma\overline{\pi}}[(1-\eta)e_t + \sigma w - \lambda Q] & \text{if} \quad e_t \geq \tilde{e} \end{cases}. \tag{10}$$

We can then claim the following:

Proposition 1 *If the following condition holds:*

$$\frac{\gamma\underline{\pi}}{1+\gamma\eta\underline{\pi}} < \frac{\tilde{e}}{\sigma w - \lambda Q} < \frac{\gamma\overline{\pi}}{1+\gamma\eta\overline{\pi}},$$

then the dynamic equation (10) admits two stable steady-states e_L^* and e_H^*, such that $e_L^* < \tilde{e} < e_H^*$.

Proof. Provided that it exists, any steady-state is stable since, in our model, $\phi'(e_t) < 1, \forall e_t > 0$. Multiplicity arises if $[\gamma\underline{\pi}/(1+\gamma\eta\underline{\pi})](\sigma w - \lambda Q) < \tilde{e} < [\gamma\overline{\pi}/(1+\gamma\eta\overline{\pi})](\sigma w - \lambda Q)$, which yields the condition above. ∎

---

[8]The existence of a threshold effect in the relation between air-pollution and mortality has been also detected, for instance, by Cakmak et al. (1999)

In particular, we will have that:

$$e_L^* = \frac{\gamma \underline{\pi}}{(1 + \gamma \eta \underline{\pi})}(\sigma w - \lambda Q) \text{ and } e_H^* = \frac{\gamma \overline{\pi}}{(1 + \gamma \eta \overline{\pi})}(\sigma w - \lambda Q). \tag{11}$$

It can be easily seen that the steady-state value of environmental quality (be it low or high) is positively affected by the survival probability ($\underline{\pi}$ or $\overline{\pi}$) and by income w (via the parameter σ, representing the effectiveness of maintenance), while it is negatively influenced by the external effect λQ.

The dynamics of our system is depicted in Figure 4. The threshold value $\tilde{e}$ identifies a poverty trap: an economy starting from an environmental quality between 0 and $\tilde{e}$ will reach the equilibrium point A, which is a steady-state characterized by both low environmental quality (e_L^*) and short life expectancy ($\underline{\pi}$). However, if initial conditions are such that $e_0 \geq \tilde{e}$, the economy will end up in the "higher" steady-state B, where longer life expectancy ($\overline{\pi}$) is associated with better environmental quality (e_H^*).
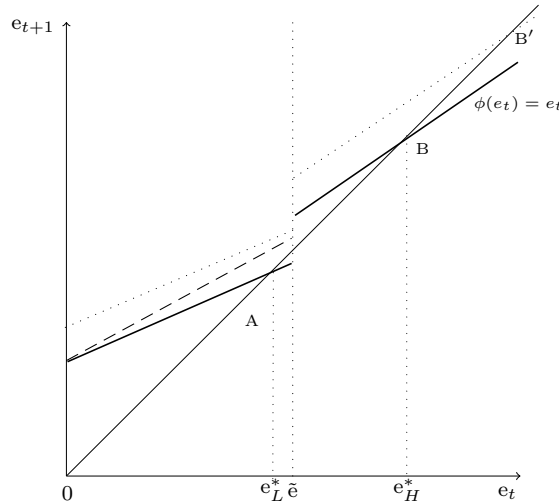

Figure 4: Environmental poverty trap

The underlying mechanism goes as follows: for initial environmental quality below the threshold value $\tilde{e}$, the survival probability is pinned down to $\underline{\pi}$. As it has been previously discussed, shorter life expectancy implies a weaker concern for the future: by optimal choices (4) and (5), and for a given income, a lower survival probability induces agents to substitute environmental

12

maintenance with consumption. Therefore, from equation (10), environmental quality decreases, ending up with the lower steady-state value e_L^*. Symmetrically, if $e_0 \geq \tilde{e}$, our economy is driven to e_H^*.

3.5 In and out of the trap

It is interesting to analyse different possible strategies to escape from the environmental poverty trap, as well as factors that could push some economies back to a low equilibrium characterized by both a bad environment and low longevity.

Before doing so, let us just underline that the very existence of this kind of environmental poverty trap implies that some countries (or regions) may even experience, over time, both environmental degradation and decay in life expectancy. Cross section data would suggest that the latter is much less common than the former. The fact that, in some cases, environmental degradation does not imply lower longevity, may be due to the fact that economic growth (neglected until now in our analysis) might, at the same time, worsen environmental quality but generate additional resources that can help increasing (or preserving) longevity. However, there is also evidence of countries where environmental degradation is associated with a reduction in life expectancy. For instance, McMichael et al. (2004) identify 40 countries that experienced a loss in longevity between 1990 and 2001 (26 between 1980 and 2001);[9] they also suggest that the resulting World divergence in terms of life expectancy might be explained by " ... (the growing) health risks consequent on large-scale environmental changes caused by human pressure". Not surprisingly, most of those countries are African or ex-Soviet countries.

The fall in life expectancy (and increased mortality risk) in Africa has often been related to mismanagement of environmental resources, pollution and anthropogenic climate change (see Patz et al. (2005), among others). In the case of the ex-USSR, the argument for a pollution-driven mortality resurgence has also been put forward, for instance, by Feachem (1994), and Jedrychowski (1995).

Let us also mention the case - particularly cherished by economists - of Easter Island. This small Pacific Island serves as a very good example of a closed system where insufficient environmental care (or better, too much human pressure on the existing natural resources, especially forestry) ultimately led to a dramatic reduction of the local population (see Diamond (2005) for a general presentation, or de la Croix and Dottori (2008)).

---

[9]Losses in life expectancy are sometimes severe, going up to 15-18 years.

3.5.1 Escaping the trap

Let us assume that our economy is initially trapped in the "low" steady-state A, characterized by bad environmental quality and short life expectancy $(e_L^*, \underline{\pi})$. Technically speaking, we can identify different ways of escaping this trap.

First, as it is clear from Figure 4, a large enough *permanent* reduction in the environmental threshold value $\tilde{e}$, such that $\tilde{e}$ becomes lower than e_L^*, will eliminate the low steady-state, thus driving our economy toward the high steady-state B. As we observed in Section 2.1, this may correspond, for instance, to an improvement in medicine effectiveness.[10] The crucial point is that in this new situation, the survival probability associated to e_L^* is $\overline{\pi}$ instead of $\underline{\pi}$. This implies greater concern about the future, more maintenance (equation (6)), less consumption, and finally convergence to the high (and now unique) steady-state B identified by $(e_H^*, \overline{\pi})$.

Second, for a fixed $\tilde{e}$, our economy can still get away from the poverty trap by means of a parallel shift-up of the transition function $\phi(e_t)$ such that the low steady-state A disappears (see Figure 4). As it can be inferred from equation (10), such an upwards shift of $\phi(e_t)$ may be induced by (i) a *permanent* income expansion, and/or (ii) a *permanent* reduction of harmful external effects on the environment.[11] A possible real world example of a smaller Q could be the global reduction in pollution due to the implementation of international environmental agreements, such as the Kyoto Protocol.

Third, the inferior steady-state A can be also eliminated if the slope of $\phi(e_t)$ increases for $e_t \in (0, \tilde{e})$. A steeper transition function may be explained, for instance, by a *permanent* rise in the survival probability in a deteriorated environment $(\underline{\pi})$ that, similarly to the reduction of $\tilde{e}$ mentioned above, can be traced back to technological progress in medical sciences, etc.

3.5.2 Back in the trap?

Intuitively, all the mechanisms we have seen above may work in the opposite direction. For instance, a reduction in w and/or an increase in Q may lead to the elimination of the high steady-state (B in Figure 4) and the economy, that would have otherwise converged to the higher steady-state, can be thrown back in the poverty trap.

---

[10]De la Croix and Sommacal (2008) have a model in which a rise in medicine effectiveness, through a longer life expectancy, promotes capital accumulation and income growth. In our setting, advances in medicine induce a different kind of investment, i.e. environmental maintenance and improvement.

[11]Even a *temporary* reduction in Q can help leaving the trap. In this case, however, escaping from the trap does not imply the elimination of the lower steady-state.

It is worth noticing that even *temporary* variations of initial conditions may be sufficient to fall into the trap. Referring to Figure 4, suppose that the environmental quality of our economy belongs to a small right neighbourhood of $\tilde{e}$: out of external intervention, the economy would converge to the high steady-state B. However, any event susceptible of reducing e_0 below $\tilde{e}$ pushes the economy into "vicious" dynamics, involving a deterioration of both environmental conditions and life expectancy. Examples of such events may range from natural disasters to episodes of very acute pollution.

This should raise a concern about the environmental awareness of countries. Neglecting environmental care, bad management of natural resources and too much exposure to environmental risks, may make countries vulnerable to even temporary events with serious long-lasting consequences: in particular, countries with a somewhat fragile environment are prone to pay high costs in terms of human development through lower life expectancy.

Furthermore, some countries might happen to be caught in the trap if they meet environmental constraints when life expectancy is still low. This could be the case of those African countries which display a low life expectancy, but are already very polluted.

3.6 Welfare analysis

In our model, agents are outlived by the consequences of their environmental choices, and they are not able to internalize the external effects of these choices on future generations. It would then be interesting to compare such a decentralized equilibrium with a "green" golden rule allocation, as defined by Chichilnisky et al. (1995). This means solving the model from the point of view of a myopic social planner, whose objective is to maximize aggregate utility in each period, thereby treating all generations symmetrically.[12]

The green golden rule allocation can be found by solving the problem of such a social planner at the steady-state, as in John and Pecchenino (1994). We then look for the optimal *steady-state* combination of consumption and environmental quality that maximizes:

$$U(c,e) = \ln c + \pi(e)\gamma \ln e, \tag{12}$$

subject to:

$$w = c + m, \tag{13}$$

---

[12]A fullfledged forward looking planner would develop an optimal intertemporal plan, but this is not central to our analysis.

15

and

$$\eta e = \sigma m - \beta c - \lambda Q, \tag{14}$$

where $\pi(e)$ can be either $\underline{\pi}$ or $\overline{\pi}$, while (13) and (14) represent, respectively, the budget and the environmental constraints at the steady-state.

Eliminating m and solving for c we obtain:

$$c = \frac{-\eta e + \sigma w - \lambda Q}{\beta + \sigma}, \tag{15}$$

which gives consumption as a function of e, in any steady-state.

After replacing c in the utility function and solving the first-order condition $\partial U / \partial e = 0$, we can determine the following "golden" value for environmental quality (in our case, the condition $\partial^2 U / \partial e^2 < 0$ always holds):

$$e^g = \frac{\gamma \pi}{(1 + \gamma \pi) \eta} (\sigma w - \lambda Q). \tag{16}$$

Let us now compare this golden allocation with the decentralized solution and describe the dynamics of the model in the two cases. In Figure 5, we represent as a solid line the transition function in the decentralized economy, while the dotted line represents the dynamic evolution of e under the social planner hypothesis. Notice that the planner maximizes utility at the beginning of each period, and therefore takes π as given, since the latter is fully determined by past environmental quality.[13]

Suppose that the decentralized economy produces multiple equilibria. Depending on the value of $\tilde{e}$, we may have two different scenarios. If $\tilde{e}$ is sufficiently larger than e_L^* (the level of environmental quality that characterizes the low decentralized steady-state), as in Figure 5a, then there will also be two golden rule allocations, each one superior to the corresponding competitive equilibrium. In fact, since $\eta < 1$, e_L^* (e_H^*) is lower than e_L^g (e_H^g), obtained replacing π with $\underline{\pi}$ ($\overline{\pi}$) in (16). If instead $\tilde{e}$ is quite close to e_L^* ($\tilde{e}'$ in Figure 5b), then it can happen that there exists a unique green golden rule allocation: in this case, we may say that the social planner is able to eliminate the lower steady-state, thus driving the economy out of the trap.

We can then claim the following:

Proposition 2 *At the steady-state, a decentralized equilibrium involves lower environmental quality than the "green" golden rule allocation. Moreover, under proper conditions, the social planner solution may imply the elimination of the environmental trap.*

---

[13]This is the main difference with a non-myopic planner, who is able to formulate an optimal intertemporal plan.

e_{t+1}

$\phi(e_t) = e_t$

$0 \quad e_L^* \quad e_L^g \; \tilde{e} \quad e_H^* \quad e_H^g \, e_t$

(a)

e_{t+1}

$\phi(e_t) = e_t$

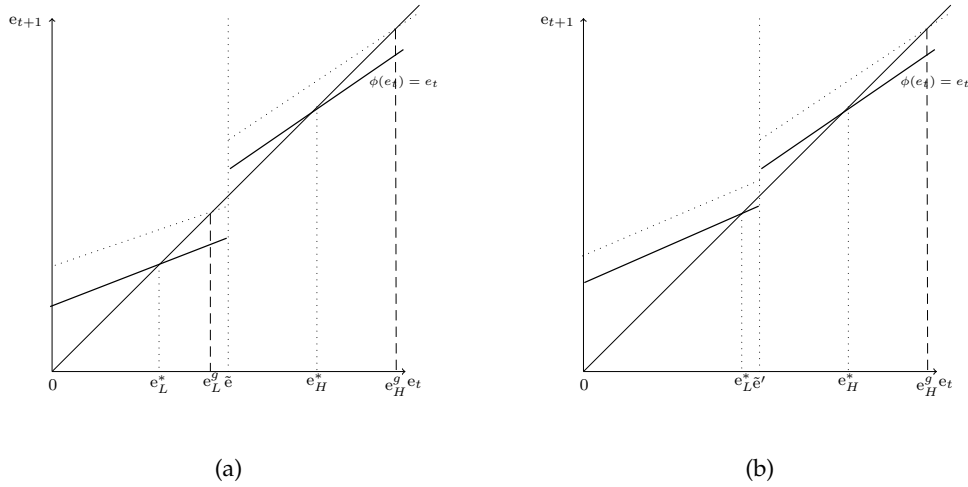$0 \quad e_L^* \tilde{e}' \quad e_H^* \quad e_H^g \, e_t$

(b)

Figure 5: The "green" golden rule

The decentralized economy is under-investing in maintenance since agents do not internalize the positive effect of environmental care on the welfare of forthcoming generations. Not surprisingly, the "distance" between the decentralized and the golden rule values of *e* is inversely related to η. At the limit, as η tends to 1, the effect of past environmental quality on the current state of the environment tends to disappear (thus, eliminating the inter-generational externality), and therefore the decentralized solution approaches the golden-rule allocation.

4 Introducing human capital accumulation

In the basic version of our model, income was completely exogenous in every period and we did not allow for any growth mechanism. In this Section, we aim at overcoming these two limitations by introducing human capital accumulation through education. We want to capture three rather simple ideas: (i) environmental preservation subtracts some resources not only from consumption but also from investment, (ii) income growth, relaxing the budget constraint, makes more maintenance possible, and (iii) growth might itself involve some pollution.[14]

---

[14]We could tell the same story if we had physical capital instead of human capital.

17

4.1 Structure of the model

Agents maximize the following utility function:

$$U = \ln c_t + \pi_t(\alpha \ln h_{t+1} + \gamma \ln e_{t+1}). \tag{17}$$

With respect to (1), we have introduced explicitly inter-generational altruism: parents care about the human capital level attained by their children (h_{t+1}); the importance attached to this term is measured by α, with $0 < \alpha < 1$. Inter-generational altruism is eventually magnified (reduced) by a higher (lower) π_t: the success (or failure) of their children will affect relatively more those parents who will live long enough to witness it. Once more, for the sake of simplicity, we neglect inter-temporal discounting, so that the preference for the future is completely defined by the survival probability.

An increased survival probability implies that agents value more future environmental quality, exactly as it was in the basic model. Moreover, it now makes agents more sympathetic to their offspring, reinforcing inter-generational altruism.

Production of a homogeneous good takes place according to the following function:

$$y_t = wh_t, \tag{18}$$

where w, that we assume to stay constant over time, is both an index of productivity and the wage rate; h_t is also aggregate human capital, once we normalize to 1 the population of our economy. As before, fertility is exogenous, constant and such that there is no population growth.

The budget constraint writes as:

$$wh_t = c_t + m_t + v_t. \tag{19}$$

Agents are paid w for each unit of human capital. Available income may be employed for three alternative purposes: current consumption (c_t), environmental maintenance (m_t) and educational investment (v_t). More precisely, v_t denotes the total amount of education bought by parents for their children, assuming that education is privately funded.

Education is pursued by parents because it can be transformed into future human capital according to the following function:

$$h_{t+1} = \delta h_t^\theta (\mu + v_t)^{1-\theta}, \tag{20}$$

where, depending on θ (with $0 < \theta < 1$), "nature" (parental human capital h_t) complements "nurture" (v_t) in the accumulation of productive skills. Notice that δ (> 0) accounts for total

factor productivity in human capital accumulation, while the parameter μ (> 0) prevents human capital from being zero even if parents do not invest in education, as in de la Croix and Doepke (2003, 2004).

Agents engage in environmental maintenance because it helps to improve future environmental quality, according to:

$$e_{t+1} = (1 - \eta)e_t + \sigma m_t - \beta c_t - \psi y_t. \tag{21}$$

This formulation reproduces (3), with two exceptions: we have now added a factor accounting for growth-induced pollution (through the coefficient $\psi > 0$), while the term representing external effects has been removed for ease of presentation. Notice that here, differently from the benchmark version of our model, we have introduced explicitly a production function. It then would seem perfectly reasonable to consider that such production can also, to some extent, affect environmental quality. Therefore, we have now two potential sources of pollution: consumption and production. As in the real world, both consumers and firms are susceptible to degrading the environment through their actions. We assume for the moment $\psi < \sigma$, thus implying that the environmental benefit produced by one unit of maintenance is larger than the environmental damage caused by one unit of production. This looks reasonable, since maintenance is completely dedicated to improving the environment, while production generates pollution only as a "by-product".

4.2 Optimal choices

Maximizing (17) subject to (19), (20), (21), $c_t > 0$, $m_t > 0$, $e_t > 0$ and $h_t > 0$, leads to the following optimal choices:

$$m_t = \frac{\sigma[\beta + \gamma(\beta + \sigma)\pi_t](\mu + wh_t) + [\sigma + (\beta + \sigma)\alpha(1 - \theta)]\psi wh_t - (1 - \eta)[\sigma + \alpha(1 - \theta)(\beta + \sigma)\pi_t]e_t}{\sigma(\beta + \sigma)\{1 + [\alpha(1 - \theta) + \gamma]\pi_t\}}, \tag{22}$$

$$v_t = \frac{\{\alpha(1 - \theta)[(1 - \eta)e_t + (\sigma - \psi)wh_t] - \gamma\mu\sigma\}\pi_t - \mu\sigma}{\sigma\{1 + [\alpha(1 - \theta) + \gamma]\pi_t\}}, \tag{23}$$

and

$$c_t = \frac{(1 - \eta)e_t + \mu\sigma + (\sigma - \psi)wh_t}{(\beta + \sigma)\{1 + [\alpha(1 - \theta) + \gamma]\pi_t\}}. \tag{24}$$

First of all, it is interesting to compare (22) with (4): the negative association between maintenance and current environmental quality still holds, as well as the positive effect of income, which is now related to *current* human capital. All other things being equal, human capital accumulation makes more resources available for environmental care. Of course, investment in

maintenance is negatively affected by α, reflecting the relative substitutability between *future* human capital and *future* environmental quality in the utility function. Finally, the positive effect of life expectancy on environmental maintenance is confirmed, provided that:

$$\gamma\sigma > \alpha(1-\theta)\beta, \tag{25}$$

as it can be inferred from:

$$\frac{\partial m_t}{\partial \pi_t} = \frac{[\gamma\sigma - \alpha(1-\theta)\beta][(1-\eta)e_t + \mu\sigma + (\sigma - \psi)wh_t)]}{\sigma(\beta+\sigma)\{1 + [\alpha(1-\theta) + \gamma]\pi_t\}^2}. \tag{26}$$

Condition (25), which we assume to hold henceforth, requires that the preference for environmental quality and the effectiveness of maintenance (γ and σ, respectively) must be strong enough to compensate for the weight attached to education (both in the utility function, through α, and in human capital formation, through $(1-\theta)$) and the detrimental effect of consumption on the environment (β).

Parental investment in education depends positively on both human capital (because of the traditional income effect and the inter-generational externality in education) and current environmental quality. If the latter is good enough, requiring a smaller investment in maintenance, it frees resources that can be allocated to education. Moreover, as expected, longer life expectancy induces stronger investment in human capital.[15] In fact, the following derivative is always positive (under the assumption that $\psi < \sigma$):

$$\frac{\partial v_t}{\partial \pi_t} = \frac{\alpha(1-\theta)[(1-\eta)e_t + \mu\sigma + (\sigma - \psi)wh_t)]}{\sigma\{1 + [\alpha(1-\theta) + \gamma]\pi_t\}^2}. \tag{27}$$

4.3 Dynamics

By replacing (22)-(24) into (20) and (21) we get the following non-linear system of two difference equations which describes the dynamics of our economy:

$$h_{t+1} = \delta h_t^\theta \left(\frac{\alpha(1-\theta)[(1-\eta)e_t + \mu\sigma + (\sigma - \psi)wh_t)]\pi_t}{\sigma\{1 + [\alpha(1-\theta) + \gamma]\pi_t\}}\right)^{1-\theta} \equiv \xi(h_t, e_t), \tag{28}$$

---

[15]This result, that we obtain for parentally-funded education, is quite common in the literature, although it may be motivated by somewhat different reasons. For instance, Galor (2005, p. 231) claims that "... the rise in the expected length of the productive life may have increased the potential rate of return to investments in children's human capital, and thus could have induced an increase in human capital formation ...". The positive effect of life expectancy on human capital accumulation can be also generalized to self-funded education: since Ben Porath (1967), it has been well established that the expectation of a longer productive life induces agents to invest more in their own human capital.

$$e_{t+1} = \frac{\gamma[(1-\eta)e_t + \mu\sigma + (\sigma - \psi)wh_t]\pi_t}{1 + [\alpha(1-\theta) + \gamma]\pi_t} \equiv \psi(h_t, e_t). \tag{29}$$

In this set-up, a steady-state equilibrium is defined as a fixed point (h^*, e^*) such that $\xi(h^*, e^*) = h^*$ and $\psi(h^*, e^*) = e^*$. Similarly to Section 3, we assume the following functional form for the survival probability:

$$\pi_t(h_t, e_t) = \begin{cases} \underline{\pi} & \text{if } e_t + \kappa h_t < J \\ \overline{\pi} & \text{if } e_t + \kappa h_t \geq J \end{cases}, \tag{30}$$

with $\kappa, J > 0$.

This formulation captures the substitutability (accounted for by κ) between human capital and environmental quality in increasing life expectancy. Notice also that J is an exogenous threshold value. In Section 3, we have explained how environmental conditions could improve survival probabilities. However, now we also assume that each agent's probability of survival is positively related to his own human capital. Such a mechanism has already been exploited by, for instance, Blackburn and Cipriani (2002) and de la Croix and Licandro (2007), in theoretical models linking growth and demographic dynamics. Apart from the obvious income effect, the positive influence of human capital on longevity may be justified by the fact that better educated people have access to better information about health, are less likely to take up unhealthy behaviour, such as smoking, becoming overweight, etc. It is also consistent with the findings of several empirical studies like, for instance, Lleras-Muney (2005).

Equation (30) paves the way to the existence of multiple steady-states, i.e. multiple solutions to the system composed by equations (28) and (29). After defining the two loci $HH \equiv \{(h_t, e_t) : h_{t+1} = h_t\}$ and $EE \equiv \{(h_t, e_t) : e_{t+1} = e_t\}$, we can claim the following:

Proposition 3 *Provided that (i) $\sigma > \psi$, (ii) proper conditions on the threshold value J hold, and (iii) the slope of HH is larger than the slope of EE, then there exist two stable steady-states A and B such that $0 < h_A^* < h_B^*$ and $0 < e_A^* < e_B^*$.*

Proof. See Appendix A ■

In particular, the "high" equilibrium is characterized by:

$$e_B^* = \frac{\gamma\mu\sigma^2\overline{\pi}}{\sigma + \{\gamma\eta\sigma + [\sigma - \delta^{\frac{1}{1-\theta}}(\sigma - \psi)w]\alpha(1-\theta)\}\overline{\pi}}, \tag{31}$$

and

$$h_B^* = \frac{\alpha(1-\theta)\delta^{\frac{1}{1-\theta}}\mu\sigma^2\overline{\pi}}{\sigma + \{\gamma\eta\sigma + [\sigma - \delta^{\frac{1}{1-\theta}}(\sigma - \psi)w]\alpha(1-\theta)\}\overline{\pi}}; \tag{32}$$

while to obtain the "low" equilibrium (h_A^*, e_A^*) we just need to replace in the above expressions $\overline{\pi}$ with $\underline{\pi}$. Notice that $w\delta^{1/(1-\theta)} < \sigma/(\sigma - \psi)$ is a sufficient condition for both steady-state values to be strictly positive. Moreover, it also ensures that the slope of HH is positive (see Appendix A).

It can be shown that the steady-state values of both environmental quality and human capital are positively affected by π and w, provided that $\psi < \sigma$. Concerning the other parameters, it is interesting to underline that e^* depends positively on θ: the more important is nature (with respect to nurture) in human capital formation, the more parents will be likely to invest in maintenance (rather than in education). Obviously, α and γ also influence positively the long-run levels of human capital and environmental care, respectively.

Let us now give a quick description of the behaviour of our dynamical system. An economy starting from an environmental quality (e_0) and parental human capital (h_0) low (high) enough $(e_0 + \kappa h_0 < (\geq)J)$ will end-up in the steady-state equilibrium A (B), which is characterized by both low (high) environmental quality and human capital, and short (longer) life expectancy. Such a situation is represented by the phase diagram in Figure 6.
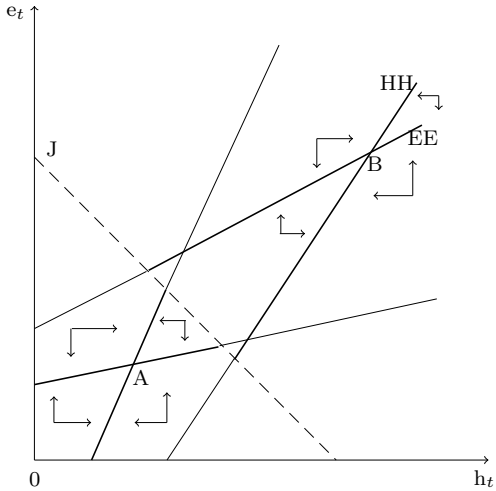

Figure 6: Phase diagram

The causal relationship linking the survival probability to both environmental quality and

human capital implies the possibility of a country being trapped in an environmental poverty trap, as in the benchmark model, and the underlying mechanism is quite similar. However, the poverty trap is now characterized by three elements, namely, low levels of: (i) environmental quality, (ii) life expectancy, and (iii) human capital.[16]

By consequence, differently from Section 3, an economy initially trapped in the "inferior" steady-state can get out of it also through exogenous factors or policies that are related to human capital. We may think of, amongst others, the introduction of public schooling or educational subsidies, or of an exogenous increase in the productivity of the schooling system (δ). In Figure 6 the latter would correspond, for instance, to a repositioning of the *EE* and *HH* loci, such that (h_0, e_0) may fall in the basin of attraction of B instead of A.

Nevertheless, as in Section 3, an economy out of the poverty trap is not safe forever and human capital can be interpreted as an additional "risk factor": a given country may fall into the environmental trap as a consequence, for instance, of a massive destruction of human capital.

4.4 Welfare analysis

Here we want to find the "green" golden-rule allocation and compare it with the equilibrium of the decentralized economy, where agents did not internalize the effects of their actions on the welfare of following generations. We will proceed as we did in Section 3.6, by solving, at the steady-state, the problem of a myopic social planner who treats all generations symmetrically, striving to maximize aggregate utility in every period.

Therefore, we look for the optimal steady-state combination of consumption, environmental quality and human capital that maximizes:

$$U(c, e, h) = \ln c + \pi(e)(\alpha \ln h + \gamma \ln e), \tag{33}$$

subject to:

$$wh = c + m + v, \tag{34}$$

$$\eta e = \sigma m - \beta c - \psi wh, \tag{35}$$

and

$$h = \delta h^\theta (v + \mu)^{1-\theta}, \tag{36}$$

---

[16]This result is consistent with stylized facts, which suggest a bimodal distribution of human capital as well. Data are available upon request.

where (34) and (35) are, respectively, the budget and the environmental constraints at the steady-state, while (36) is the stationary production function for human capital. Notice also that $\pi(e)$ can be either $\underline{\pi}$ or $\overline{\pi}$.

Eliminating m and v, and solving for c, we obtain:

$$c = \frac{-\eta e + \mu\sigma + [(\sigma - \psi)w - \sigma\delta^{\frac{1}{\theta-1}}]h}{\beta + \sigma}.$$

(37)

After replacing c in the utility function, we can solve the system made of the two first-order conditions $\partial U/\partial e = 0$ and $\partial U/\partial h = 0$ to obtain:

$$e^g = \frac{\alpha\mu\sigma\pi}{\eta[1 + (\alpha + \gamma)\pi]}$$

(38)

and

$$h^g = \frac{\alpha\mu\sigma\pi}{[\sigma\delta^{\frac{1}{\theta-1}} - (\sigma - \psi)w][1 + (\alpha + \gamma)\pi]}.$$

(39)

We are ensured that this solution represents a maximum since: $\partial^2 U/\partial e^2 < 0$ and $\partial^2 U/\partial h^2 < 0$. After comparing e^g with e^*, we can claim the following:

Proposition 4 *At the steady-state, for sufficiently low values of η, the decentralized equilibrium involves lower environmental quality than the "green" golden rule allocation. Moreover, under proper conditions, the social planner solution may imply the elimination of the environmental trap.*

In particular, we need $\eta < \hat{\eta}$, where:

$$\hat{\eta} \equiv \frac{\sigma + [\sigma - \delta^{\frac{1}{1-\theta}}(\sigma - \psi)w]\alpha(1 - \theta)\pi}{\sigma(1 + \alpha\pi)}.$$

(40)

Provided that the stability condition mentioned in Proposition 3 holds, $\hat{\eta}$ is positive. Moreover, for α tending to 0, $\hat{\eta}$ tends to 1, thus reproducing the case analysed in Section 3.6. This is not surprising, since α represents the weight of human capital in the utility function.

Moreover, depending on how much the decentralized low steady-state is close to J (otherwise said, $J - (e_A^* + \kappa h_A^*)$ should be sufficiently small), there is the possibility that the golden rule allocation is unique. In other words, a social planner who internalizes inter-generational externalities might be able to drive the economy out of the trap.

The dynamic mechanism producing this result can be seen as a straightforward two-dimensional translation of the one that has been analysed in Section 3.6.

5 Conclusions

In this paper we have studied the interplay between life expectancy and the environment, as well as its dynamic implications. The basic mechanism, upon which our theoretical model is built, is very simple. On the one hand, environmental quality depends on life expectancy, since agents who expect to live longer have a stronger concern for the future and therefore invest more in environmental care. On the other hand, it is reasonable to presume that longevity is affected by environmental conditions. By modelling environmental quality as an asset that can be accumulated over time, we have shown that life expectancy and environmental dynamics can be jointly determined, and multiple equilibria may arise. In particular, we have focused on the existence of an environmental kind of poverty trap, characterized by both low life expectancy and poor environmental performance. Possible "escape" strategies, as well as factors affecting the risk to be caught in such a trap, have been discussed. Both the correlation between environmental performance and life expectancy, and possible non-ergodic dynamics, are consistent with stylized facts.

Our model is also robust to the introduction of a very simple growth mechanism via human capital accumulation. If education depends on life expectancy, and survival probabilities are affected by both environmental quality and human capital, we can always end up with multiple development regimes, the only difference being that the low-life-expectancy/poor-environment trap would be characterized by low human capital as well.

Moreover, some welfare analysis of the model suggests that the decentralized equilibrium is inefficient: agents do not internalize the effects of their choices on future generations. Therefore, a social planner who internalizes inter-generational externalities might achieve a superior equilibrium and, under proper conditions, might be able to drive the economy out of an environmental poverty trap.

Finally, as interesting extensions and possible directions for further research, we would suggest: (i) to introduce heterogeneity among agents, moving from a representative agent set-up to a political economy model, where environmental choices are determined through voting; (ii) to enhance the demographic part of the model, allowing for endogenous fertility and relating environmental quality to demographic factors other than longevity (population density, for instance).

Appendices

A Proof of Proposition 3

The proof is organized as follows. We will first characterize the two loci HH and EE, and then analyse the existence, multiplicity and stability of the steady-state equilibria.

Let us recall the definition of the two loci: $HH \equiv \{(h_t, e_t) : h_{t+1} = h_t\}$ and $EE \equiv \{(h_t, e_t) : e_{t+1} = e_t\}$.

A.1 Locus HH

From equation (28) we get that $h_{t+1} - h_t = \xi(h_t, e_t) - h_t$, where π_t is given by equation (30). Therefore, the locus HH writes as:

$$e_t = -\frac{\sigma\mu}{1-\eta} + \frac{\sigma\{1 + [\alpha(1-\theta) + \gamma]\pi_t\} - \alpha(1-\theta)(\sigma - \psi)w\pi_t\delta^{\frac{1}{1-\theta}}}{\alpha(1-\theta)(1-\eta)\pi_t\delta^{\frac{1}{1-\theta}}}h_t, \qquad (A.1)$$

where $\pi_t = \underline{\pi}\ (= \overline{\pi})$ for $e_t + \kappa h_t < J\ (\geq J)$. As we can see in Figure 6, locus HH is a discontinuous function divided into two parts (both straight lines) by $e_t = J - \kappa h_t$. Its intersection with the y-axis (i.e. the intercept) is given by $e_{t_{HH}}\ |_{h_t=0} = -\sigma\mu/(1-\mu) < 0$, while its slope can be expressed as:

$$\frac{\partial e_t}{\partial h_t} = \frac{\sigma\{1 + [\alpha(1-\theta) + \gamma]\pi_t\} - \alpha(1-\theta)(\sigma - \psi)w\pi_t\delta^{\frac{1}{1-\theta}}}{\alpha(1-\theta)(1-\eta)\pi_t\delta^{\frac{1}{1-\theta}}} \equiv s_h(\pi_t), \qquad (A.2)$$

where $\pi_t = \underline{\pi}\ (= \overline{\pi})$ for $e_t + \kappa h_t < J\ (\geq J)$. Indeed, as it is clear from the above equation, for s_h to be positive, we just need to have a positive numerator. Moreover, one can also verify that $\partial s_h(\pi)/\partial \pi < 0$. This implies that the first portion of the locus HH (given by $s_h(\underline{\pi})$) is steeper than the second one ($s_h(\overline{\pi})$), as depicted in Figure 6.

A.2 Locus EE

Equation (29) yields $e_{t+1} - e_t = \psi(h_t, e_t) - e_t$, where π_t is given by equation (30). Therefore, the locus EE can be written as:

$$e_t = -\frac{\gamma\sigma\mu\pi_t}{\gamma(1-\eta)\pi_t - \{1 + [\alpha(1-\theta) + \gamma]\pi_t\}} - \frac{\gamma(\sigma - \psi)w\pi_t}{\gamma(1-\eta)\pi_t - \{1 + [\alpha(1-\theta) + \gamma]\pi_t\}}h_t, \quad (A.3)$$

where $\pi_t = \underline{\pi}\ (= \overline{\pi})$ for $e_t + \kappa h_t < J\ (\geq J)$. As it happened for HH, the locus EE is also a discontinuous function divided into two different parts (once more straight lines) by $e_t = J - \kappa h_t$.

Moreover:

$$e_{t_{EE}} \big|_{h_t=0} = -\frac{\gamma \sigma \mu \pi_t}{\gamma(1-\eta)\pi_t - \{1 + [\alpha(1-\theta) + \gamma]\pi_t\}},$$

while the slope of *EE* is given by:

$$\frac{\partial e_t}{\partial h_t} = -\frac{\gamma(\sigma - \psi)w\pi_t}{\gamma(1-\eta)\pi_t - \{1 + [\alpha(1-\theta) + \gamma]\pi_t\}} \equiv s_e(\pi_t), \tag{A.4}$$

where, as usual, $\pi_t = \underline{\pi} \ (= \overline{\pi})$ for $e_t + \kappa h_t < J \ (\geq J)$. One can easily observe that the denominator of the previous equation is strictly negative. Therefore, $e_{t_{EE}} \big|_{h_t=0} > 0$ and, provided that $\sigma > \psi$, $s_e > 0$. Moreover, since $\partial(e_{t_{EE}} \big|_{h_t=0})/\partial \pi > 0$, the y-intercept corresponding to $\pi_t = \overline{\pi}$ is larger than the one defined by $\pi_t = \underline{\pi}$. Finally, we also have $\partial s_e(\pi)/\partial \pi > 0$, for $\sigma > \psi$. Consequently, the slope of the first portion of the locus *EE* (given by $s_e(\underline{\pi})$) is smaller than the slope of the second part ($s_e(\overline{\pi})$), as represented in Figure 6.

A.3 Existence, multiplicity and stability of steady-states

Provided that $s_h > s_e$ and $\sigma > \psi$, there *exist* two points $A \equiv (h_A, e_A) = EE(\underline{\pi}) \cap HH(\underline{\pi})$ and $B \equiv (h_B, e_B) = EE(\overline{\pi}) \cap HH(\overline{\pi})$, such that $0 < h_A < h_B$ and $0 < e_A < e_B$. A and B are *both* steady-states if $e_A + \kappa h_A < J < e_B + \kappa h_B$. Figure 6 provides a straightforward illustration of this condition: the dashed line $e_t + \kappa h_t = J$ should lie between A and B.

Let us now study the *stability* of A and B. Consider first the locus HH, and take a point $(\overline{h}, \overline{e}) \in HH$. For a fixed $e_t = \overline{e}$, and using (A.1), the dynamics of h_t are given by the following expression:

$$\Delta h_t = \delta h_t^\theta \left\{ \frac{\sigma\{1 + [\alpha(1-\theta)+\gamma]\pi_t\} - \alpha(1-\theta)(\sigma-\psi)w\pi_t \delta^{\frac{1}{1-\theta}}}{\sigma\{1 + [\alpha(1-\theta)+\gamma]\pi_t\}\delta^{\frac{1}{1-\theta}}}\overline{h} + \frac{\alpha(1-\theta)(\sigma-\psi)w\pi_t}{\sigma\{1 + [\alpha(1-\theta)+\gamma]\pi_t\}}h_t \right\}^{1-\theta} - h_t, \tag{A.5}$$

where $\pi_t = \underline{\pi} \ (= \overline{\pi})$ for $e_t + \kappa h_t < J \ (\geq J)$. If $s_h > s_e$, then the numerator of equation (A.2) is positive, since $s_e > 0$. Consequently, we can verify that, for $h_t > \overline{h} \ (< \overline{h})$, $\Delta h_t < 0 \ (> 0)$. Hence, h_t decreases (increases). Similarly, let us now consider a point $(\overline{h}, \overline{e}) \in EE$. For a fixed $h_t = \overline{h}$, and taking (A.3), the dynamics of e_t are given by the following expression:

$$\Delta e_t = \frac{\gamma(1-\eta)\pi_t - \{1 + [\alpha(1-\theta)+\gamma]\pi_t\}}{1 + [\alpha(1-\theta)+\gamma]\pi_t}(e_t - \overline{e}), \tag{A.6}$$

where $\pi_t = \underline{\pi} \ (= \overline{\pi})$ for $e_t + \kappa h_t < J \ (\geq J)$. Since the numerator is negative, it is clear that, for $e_t > \overline{e} \ (< \overline{e})$, $\Delta e_t < 0 \ (> 0)$. Hence, e_t decreases (increases).

References

[1] Azariadis, C. (1996): "The economics of poverty traps. Part one: complete markets", *Journal of Economic Growth* 1, 449-486.

[2] Azariadis, C. and J. Stachurski (2005): "Poverty traps", in Aghion, P. and S.N. Durlauf (eds.): *Handbook of Economic Growth* 1 (1), 295-384.

[3] Baland, J.-M. and J.-P. Platteau (1996): *Halting the degradation of natural resources: is there a role for rural communities*, Clarendon Press, Oxford, UK.

[4] Ben Porath, Y. (1967): "The production of human capital and the life cycle of earnings", *Journal of Political Economy* 75, 352-365.

[5] Blackburn, K. and G.P. Cipriani (2002): "A model of longevity, fertility and growth", *Journal of Economic Dynamics & Control* 26, 187-204.

[6] Cakmak,S., R.T. Burnett and D. Krewski (1999): "Methods for detecting and estimating population threshold concentrations for air pollution-related mortality with exposure measurement error", *Risk Analysis* 19 (3), 487-496.

[7] Chakraborty, S. (2004): "Endogenous lifetime and economic growth", *Journal of Economic Theory* 116, 119-137.

[8] Chichilnisky, G., G. Heal and A. Beltratti (1995): "The green golden rule", *Economics Letters* 49, 175-179.

[9] Dasgupta, P. and K.-G. Mäler (2003): "The economics of non-convex ecosystems: Introduction", *Environmental and Resource Economics* 26, 499-525.

[10] de la Croix, D. and M. Doepke (2003): "Inequality and growth: why differential fertility matters", *American Economic Review* 93 (4), 1091-1113.

[11] de la Croix, D. and M. Doepke (2004): "Public versus private education when differential fertility matters", *Journal of Development Economics* 73, 607-629.

[12] de la Croix, D. and D. Dottori (2008): "Easter Island collapse: a tale of population race", *Journal of Economic Growth* 13, 27-55.

[13] de la Croix, D. and O. Licandro (2007): "'The child is father of the man': implications for the demographic transition", *mimeo*.

[14] de la Croix, D. and A. Sommacal (2008): "A theory of medical effectiveness, differential mortality, income inequality and growth for the pre-industrial England", *Mathematical Population Studies* forthcoming.

[15] Diamond, J. (2005): *Collapse: how societies choose to fail or survive*, Viking Books, New York, NY.

[16] Elo, I.T. and S.H. Preston (1992): "Effects of early-life conditions on adult mortality: a review", *Population Index* 58 (2), 186-212.

[17] Evans, M.F. and V.K. Smith (2005): "Do new health conditions support mortality-air pollution effects?", *Journal of Environmental Economics and Management* 50, 496-518.

[18] Feachem, R. (1994): "Health decline in Eastern Europe", *Nature* 367, 313-314.

[19] Galor, O. (2005): "From stagnation to growth: unified growth theory", in Aghion, P. and S.N. Durlauf (eds.): *Handbook of Economic Growth* 1 (1), 171-293.

[20] Hartigan, J.A. and P.M. Hartigan (1985): "The dip test of unimodality", *Annals of Statistics* 13, 70-84.

[21] Jedrychowski, W. (1995): "Review of recent studies from Central and Eastern Europe associating respiratory health effects with high levels of exposure to "traditional" air pollutants", *Environmental Health Perspectives* 103 (suppl. 2), 15-21.

[22] Jouvet, P.-A., Ph. Michel and J.-P. Vidal (2000): "Intergenerational altruism and the environment", *Scandinavian Journal of Economics* 102 (1), 135-150.

[23] Jouvet, P.-A., P. Pestieau and G. Ponthière (2007): "Longevity and environmental quality in an OLG model", *CORE Discussion Paper* 2007/69.

[24] Lleras-Muney, A. (2005): "The relationship between education and adult mortality in the United States", *Review of Economic Studies* 72, 189-221.

[25] McMichael, A.J., M. McKee, V. Shkolnikov and T. Valkonen (2004): "Mortality trends and setbacks: global convergence or divergence?", *Lancet* 363, 1155-1159.

[26] Ono, T. (2002): "The effects of emission permits on growth and the environment?", *Environmental and Resource Economics* 21, 75-87.

[27] Ono, T. and Y. Maeda (2001): "Is aging harmful to the environment?", *Environmental and Resource Economics* 20, 113-127.

[28] Patz, J.A., D. Campbell-Lendrum, T. Holloway and J.A. Foley (2005): "Impact of regional climate change on human health", *Nature* 438, 310-317.

[29] Pecchenino, R. and A. John (1994): "An overlapping generations model of growth and the environment", *Economic Journal* 104, 1393-1410.

[30] Pope, C.A. III, D.V. Bates and M.E. Raizenne (1995): "Health effects of particulate air pollution: time for reassessment?", *Environmental Health Perspectives* 103 (5), 472-480.

[31] Popp, D. (2001): "Altruism and the demand for environmental quality", *Land Economics* 77 (3), 339-349.

[32] Scheffer, M., S. Carpenter, J.A. Foley, C. Folke and B. Walker (2001): "Catastrophic shifts in ecosystems", *Nature* 413, 591-596.

[33] United Nations (2007): *World Population Prospects: the 2006 revision*. [Data available on-line at http://unstats.un.org/unsd/demographic/products/socind/health.htm]

[34] Yale Center for Environmental Law and Policy (2006): *Environmental Performance Index*. [Data available on-line at http://epi.yale.edu]