Life expectancy and the environment*

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Abstract

We present an OLG model in which life expectancy and environmental quality dynamics are jointly determined. Agents may invest in environmental care, depending on how much they expect to live. In turn, environmental conditions affect life expectancy. As a result, our model produces a positive correlation between longevity and environmental quality, both in the long-run and along the transition path. Eventually, multiple equilibria may also arise: some countries might be caught in a low-life-expectancy / low-environmental-quality trap. This outcome is consistent with stylized facts relating life expectancy and environmental performance measures. We also discuss the welfare and policy implications of the intergenerational externalities generated by individual choices. Finally, we show that our results are robust to the introduction of growth dynamics based on physical or human capital accumulation.

JEL classification: J24; O11; O40; 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

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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), Pope (2000), Pope et al. (2004) 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 capable 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 positively 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 stylized facts highlighted above. To do that, we model explicitly the two-way causality between the environment and longevity, which generates a positive dynamic correlation between the two variables. This kind of interaction, which is central to our analysis, might in turn also justify the existence of an environmental poverty trap, characterized by both bad environmental conditions and short life expectancy. Moreover, we are able to identify inter-generational externalities, and study how they might be corrected by policy intervention.

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. 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: 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 in turn affected by environmental conditions, the resulting two-sided feedback produces a positive correlation between the two variables, both at the steady-state and along the transition path.

Depending on the shape of the survival probability function, our model can also allow for multiple equilibria and may explain the existence of poverty traps: initial conditions do matter and a given economy may be caught in a high-mortality/poor-environment trap. In particular, we build an example based on a convex-concave function linking environmental quality and life expectancy, which is backed up by some well-established scientific literature (see Cakmak et al. (1999) and Scheffer et al. (2001)). Possible strategies to escape from the trap will be also identified and discussed.

After analyzing the welfare and policy implications of our benchmark model, we introduce human capital accumulation so as to deal with endogenous income dynamics. Parents can use their income to also educate their children, while survival probabilities are affected by both environmental quality and education. Considering human capital led growth, we are able to see that the positive dynamic correlation between life expectancy and the environment still holds, and extends to income in the long-run. However, we also find that short-run deviations, which allow the environment to worsen as income increases, are possible. Under proper conditions, we may eventually end up with multiple development regimes, where the low-life-expectancy/poor-environment trap is now characterized by low human capital as well.

Our model is primarily related to those papers that have analyzed environmental issues in a dynamic OLG framework. Among them, John and Pecchenino (1994) deal with environmental maintenance as an inter-generational problem, but life expectancy is assumed to be exogenous and plays no role in their model. 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 life expectancy in defining environmental choices and leave no room for maintenance. Our model is also somewhat related to Jouvet et al. (2000), who use inter-generational altruism to explain environmental choices.

Let us also point out that, although environmental poverty traps have been already studied by John and Pecchenino (1994) and Ikefuji and Horii (2007), these papers overlook the role of life expectancy, which in contrast we consider as being a crucial factor behind the existence of multiple equilibria. In this respect, our paper is related to Blackburn and Cipriani (2002), or

Chakraborty (2004), in which life expectancy is regarded as a possible cause of underdevelopment traps (although not linked to the environment).

The remainder of the paper is organized as follows. Section 2 presents some stylized facts on environmental quality and life expectancy that provide the motivation of our study. Section 3 introduces and solves the basic model, discussing its dynamic properties and welfare implications. An extended version of the model, allowing for human capital accumulation, is analyzed in Section 4. Section 5 concludes.

2 Stylized facts

Here we want to present the 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", which 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 0 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. Using the EPI allows us to avoid a myopic view of environmental quality, according to which environmental degradation can be traced back only to industrial activity and pollution. In fact, poor environmental quality can also be explained by factors like mismanagement of natural resources, deforestation, overgrazing, unsanitary practices, etc.[1] 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, which is obtained removing the child mortality factor.[2]

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

[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.

(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.*

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.

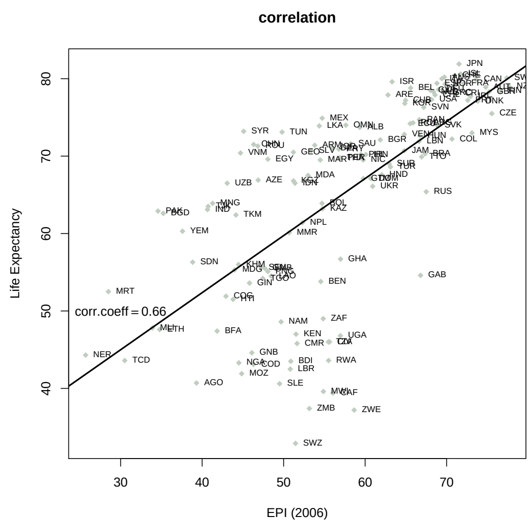


Figure 1: Environmental quality and life expectancy
Sources: YCELP (2006), UN (2007)

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 histograms and kernel density estimates (with optimal bandwidth), displays bimodal distributions of both variables across countries.[3]

[3]In both cases, the null hypothesis of unimodality is rejected by the Hartigan's *dip* test, which 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,

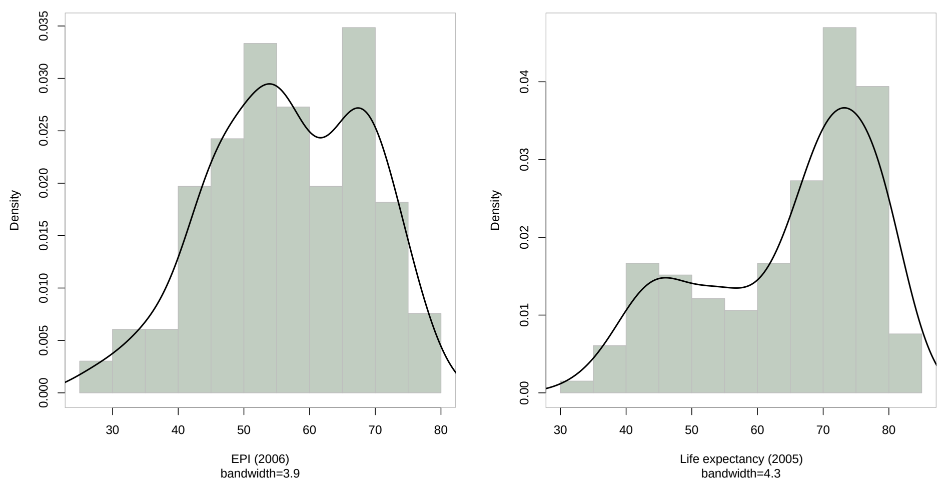


Figure 2: Bimodal distribution of environmental quality and life expectancy
Sources: YCELP (2006), UN (2007)

We believe that this double bimodality can be interpreted as a trap, since there is a high degree of overlap in the lower modes of the two distributions represented in Figure 2. For instance, out of the 48 countries in the lower mode of the life expectancy distribution (less than 58 years), only one shows up in the upper mode of the EPI distribution (EPI score larger than 62). Moreover, if we divide both distributions into two groups of equal size, we find that (i) out of 66 countries with a EPI index lower than the median value (56.04), 54 also belong to the group characterized by a life expectancy below the median (69.5), and (ii) out of the 66 countries with lower-than-median life expectancy, 55 also exhibit a below-the-median value of the EPI.

Among "trapped" economies we find, together with African countries, the vast majority of ex-USSR republics. The low life expectancy in Africa has often been related to mismanagement of environmental resources, pollution and anthropogenic climate change (see, among others, Patz et al., 2005). The argument for a pollution-driven mortality resurgence has also been put forward by McMichael et al. (2004) and, in the case of ex-USSR, by Feachem (1994) and Jedrychowski (1995).

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 rejected because $d > 0.0370$ (at the 5% significance level). 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 income between current consumption and environmental maintenance. Consumption, generating pollution and/or increasing pressure on natural resources, involves 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 a utility function $U_t(c_t, e_{t+1})$, such that $\partial U_t(\cdot)/\partial c_t > 0$, $\partial U_t(\cdot)/\partial e_{t+1} > 0$, $\partial^2 U_t(\cdot)/\partial c_t^2 < 0$, $\partial^2 U_t(\cdot)/\partial e_{t+1}^2 < 0$, $\lim_{c_t \to 0} \partial U_t(\cdot)/\partial c_t = +\infty$, and $\lim_{e_{t+1} \to 0} \partial U_t(\cdot)/\partial e_{t+1} = +\infty$. In particular, in order to get closed-form solutions, we assume:

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

People care about adult consumption (c_t) and environmental quality when old (e_{t+1}); $\gamma > 0$ represents the weight agents give to the future environment (green preferences), while π_t denotes the survival probability, which 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.).[4] Broadly speaking, e_t can be seen as an index of the amenity (use and non-use) value of the environment.

Adult individuals face the following budget constraint:

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

[4]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.

they allocate their income (w_t) between consumption and environmental maintenance (m_t). In this benchmark version of our model, income is assumed to be exogenous.[5] Environmental maintenance summarizes all the actions that agents can take in order to preserve and improve environmental conditions.

Following John and Pecchenino (1994), 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 $0 < \eta < 1$.

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 exogenous external effects on the environment: $\lambda Q_t > 0$ (< 0) represents the total impact of a harmful (beneficial) activity.[6]

Notice that a reduction in c_t has a double effect on the environment: it directly affects environmental quality through 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.[7]

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 $U_t(c_t, e_{t+1})$ subject to (2), (3), $c_t > 0$, $m_t > 0$ and $e_t > 0$. With a general utility function, the optimality condition writes as:

$$\frac{\partial U_t}{\partial c_t} = (\beta + \sigma)\frac{\partial U_t}{\partial e_{t+1}}. \tag{4}$$

Using equation (1), optimal choices are then given by:

$$m_t = \frac{\lambda Q_t - (1-\eta)e_t + [\beta + \gamma(\beta+\sigma)\pi_t]w_t}{(\beta+\sigma)(1+\gamma\pi_t)}, \tag{5}$$

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

[6] Natural disasters or episodes of acute pollution, like oil slicks or the Chernobyl accident, 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.

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

and

$$c_t = \frac{(1-\eta)e_t + \sigma w_t - \lambda Q_t}{(\beta+\sigma)(1+\gamma\pi_t)}. \tag{6}$$

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

From (5) and (6), 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 John and Pecchenino (1994).

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

$$\frac{\partial m_t}{\partial \pi_t} = \frac{\gamma[(1-\eta)e_t + \sigma w_t - \lambda Q_t]}{(\beta+\sigma)(1+\gamma\pi_t)^2}, \tag{7}$$

which is positive for interior solutions, a higher survival probability induces more maintenance, since it raises stronger concerns for the future state of the environment. This paves the way for a positive correlation between longevity and environmental quality, along the transition path.

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 (5) and (6) into (3), we get the following dynamic difference equation, describing the evolution of environmental quality over time:

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

So far 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 $\partial\pi(e_t)/\partial e_t > 0$, $\lim_{e_t \to 0} \pi(e_t) = \underline{\pi}$ and $\lim_{e_t \to \infty} \pi(e_t) = \overline{\pi}$, with $0 < \underline{\pi} < \overline{\pi} < 1$. This formulation is consistent with a large body of medical and epidemiological literature showing strong and clear effects of environmental conditions on adult mortality, like for instance

Elo and Preston (1992), Pope et al. (1995, 2004), Pope (2000) and Evans and Smith (2005). Such effects are obtained after controlling for income and other socio-economic factors. 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.

Let us underline that agents cannot improve their own survival probability by investing in maintenance. This is consistent with equation (3), where current environmental choices (especially m_t) affect the future state of the environment. Any investment in maintenance will be rewarded, in terms of environmental quality and life expectancy, only in the future period. This introduces inter-generational externalities, whose consequences will be addressed in Subsection 3.6.

The dynamics of our model are now given by:

$$e_{t+1} = \frac{\gamma\pi(e_t)}{1+\gamma\pi(e_t)}[(1-\eta)e_t + \sigma w_t - \lambda Q_t] \equiv \phi(e_t), \tag{9}$$

where, for the sake of simplicity, w_t and Q_t are assumed to be not only exogenous but also constant, so that $w_t = w$ and $Q_t = Q$.

This kind of dynamics results from the two-sided feedback between life expectancy and the environment, described by $m_t = m(\pi_t)$ and $\pi_t = \pi(e_t)$, respectively. 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. 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. From equation (9) we can infer that the steady-state value of environmental quality e^* (and consequently life expectancy π^*) is positively affected by income w (through the effectiveness of maintenance, σ) and preferences for the environment (γ), while it is negatively influenced by the external effect λQ and the natural rate of deterioration η.

Non-ergodicity and multiple steady-states may instead occur if $\phi(\cdot)$ displays one or more inflection points, being for instance first convex and then concave. 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 (see Figure 3).

A transition function $\phi(e_t)$ compatible with the existence of multiple equilibria might be generated by a variety of functional forms describing the survival probability $\pi(e_t)$. In particular, a step-function approximation of a convex-concave $\pi(e_t)$ is convenient to get analytical results.[8]

[8]Notice that, however, the existence of multiple equilibria is not constrained by assuming a convex-concave $\pi(e_t)$.

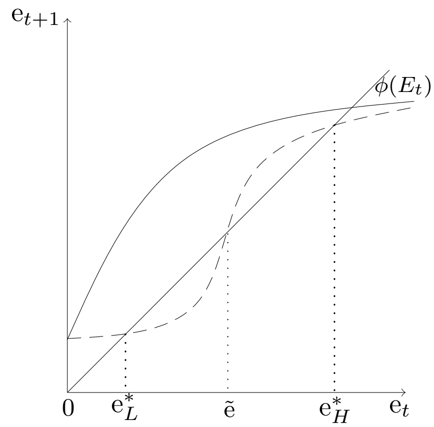


Figure 3: Dynamics

In this case, a substantial improvement in the survival probability can be achieved only after a given environmental threshold is attained. This is consistent with the idea that environmental degradation may affect ecosystems, or human health, following a convex-concave relationship. 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 multiple equilibria. Threshold-effects, non-smooth dynamics and regime shifts in ecosystems are indeed commonly assumed in natural sciences, as pointed out by Scheffer et al. (2001).[9]

3.4 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 conditions:

$$\pi(e_t) = \begin{cases} \underline{\pi} & \text{if} \quad e_t < \tilde{e} \\ \overline{\pi} & \text{if} \quad e_t \geq \tilde{e} \end{cases}, \tag{10}$$

Multiplicity of steady-state is also compatible, for instance, with a concave $\pi(e_t)$ of the type $\pi(e_t) = \min\{\underline{\pi} + Ae_t^{\upsilon}, \overline{\pi}\}$, with $A > 0$ and $0 < \upsilon \leq 1$. We are thankful to an anonymous referee for pointing out this possibility.

[9]See also Baland and Platteau (1996), who 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. 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).

where $\overline{\pi} > \underline{\pi}$, and $\tilde{e}$ is an exogenous threshold value of environmental quality, above (below) which the value of the survival probability is high (low). 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 in a deteriorated environment. A high $\tilde{e}$ might instead represent the case of a developing country, where health services are so poorly performing that mortality remains high even under pretty good environmental conditions.

Given equation (10), the transition function $\phi(e_t)$ becomes:

$$\phi(e_t) = \begin{cases} \frac{\gamma\underline{\pi}}{1+\gamma\underline{\pi}}[(1-\eta)e_t + \sigma w - \lambda Q] & \text{if} \quad e_t < \tilde{e} \\ \frac{\gamma\overline{\pi}}{1+\gamma\overline{\pi}}[(1-\eta)e_t + \sigma w - \lambda Q] & \text{if} \quad e_t \geq \tilde{e} \end{cases}. \tag{11}$$

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 (11) 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 $\phi'(e_t) < 1$, $\forall e_t > 0$. 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. ∎

In particular, we have that:

$$e_L^* = \frac{\gamma\underline{\pi}}{(1+\gamma\eta\underline{\pi})}(\sigma w - \lambda Q) \text{ and } e_H^* = \frac{\gamma\overline{\pi}}{(1+\gamma\eta\overline{\pi})}(\sigma w - \lambda Q). \tag{12}$$

As shown by Figure 4, the threshold value $\tilde{e}$ identifies a poverty trap: an economy starting 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 (pinned down to $\underline{\pi}$). In fact, a lower survival probability induces agents to substitute environmental maintenance with consumption. 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 a healthier environment (e_H^*).

3.5 In and out of the trap

The very existence of an environmental trap implies that some countries (or regions) may experience, over time, both environmental degradation and decay in life expectancy. Cross-section

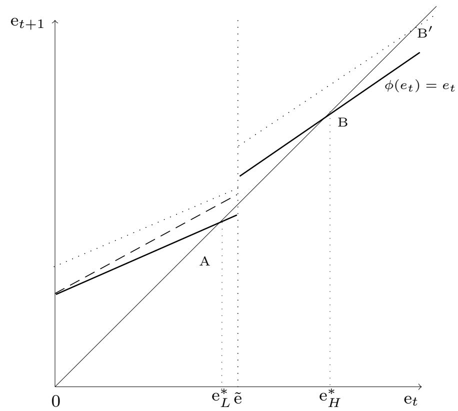


Figure 4: Environmental poverty trap

data would suggest that the latter is much less common than the former. Environmental degradation might not imply lower longevity because economic growth (neglected until now in our analysis) can harm the environment, but also generate additional income to increase (or preserve) 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 decrease in longevity between 1990 and 2001.[10] 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". We can also mention the case - particularly cherished by economists - of Easter Island, which serves as a good example of a closed system where insufficient environmental care (or better, too much pressure on natural resources) ultimately led to a dramatic reduction of the local population (see Diamond (2005), or de la Croix and Dottori (2008)).

Let us now go back to our formal framework and assume that our economy is initially trapped in the low steady-state (A, in Figure 4) characterized by $(e^*_L, \underline{\pi})$. We can identify three different ways of escaping this trap: (i) a large enough permanent reduction in the threshold value $\tilde{e}$, (ii) a parallel shift-up of the function $\phi(e_t)$, and (iii) an increase of the slope of $\phi(e_t)$. The first one, as already seen, might correspond to improvements in medicine.[11] The second may

[10]Most of them are African or ex-Soviet countries. Losses in longevity are sometimes severe, going up to 15-18 years, and "in several West African countries, (they) are not obviously attributable to HIV/AIDS".

[11]In de la Croix and Sommacal (2008), advances in medicine, through a longer life expectancy, promote capital

be induced by a permanent income expansion and/or reduction of harmful external effects.[12]. The third one may be instead explained by a permanent rise of $\underline{\pi}$ that, similar to a reduction of $\tilde{e}$, can be traced back to technological progress in medical sciences, etc. Whatever the case, e_L^* would be associated with a greater concern about the future, implying more maintenance, less consumption, and finally convergence to the high (and now unique) steady-state B defined by $(e_H^*, \overline{\pi})$.

Intuitively, all the above channels may work in the opposite direction: a reduction in w and/or an increase in Q may lead to the elimination of the high steady-state and an economy, which would have otherwise ended up there, can be thrown back in the poverty trap. Even temporary shocks (such as natural disasters or episodes of acute pollution) may be sufficient to fall in the trap. This raises a concern about the environmental awareness of countries. Neglecting environmental care and a bad management of natural resources may make countries vulnerable to even temporary events with serious long-lasting consequences for human development. Furthermore, some countries might find themselves trapped if they meet environmental constraints when life expectancy is still low. This could be the case of those African countries that 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 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 social planner, whose objective is to maximize aggregate utility at the steady-state. The case of a full-fledged forward-looking planner, who also cares about generations along the transition path and thus develops an optimal inter-temporal plan, will be analyzed in Appendix A.

As in John and Pecchenino (1994), we then look for the optimal steady-state combination of consumption and environmental quality that maximizes $U(c, e)$, subject to:

$$\eta e = \sigma w - (\beta + \sigma)c - \lambda Q, \tag{13}$$

which summarizes the budget and the environmental constraints, at the steady-state.

accumulation and growth. In our setting, they induce a different kind of investment, *i.e.* environmental maintenance.

[12]A possible real world example of a smaller Q could be the implementation of international agreements, such as the Kyoto Protocol. Notice that 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.

The resulting optimality condition is given by:

$$\frac{\partial U}{\partial c} = \frac{\beta + \sigma}{\eta} \left(\frac{\partial U}{\partial e} + \frac{\partial U}{\partial \pi} \frac{\partial \pi}{\partial e} \right). \tag{14}$$

Comparing (14) with (4) at the steady-state, we can see immediately that the golden rule allocation does not coincide with the decentralized equilibrium, since (i) $\eta < 1$, and (ii) $\partial \pi / \partial e \neq 0$. In fact, as soon as there are intergenerational externalities linked to environmental quality (as an argument of the utility function and as a factor affecting life expectancy), individual agents consume more (and invest less in maintenance) than it would be socially optimal. 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.*

The "distance" between the decentralized and the golden rule values of e is inversely related to η, while it is increasing in $\|\partial \pi / \partial e\|$. At the limit, as η tends to 1 and $\partial \pi / \partial e$ tends to 0, the effect of environmental care on the future state of the environment and life expectancy vanishes, thus eliminating inter-generational externalities. Therefore, the decentralized solution approaches the golden rule allocation.

In order to achieve an optimal allocation in the decentralized economy, environmental policies can be implemented. Consider for instance a tax levied on consumption, so that its price becomes $(1 + \tau)$ (instead of 1): given the structure of our model, this boils down to taxing pollution. Tax receipts will be then transferred in a lump-sum way to agents.[13] If this is the case, decentralized agents define their optimal choices according to:

$$\frac{\partial U}{\partial c} = [\beta + (1 + \tau)\sigma] \frac{\partial U}{\partial e}. \tag{15}$$

Equating (14) and (15), we can deduce the tax rate that realizes the optimal allocation:

$$\tau^* = \frac{(\beta + \sigma)}{\eta \sigma} \left[(1 - \eta) + \frac{\frac{\partial U}{\partial \pi} \frac{\partial \pi}{\partial e}}{\frac{\partial U}{\partial e}} \right]. \tag{16}$$

It can be noticed that the smaller the size of external effects, the lower the environmental tax. In addition, τ^* depends positively on β (which magnifies, through the pollution term in (3), the intergenerational externality), and negatively on σ (which, defining the effectiveness of maintenance, reduces the size of negative external effects).

In order to get some further insight, we specify the utility function as in (1) and the survival probability π as in (10), so that $\partial \pi / \partial e = 0$.[14] We can accordingly determine the following

[13] Our analysis would hold qualitatively unaffected, if taxes were used to subsidize maintenance.

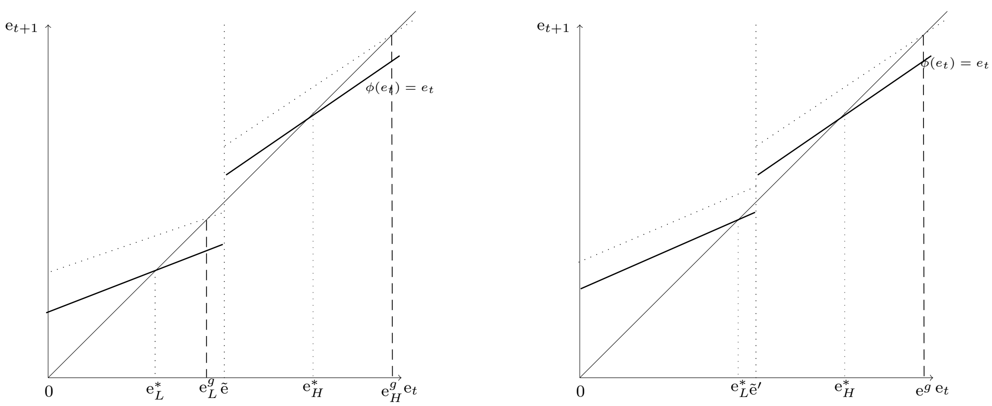
[14] Therefore, one of the two externalities disappears and the tax rate in (16) simplifies into $\tau^* = (1 - \eta)(\beta + \sigma)/(\eta\sigma)$.

"golden" value for environmental quality:

$$e^g = \frac{\gamma\pi}{(1+\gamma\pi)\eta}(\sigma w - \lambda Q), \tag{17}$$

which can be compared to the case of a decentralized economy producing multiple equilibria (as defined by e_L^* and e_H^* in (12)).

Let us now describe the dynamics of the model, under the social planner and in the private case, respectively. In Figure 5, we draw as a solid line the transition function for the decentralized economy, while the dotted line represents the dynamic evolution of e under the social planner hypothesis.



(a) (b)

Figure 5: The green golden rule

Depending on the value of $\tilde{e}$, we may have two different scenarios. If $\tilde{e}$ is sufficiently larger than e_L^*, as in Figure 5a, then there will also be two golden rule allocations, each one superior to the corresponding competitive equilibrium. If instead $\tilde{e}$ is close enough to e_L^* ($\tilde{e}'$ in Figure 5b), then there exists a unique green golden rule allocation; in this case we may say that the social planner eliminates the lower steady-state, thus driving the economy out of the trap.[15]

[15]Whether the social planner circumvents the poverty trap depends crucially on the shape of the $\pi(\cdot)$ function. Suppose to have, for instance, a low $\underline{\pi}$ and/or a high $\tilde{e}$ in (10): in this case, although the planner's optimality condition (14) implies less consumption and more maintenance (with respect to the decentralized economy), this does not necessarily translate into a higher survival probability ($\overline{\pi}$), at the steady-state.

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 this limitation 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.[16] A complementary analysis, with investment concerning physical capital instead of human capital, will be developed in Appendix B.

4.1 Structure of the model

Agents maximize the following utility function:

$$U_t(c_t, h_{t+1}, e_{t+1}) = \ln c_t + \pi_t(\alpha \ln h_{t+1} + \gamma \ln e_{t+1}), \tag{18}$$

where, 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}), and the importance attached to this term is measured by $\alpha \in (0, 1)$. 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. As it was in the basic model, an increased survival probability implies also that agents put more value on future environmental quality.

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

$$y_t = wh_t, \tag{19}$$

where w, which 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 one the population of our economy. As before, fertility is exogenous, constant and such that there is no population growth.

[16] Ikefuji and Horii (2007) also have a model with poverty-environment traps related to human capital. However, life expectancy plays no role in their framework. Moreover, since they do not allow for maintenance, they are not able to consider a trade-off between investment and environmental preservation. Finally, in their model higher human capital necessarily implies lower pollution, thus neglecting that growth itself is potentially polluting.

The budget constraint writes as:

$$wh_t = c_t + m_t + v_t. \tag{20}$$

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:

$$h_{t+1} = \delta h_t^{\theta} (\mu + v_t)^{1-\theta}, \tag{21}$$

where, depending on $\theta \in (0, 1)$, "nature" (parental human capital h_t) complements "nurture" (v_t) in the accumulation of productive skills. Notice that $\delta > 0$ accounts for total factor productivity in education, while the parameter $\mu > 0$ 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 maintenance because it helps to improve future environmental quality, according to:

$$e_{t+1} = (1 - \eta)e_t + \sigma m_t - \beta c_t - \psi y_t. \tag{22}$$

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. Since here, differently from the benchmark model, we have introduced explicitly a production function, it seems reasonable to consider that such production can also, to some extent, affect environmental conditions. 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. 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 sensible, since maintenance is completely dedicated to improving the environment, while production generates pollution only as a "by-product".

4.2 Optimal choices

Maximizing (18) subject to (20), (21), (22), $c_t > 0$, $m_t > 0$, $e_t > 0$ and $h_t > 0$, leads to the following optimal choices:

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

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

and

$$c_t = \frac{(1-\eta)e_t + \mu\sigma + (\sigma-\psi)wh_t}{(\beta+\sigma)\{1 + [\alpha(1-\theta)+\gamma]\pi_t\}}. \tag{25}$$

First of all, it is interesting to compare (23) with (5): 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 income 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:

$$\gamma\sigma > \alpha(1-\theta)\beta, \tag{26}$$

as it can be inferred from:

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

Condition (26), 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 a stronger investment in human capital.[17] In fact, provided that $\psi < \sigma$, the following derivative is always positive:

$$\frac{\partial v_t}{\partial \pi_t} = \frac{\alpha(1-\theta)[(1-\eta)e_t + \mu\sigma + (\sigma-\psi)wh_t)]}{\sigma\{1+[\alpha(1-\theta)+\gamma]\pi_t\}^2}. \tag{28}$$

Based on equations (27) and (28), a positive correlation between life expectancy and both environmental quality and human capital arises, along the transition path.

4.3 Dynamics

By replacing (23)-(25) into (21) and (22), we get the following non-linear system of two difference equations, which describes the dynamics of our economy:

$$h_{t+1} = \delta h_t^{\theta} \left(\frac{\alpha(1-\theta)[(1-\eta)e_t + \mu\sigma + (\sigma-\psi)wh_t)]\pi_t}{\sigma\{1+[\alpha(1-\theta)+\gamma]\pi_t\}} \right)^{1-\theta} \equiv \xi(h_t, e_t), \tag{29}$$

$$e_{t+1} = \frac{\gamma[(1-\eta)e_t + \mu\sigma + (\sigma-\psi)wh_t)]\pi_t}{1+[\alpha(1-\theta)+\gamma]\pi_t} \equiv \zeta(h_t, e_t). \tag{30}$$

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

$$\pi_t(h_t, e_t) = \begin{cases} \underline{\pi} & \text{if} \quad e_t + \kappa h_t < J \\ \overline{\pi} & \text{if} \quad e_t + \kappa h_t \geq J \end{cases}, \tag{31}$$

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 longevity. However, now we also assume that each agent's probability of survival is positively related to her own human capital. Such a mechanism has already been exploited, for instance, by Blackburn and Cipriani (2002) and de la Croix and Licandro (2007), in theoretical models linking growth and demographic dynamics. Apart from an obvious income effect, the positive influence of human capital on longevity may be justified by the fact that better educated people

[17] This result, that we obtain for parentally-funded education, is quite common in the literature, although it may be motivated by 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.

have access to better information about health and are less likely to take up unhealthy behavior (such as smoking, becoming overweight, etc.) This is also consistent with the findings of several empirical studies like, for instance, Lleras-Muney (2005).

Equation (31) paves the way to the existence of multiple steady-states, *i.e.* multiple solutions to the system composed by (29) and (30). 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) $\psi < \sigma$, (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 C ■

In particular, the high equilibrium is characterized by:

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

and

$$h_B^* = \frac{\alpha(1-\theta)\delta^{\frac{1}{1-\theta}}\mu\sigma^2\overline{\pi}}{\sigma + \{\gamma\eta\sigma + [\sigma - \delta^{\frac{1}{1-\theta}}(\sigma - \psi)w]\alpha(1-\theta)\}\overline{\pi}}, \tag{33}$$

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

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 both human capital and environmental care. All these findings do not depend on the multiplicity of equilibria, and would apply to the case of a unique steady-state as well.

Let us now give a quick description of the behavior of our dynamical system. An economy starting from low (high) enough environmental quality and parental human capital, so that $e_0 + \kappa h_0 < J$ ($\geq J$), 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.

The causal relationship linking the survival probability to both environmental quality and human capital implies the possibility of a country being stuck in a poverty trap, as in the benchmark

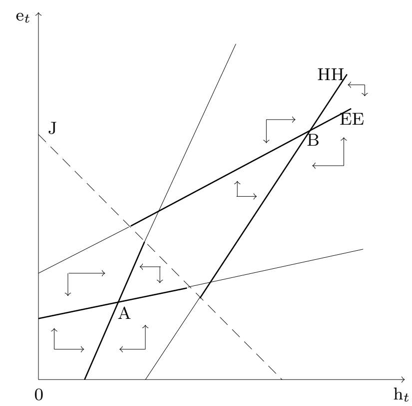


Figure 6: Phase diagram

model, and the underlying mechanism is quite similar. However, the trap is now characterized by three elements, namely low levels of: (i) environmental quality, (ii) life expectancy, and (iii) human capital.[18] 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 an exogenous increase in the productivity of the schooling system (δ). In Figure 6, the latter would correspond 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.

Finally, we would emphasize that the dynamics represented in the above diagram are also consistent with the so-called environmental Kuznets curve (Grossman and Krueger, 1995). An economy starting with low human capital and a fairly good environmental quality, will first experience a deterioration of environmental conditions as it develops, but will then see its environment improving for further stages of growth.

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 do not internalize the effects of their actions on the welfare

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

of following generations. We will proceed as we did in Section 3, by solving, at the steady-state, the problem of a social planner who treats all generations symmetrically and strives to maximize aggregate utility.

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

$$U(c,e,h) = \ln c + \pi(e)(\alpha \ln h + \gamma \ln e), \tag{34}$$

subject to:

$$wh = c + m + v, \tag{35}$$

$$\eta e = \sigma m - \beta c - \psi w h, \tag{36}$$

and

$$h = \delta h^{\theta}(v+\mu)^{1-\theta}. \tag{37}$$

Notice that (35) and (36) are, respectively, the budget and the environmental constraints at the steady-state, while (37) is the stationary production function for human capital.

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

$$c = \frac{-\eta e + \mu\sigma + [(\sigma-\psi)w - \sigma\delta^{\frac{1}{\theta-1}}]h}{\beta+\sigma}. \tag{38}$$

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:

$$e^{g} = \frac{\alpha\mu\sigma\pi}{\eta[1+(\alpha+\gamma)\pi]} \tag{39}$$

and

$$h^{g} = \frac{\alpha\mu\sigma\pi}{[\sigma\delta^{\frac{1}{\theta-1}} - (\sigma-\psi)w][1+(\alpha+\gamma)\pi]}, \tag{40}$$

where, consistently with our analytical example, π can be either $\underline{\pi}$ or $\overline{\pi}$. 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:

$$\hat{\eta} \equiv \frac{\sigma + [\sigma - \delta^{\frac{1}{1-\theta}}(\sigma - \psi)w]\alpha(1-\theta)\pi}{\sigma(1+\alpha\pi)}. \tag{41}$$

Provided that the conditions mentioned in Proposition 3 hold, $\hat{\eta}$ is positive. In addition, for α tending to 0, $\hat{\eta}$ tends to 1, thus reproducing the case analyzed in Section 3. This is not surprising, since α represents the weight of human capital in the utility function.

Moreover, depending on how close the decentralized low steady-state is to J, 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.

Finally, let us point out that the socially optimal allocation can be decentralized by means of suitable tax/subsidy policies of the kind we have studied in Section 3. The main findings (in terms, for instance, of optimal environmental taxation) would not be different from the benchmark model. However, since further sources of externalities (related to human capital) are now present, additional instruments would be needed.

5 Conclusions

In this paper we have studied the interplay between life expectancy and the environment, and the resulting 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, longevity is affected by environmental conditions. By modeling environmental quality as an asset that can be accumulated over time, we have shown that life expectancy and environmental dynamics can be jointly determined. Eventually, multiple equilibria may arise, defining an environmental kind of poverty trap characterized by both low life expectancy and poor environmental performance. Both the correlation between environment and longevity, 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 show that the positive dynamic correlation between longevity and environmental quality is preserved, and extends to income (in the long-run).

Moreover, our welfare analysis suggests that decentralized equilibria are inefficient. Agents do not internalize the effects of their choices on future generations. A social planner who takes these inter-generational externalities into account might achieve a superior equilibrium. We also show that the optimal allocation can be decentralized by means of appropriate environmental policies.

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); (iii) to explore alternative policy options suitable for restoring optimality.

Appendices

A Optimality of the dynamics

Let us now consider a full-fledged, forward-looking social planner, who seeks to maximize a social welfare function including all generations (both at the steady-state and along the transition path). The Lagrangian for this problem is:

$$\mathcal{L} = \nu^{-1} U_{-1} + \sum_{t=0}^{\infty} \nu^t \left\{ U_t(c_t, e_{t+1}) + \lambda_{t+1}[(1-\eta)e_t + \sigma w - (\sigma+\beta)c_t - e_{t+1}] \right\}, \tag{A.1}$$

where λ_{t+1} is the Lagrangian multiplier, corresponding to the shadow price of environmental quality and $\nu \in (0,1)$ accounts for inter-temporal discounting. From the two f.o.c.'s ($\partial\mathcal{L}/\partial c_t = 0$ and $\partial\mathcal{L}/\partial e_{t+1} = 0$), we obtain the following optimality condition:

$$\frac{\partial U_t}{\partial c_t} = (\beta+\sigma)\left[\frac{\partial U_t}{\partial e_{t+1}} + \nu \frac{\partial U_{t+1}}{\partial \pi_{t+1}} \frac{\partial \pi_{t+1}}{\partial e_{t+1}} + \nu \lambda_{t+2}(1-\eta)\right]. \tag{A.2}$$

Comparing the above expression with (4), we see that for the decentralized equilibrium to be socially optimal, we would need:

$$\frac{\partial U_{t+1}}{\partial \pi_{t+1}} \frac{\partial \pi_{t+1}}{\partial e_{t+1}} + \lambda_{t+2}(1-\eta) = 0, \tag{A.3}$$

which never holds, unless $\partial\pi_{t+1}/\partial e_{t+1} = 0$ and $\eta = 1$. Equation (A.3) allows us to identify two different inter-generational externalities, both related to m_t. The first term accounts for the effect of maintenance on the survival probability of future generations; the second one is due to the direct effect of maintenance on future environmental quality.

As in Section 3, inefficiencies can be corrected by means of environmental taxes. Since both externalities are related to the same source (maintenance), it turns out that one policy instrument is sufficient to achieve optimality. If τ_t is the tax rate on consumption at time t, decentralized agents allocate their resources according to:

$$\frac{\partial U_t}{\partial c_t} = [\beta + (1+\tau_t)\sigma]\frac{\partial U_t}{\partial e_{t+1}}. \tag{A.4}$$

Therefore, by equating (A.2) and (A.4), and solving for τ_t, we get the optimal tax trajectory:

$$\tau_t^* = \frac{\nu(\beta+\sigma)\left[\frac{\partial U_{t+1}}{\partial \pi_{t+1}}\frac{\partial \pi_{t+1}}{\partial e_{t+1}} + \lambda_{t+2}(1-\eta)\right]}{\sigma \frac{\partial U_t}{\partial e_{t+1}}}. \tag{A.5}$$

It can be easily checked that the intensity of taxation depends on the size of the inter-generational external effects, $\partial\pi_{t+1}/\partial e_{t+1}$ and $(1-\eta)$, respectively. Concerning the other parameters, it should be noticed that a higher ν, implying a greater concern for future generations, requires the tax rate to be heavier, while the effect of β and σ is as in Subsection 3.6.

B Physical capital

Here, we want to show that our benchmark model is robust to the introduction of physical capital. Since the latter is built on savings, the optimization problem of our representative agent needs to be modified. The utility function is now:

$$U_t(c_t, c_{t+1}, e_{t+1}) = \log c_t + \pi_t(\rho \log c_{t+1} + \gamma \log e_{t+1}), \tag{A.6}$$

where $\rho \in (0,1)$, which might be eventually set equal to $(1-\gamma)$, measures the preference for future consumption. The first-period budget constraint becomes:

$$w_t = c_t + m_t + s_t, \tag{A.7}$$

so that we explicitly introduce savings (s_t) in our analysis. Savings will be used to finance future consumption, according to:

$$c_{t+1} = \frac{s_t R_{t+1}}{\pi_t}, \tag{A.8}$$

where R_{t+1} denotes the interest factor at time $t+1$. As pointed out by Chakraborty (2004), the above expression is also consistent with the assumption of a perfect annuity market, and takes into account that agents are not sure to survive to their third period of life. In fact, they are perfectly aware that only with a probability π_t, they will be able to enjoy their current savings as future consumption.

To determine the factor prices w_t and R_{t+1}, we can introduce a neo-classical production function that, in per-capita terms, can be simply written as $y_t = f(k_t)$.

Investment is made out of savings; the law of motion for the stock of physical capital writes as:

$$k_{t+1} = (1-\iota)k_t + s_t, \tag{A.9}$$

where $\iota \in (0,1]$ is the depreciation rate of capital.

The dynamics of environmental quality are described by:

$$e_{t+1} = (1-\eta)e_t + \sigma m_t - \beta c_t - \epsilon k_t, \tag{A.10}$$

with $\epsilon > 0$. With respect to equation (3), we have added the ϵk_t term to take into account that also the use of capital in production, and not only consumption, is potentially polluting.

In this economy, individual agents select m_t and s_t (and implicitly define an optimal inter-temporal consumption plan), so as to maximize $U_t(c_t, c_{t+1}, e_{t+1})$ subject to (A.7), (A.8) and (A.10). Their optimizing behavior implies, in general terms:

$$\frac{\partial U_t}{\partial c_{t+1}} = \frac{\sigma \pi_t}{R_{t+1}} \frac{\partial U_t}{\partial e_{t+1}}, \tag{A.11}$$

along with (4). If we take the logarithmic utility function (A.6) and use (A.8), we obtain:

$$\gamma \sigma s_t = \rho e_{t+1}. \tag{A.12}$$

Abstracting from corner solutions, optimal choices are thus given by:

$$m_t = \frac{[\epsilon k_t - (1-\eta)e_t][\sigma + \rho(\beta+\sigma)\pi_t] + \sigma[\beta + \gamma(\beta+\sigma)\pi_t]w_t}{\sigma(\beta+\sigma)[1+(\rho+\gamma)\pi_t]}, \tag{A.13}$$

$$s_t = \frac{\rho \pi_t [(1-\eta)e_t - \epsilon k_t + \sigma w_t]}{\sigma + (\rho+\gamma)\sigma\pi_t}, \tag{A.14}$$

and

$$c_t = \frac{(1-\eta)e_t - \epsilon k_t + \sigma w_t}{(\beta+\sigma)[1+(\rho+\gamma)\pi_t]}. \tag{A.15}$$

It can be noticed that investments in environmental care m_t depend positively on the existing stock of physical capital, through two different channels: the first one is related to more pollution (ϵk_t) requiring more maintenance, while the second one accounts for a straightforward income effect (since $w_t = w(k_t)$). Conversely, investment in physical capital (savings) is an increasing function of environmental quality, due to a substitution effect: a healthier environment needs less maintenance, thus freeing resources for alternative purposes.

In the long-run, this kind of interplay translates into a positive correlation between the stationary values of capital and environmental quality. In fact, combining (A.9) and (A.12), we obtain $\gamma\iota\sigma k^* = \rho e^*$. It is then clear that, for instance, as soon as multiple equilibria become possible (depending on the shape of $\pi(e_t)$), the corresponding poverty trap will be characterized by low levels of life expectancy and both environmental quality and physical capital.

Once we replace optimal choices (A.13), (A.14) and (A.15) into (A.9) and (A.10), and consider that $w_t = f(k_t) - k_t f'(k_t)$, we can compute the steady-state values for environmental quality and physical capital. Take for instance a Cobb-Douglas production function, such that $y_t = Bk_t^{\chi}$ (with $\chi \in (0,1)$ and $B > 0$), and assume a survival probability function as in (10). The steady-state level(s) of physical capital would then be given by:

$$k^* = \left\{ \frac{B\rho\sigma(1-\chi)\pi}{\iota\sigma + [\epsilon\rho + \iota\sigma(\gamma\eta + \rho)]\pi} \right\}^{\frac{1}{1-\chi}}. \tag{A.16}$$

The stationary value(s) for environmental quality can be accordingly determined, using $e^* = (\gamma\iota\sigma/\rho)k^*$.

C Proof of Proposition 3

The proof is organized as follows. We will first characterize the two loci HH and EE, and then analyze the existence, multiplicity and stability of the steady-states. Let us now recall the definitions of the two loci: $HH \equiv \{(h_t, e_t) : h_{t+1} = h_t\}$ and $EE \equiv \{(h_t, e_t) : e_{t+1} = e_t\}$.

C.1 Locus HH

From equation (29) we get that $h_{t+1} - h_t = \xi(h_t, e_t) - h_t$, where π_t is given by equation (31). Therefore, the locus HH writes as:

$$e_t = -\frac{\sigma\mu}{1-\eta} + \frac{\sigma\{1 + [\alpha(1-\theta) + \gamma]\pi_t\} - \alpha(1-\theta)(\sigma-\psi)w\pi_t\delta^{\frac{1}{1-\theta}}}{\alpha(1-\theta)(1-\eta)\pi_t\delta^{\frac{1}{1-\theta}}} h_t, \tag{A.17}$$

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 is given by $e_{t_{HH}} \mid_{h_t=0} = -\sigma\mu/(1-\mu) < 0$, while its slope can be expressed as:

$$\frac{\partial e_t}{\partial h_t} = \frac{\sigma\{1+[\alpha(1-\theta)+\gamma]\pi_t\} - \alpha(1-\theta)(\sigma-\psi)w\pi_t\delta^{\frac{1}{1-\theta}}}{\alpha(1-\theta)(1-\eta)\pi_t\delta^{\frac{1}{1-\theta}}} \equiv s_h(\pi_t), \qquad \text{(A.18)}$$

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.

C.2 Locus EE

Equation (30) yields $e_{t+1} - e_t = \zeta(h_t, e_t) - e_t$, where π_t is given by equation (31). Therefore, the locus EE can be written as:

$$e_t = -\frac{\gamma\sigma\mu\pi_t}{\gamma(1-\eta)\pi_t - \{1+[\alpha(1-\theta)+\gamma]\pi_t\}} - \frac{\gamma(\sigma-\psi)w\pi_t}{\gamma(1-\eta)\pi_t - \{1+[\alpha(1-\theta)+\gamma]\pi_t\}}h_t, \qquad \text{(A.19)}$$

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

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

while the slope of EE is given by:

$$\frac{\partial e_t}{\partial h_t} = -\frac{\gamma(\sigma-\psi)w\pi_t}{\gamma(1-\eta)\pi_t - \{1+[\alpha(1-\theta)+\gamma]\pi_t\}} \equiv s_e(\pi_t), \qquad \text{(A.20)}$$

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, $e_{t_{EE}} \mid_{h_t=0} > 0$ and, provided that $\sigma > \psi$, $s_e > 0$. Moreover, since $\partial(e_{t_{EE}} \mid_{h_t=0})/\partial\pi > 0$, 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.

C.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.17), the dynamics of h_t are described by:

$$h_{t+1} = \delta h_t{}^{\theta} \left\{ \frac{\sigma\{1 + [\alpha(1-\theta) + \gamma]\pi_t\} - \alpha(1-\theta)(\sigma - \psi) w \pi_t \delta^{\frac{1}{1-\theta}}}{\sigma\{1 + [\alpha(1-\theta) + \gamma]\pi_t\}\delta^{\frac{1}{1-\theta}}} \overline{h} + \frac{\alpha(1-\theta)(\sigma-\psi) w \pi_t}{\sigma\{1 + [\alpha(1-\theta)+\gamma]\pi_t\}} h_t \right\}^{1-\theta}, \tag{A.21}$$

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.18) 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.19), the dynamics of e_t are given by the following expression:

$$\Delta e_t = \frac{\gamma(1-\eta)\pi_t - \{1 + [\alpha(1-\theta)+\gamma]\pi_t\}}{1 + [\alpha(1-\theta)+\gamma]\pi_t}(e_t - \overline{e}), \tag{A.22}$$

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] 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.

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

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

[4] 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.

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

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

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

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

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

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

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

[12] 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.

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

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

[15] 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.

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

[17] 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.

[18] Grossman, G. and A. Krueger (1995): ”Economic growth and the environment”, *Quarterly Journal of Economics* 110 (2), 353-377.

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

[20] Ikefuji, M. and R. Horii (2007): ”Wealth heterogeneity and escape from the poverty-environment trap”, *Journal of Public Economic Theory* 9 (6), 1041-1068.

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

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

[24] Jouvet, P.-A., Ph. Michel and G. Rotillon (2005): ”Optimal growth with pollution: how to use pollution permits?”, *Journal of Economic Dynamics & Control* 29, 1597-1609.

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

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

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

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

[29] 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.

[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] Pope, C.A. III (2000): ”Epidemiology of fine particulate air pollution and human health: biologic mechanisms and who’s at risk?”, *Environmental Health Perspectives* 108 (4), 713-723.

[32] Pope, C.A. III, R.T. Burnett, G.D. Thurston, M.J. Thun, E.E. Calle, D. Krewski and J.J. Godleski (2004): ”Cardiovascular mortality and longterm exposure to particulate air pollution: epidemiological evidence of general pathophysiological pathways of disease”, *Circulation* 109 (1), 71-77.

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

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

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