The Environmental Kuznets Curve in a World of Irreversibility

Fabien Prieur

NOTA DI LAVORO 57.2007

MAY 2007

CCMP – Climate Change Modelling and Policy

Fabien Prieur, *GREQAM and INRA-LAMETA*

Corso Magenta, 63, 20123 Milano (I), web site: www.feem.it, e-mail: working.papers@feem.it

The Environmental Kuznets Curve in a World of Irreversibility

Summary

We develop an overlapping generations model where consumption is the source of polluting emissions. Pollution stock accumulates with emissions but is partially assimilated by nature at each period. The assimilation capacity of nature is limited and vanishes beyond a critical level of pollution. We first show that multiple equilibria exist. More importantly, some exhibit irreversible pollution levels although an abatement activity is operative. Thus, the simple engagement of maintenance does not necessarily suffice to protect an economy against convergence toward a steady state having the properties of an ecological and economic poverty trap. In contrast with earlier related studies, the emergence of the environmental Kuznets curve is no longer the rule. Instead, we detect a sort of degenerated Environmental Kuznets Curve that corresponds to the equilibrium trajectory leading to the irreversible solution.

Keywords: Overlapping Generations, Irreversible Pollution, Poverty Trap, Environmental Kuznets Curve

JEL Classification: Q56, D62, D91

Address for correspondence:

Fabien Prieur
GREQAM and INRA-LAMETA
2, place Viala
34060 Montpellier
France
E-mail: prieur@supagro.inra.fr

1 Introduction

In the early 1990's, empirical literature developed with the purpose of studying the relationship between economic growth and pollution (World Bank [1992], Grossman and Krueger [1993], [1995], among others). The main finding was the detection of the Environmental Kuznets Curve (EKC). The EKC represents the inverted U-shaped relation between income and the concentration of some air (SO_2, CO, NO_x) and water (nitrates, heavy metals, fecal coliform) pollutants. The thinking behind its emergence is the following: during the first stages of industrialization, pollution grows rapidly as priority is given to wealth accumulation. People are more concerned with their employment and their income than with the quality of air or water (Dasgupta *et al.* [2002]). In more advanced development stages, people attach more value to the environment as soon as revenues increase. This "green" awareness then calls for environmental regulations that succeed in reducing pollution.

Over the past 15 years, literature on the EKC has increased exponentially. As mentioned by Copeland and Taylor [2003], recent empirical studies mainly have tried to confirm or invalidate the existence of the ECK by adding new explanatory variables (like an index of democracy) to the regression, verifying its validity for other types of pollutants, or testing the robustness of the results to the data used. To summarize, these contributions (see Stern [1998], for a survey) show that the EKC generally is observed for the aforementioned short-lived and local pollutants while stock pollutants, like CO_2, seem to be monotonically and positively related to income (exceptions are Carson *et al.* [1997] and Schmalensee *et al.* [1998] who also detect an EKC for CO_2).

On the theoretical side, this literature attempts to provide (often complementary) explanations of the emergence of the EKC (see Dinda [2004] for a detailed survey). Among the arguments advanced is the role of income elasticity of demand for environmental goods (Brock and Taylor [2004]) or the interaction between the scale, composition and technical effects incorporated in the growth process (Copeland and Taylor [2003]). The nature of institutions (Jones and Manuelli [2001], Yu [2005]), by determining the efficiency of environmental regulation, and free trade (Suri and Chapman [1998]) also play crucial roles. In a simple static model, Andreoni and Levinson [2001] propose another explanation based on the existence of increasing returns in abatement technology. In growth models, John and Pecchenino [1994], Selden and Song [1995] and Stokey [1998] show that the EKC results from a switch to abatement activities or, the adoption of less polluting technologies. For instance, John and Pecchenino [1994] emphasize that the regime switch to maintenance creates two distinct development stages. In the first phase (for low levels of income and pollution), agents favour consumption and capital accumulation. In other words, they do not maintain the environment and economic growth is associated with environmental degradation. Once the economy has reached a sufficient level of wealth and/or suffers from important environmental damage, agents are willing to clean up the environment. During the second period, growth is then accompanied by a continuous improvement in the environment. The EKC results from the combination of these two stages.

Two main controversies surround the EKC. The first is methodological. Indeed, Stern [2003] and Stern and Perman [2003], by pointing out the econometric weakness of most of the empirical studies (bias due to the omission of explanatory variables, problem of causality...) express reserves about the robustness of the studies' results and, even more, about the existence of such a relation. Stern [2003] also criticizes theoretical works that prove the existence of the EKC and notes that: "*it seems fairly easy to develop models that generate EKCs under appropriate assumptions... Furthermore, if, in fact, the EKC for emissions is monotonic as more recent evidence suggests, the ability of a model to produce an inverted U-shaped curve is not a particularly desirable property*". The second controversy is more ethical and concerns a possible interpretation of the EKC that it is possible to pollute as much as one wants today because once the economy becomes rich it will be possible to reverse the trend by compensating for past damage to the environment. Dasgupta and Mäler [2002] oppose the idea that economic development is "mechanically" sustainable, basing their argument on the notion of irreversibility of environmental damage introduced in earlier works in biology and ecology (Holling [1973], Peterman [1980]).

These studies showed that some ecosystems can possess more than one stable equilibrium. Multiplicity implies that these ecosystems, when submitted to strong perturbations, are unable to recover their original state. The most famous evidence of irreversibility is given by the eutrophication of shallow lakes. These lakes are subject to pollution resulting from the use of fertilizers (that contains nutritive substances like white phosphorus and nitrates). Nutrients flow through rivers into the lakes. Beyond a certain threshold, this leads to the proliferation of microscopic algae (like phytoplankton) which, by producing light filters and capturing oxygen, disrupt the development of flora and fauna and even cause the extinction of natural species. These ecosystems finally reach a new equilibrium with less biodiversity. More importantly, putting this example aside, Dasgupta and Mäler [2002] stress that the notion of irreversibility also can be extended to global pollution problems like the repercussions of greenhouse gases emissions on the climate.

The potential irreversibility of pollution challenges the assumption, used almost systematically in growth models (see Keeler *et al.* [1971], Van der Ploeg and Withagen [1991], Gradus and Smulders [1993], John and Pecchenino [1994] among others), that Nature is able to assimilate pollutants at a constant rate. Many authors (Forster [1975], Comolli [1977] and Dasgupta [1982]) have proposed a new formulation of the decay function incorporating the idea that high pollution levels drastically alter the waste assimilation capacity of Nature. In fact, from their point of view, it is unreasonable to think that the higher the level of pollution, the greater will be Nature's ability to absorb pollution. Following this recommendation, several authors (Forster [1975], Cesar and de Zeeuw [1994], Tahvonen and Withagen [1996], Tahvonen and Salo [1996] or Toman and Withagen [2000]) consider an inverted U-shaped decay function that notably expresses a limited natural capacity to assimilate pollution. The major result of this literature, which basically uses optimal control models, is the existence of multiple equilibria among which are some associated with irreversible pollution.

This study addresses the following question: why may irreversible pollution challenge the emergence of the EKC? More precisely, our aim is to measure the repercussions of irreversibility on the relationship between growth and the environment. Three related questions immediatly arise: What is the impact of environmental degradation on prospects for growth? Is it innocuous in relation to economic activities? If not, how does it compromise the process of wealth accumulation? To answer these questions, John and Pecchenino [1994]'s overlapping generations model is extended with an inverted U-shaped decay function. The reason is that the paper written by John and Pecchenino [1994] is one of the most famous to generate the EKC in growth models. In addition, our intuition tells us that the relationship obtained in their model with a stock pollutant is widely conditioned by a controversial assumption of a constant rate of assimilation.

We first prove the existence of multiple equilibria with diametrically opposite properties. Some of them notably exhibit irreversible pollution although maintenance activity is operative. This result differs from John and Pecchenino [1994], who show that maintenance is sufficient to improve environmental quality.[1] More interestingly, these "irreversible" equilibria have the characteristics of poverty traps. The important point here is that economic poverty results from ecological poverty. In fact, when agents do not have enough incentive to stop polluting, economic growth is accompanied by the accumulation of ecological debt. But, due to the irreversible character of some pollution, the debt may be such that, once the economy engages in maintenance, this effort does not suffice to avoid the irrevocable degradation of the environment. This, in turn, creates an economic recession since the agents, who have no other choice but to devote a sizeable share of their resources to maintenance, sacrifice wealth accumulation. Thus, environmental degradation is not innocuous to growth. To the contrary, it affects private sector decisions and may lead to a poverty trap.

This result contributes to the growing literature, initiated by Azariadis and Drazen [1990], on poverty traps. It provides a new explanation of their emergence that resides in the existence of a threshold effect in the regeneration capacity of Nature. Finally, the dynamic analysis echoes Dasgupta and Mäler [2002]'s warning: the EKC no longer makes sense once one admits the potential irreversibility of environmental damages. Rather, our numerical simulations detect a degenerated EKC corresponding to the equilibrium trajectory that leads to the poverty trap.

The paper is organized as follows: Section 2 presents the model; Section 3 provides a detailed analysis of the equilibrium; Section 4 studies the dynamics with numerical simulations; and Section 5 concludes.

---

[1] This property being the key element explaining the second stage of development in their model.

2 The model

We develop an overlapping generations model *à la* Allais [1947], Samuelson [1958] and Diamond [1965]. In a perfectly competitive world, firms produce a single homogeneous good used for both consumption and investment. In addition, consumption generates polluting emissions.

2.1 The Dynamics of Pollution and the Environment

In the absence of human activity, pollution accumulation, for non-negative levels of the stock P_t, is described by the following equation:

$$P_{t+1} = P_t - \Gamma(P_t) \tag{1}$$

where $\Gamma(P_t)$ corresponds to the natural decay function that gives the amount of pollution assimilated by nature each period. Nature's ability to absorb pollution depends on the level of the pollutant concentration. Following Forster [1975], Cesar and de Zeeuw [1994] and Tahvonen and Withagen [1996], we assume an inverted U-shape decay function (see figure 1). Its properties, summarized in the assumption below, convey the idea that after a certain point, high levels of pollution alter the natural regeneration capacity in an irreversible way.

Assumption 1. $\Gamma(P) : \mathbb{R}^+ \to \mathbb{R}^+$ *is* $\mathcal{C}^2$ *and concave (*$\Gamma''(P) \leq 0$*) over the interval* $[0, P]$*. It is first increasing from* $\Gamma(0) = 0$ *to a level* $\tilde{P}$ *then, decreasing until the pollution reaches the irreversibility threshold* $\bar{P}$ *(*$\Gamma'(P) > 0 \ \forall P \in [0, \tilde{P})$*,* $\Gamma'(P) < 0 \ \forall P \in (\tilde{P}, \bar{P})$ *with* $\tilde{P} < \bar{P}$*). Beyond this value, assimilation is nil:* $\Gamma(P) = 0 \ \forall P \geq \bar{P}$*. The amount of pollution assimilated at each period is lower than the stock i.e.* $\Gamma(P) < P \ \forall P > 0$*.*

For low pollution levels ($P_t \leq \tilde{P}$), the volume absorbed by Nature at first increases with the stock. Beyond the turning point $\tilde{P}$, the assimilation of waste then decreases with the pollutant concentration. Finally, as soon as pollution reaches the threshold value $\bar{P}$, the regeneration capacity is permanently exhausted and pollution becomes irreversible. In other words, once the stock has exceeded the critical level $\bar{P}$, Nature reveals itself unable to assimilate pollution.

Let Q_t be an index of environmental quality such as the quality of air or water. Following John and Pecchenino [1994], pollution is assumed to impair Q_t according to the relation $Q_t = \bar{Q} - P_t$, where $\bar{Q}$ represents the highest stationary level of environmental quality reached when pollution is nil. Assuming non-negative pollution levels boils down to considering $\bar{Q}$ as the upper bound of the domain of definition of Q_t. The dynamics of environmental quality are given by:

$$Q_{t+1} = N(Q_t) \tag{2}$$

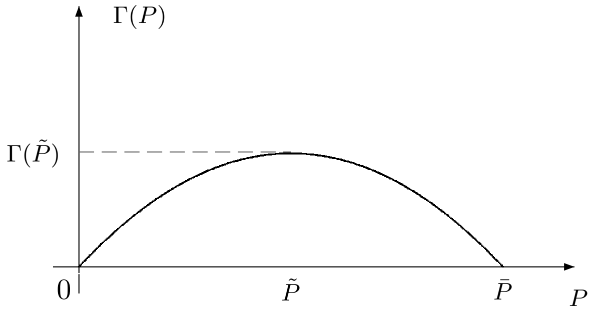

Figure 1: The assimilation function

with $N(Q_t) : Q_t \in]-\infty, \bar{Q}] \rightarrow]-\infty, \bar{Q}]$ the function defined as follows:

$$N(Q_t) = \begin{cases} Q_t & \forall Q_t \leq \bar{Q} - \bar{P} \\ Q_t + \Gamma(\bar{Q} - Q_t) & \forall Q_t \in]Q - \bar{P}, \bar{Q}] \end{cases} \tag{3}$$

Its properties derive immediately from those of the decay function. For the levels of Q_t corresponding to irreversible pollution ($Q_t \leq \bar{Q} - \bar{P}$), it is simply linear. Beyond the threshold level $\bar{Q} - \bar{P}$, this function is increasing in Q_t and concave (see appendix A.1).

The next subsections set out the private agents' choices and trade-offs.

2.2 Production

Under perfect competition, firms produce the final good Y_t with a constant return to scale technology using labor L_t and capital K_t:

$$Y_t = F(K_t, L_t). \tag{4}$$

Since the production function is homogeneous of degree one, it can be expressed by its intensive form: $f(k_t)$ with $k_t = K_t/L_t$,the capital-labor ratio.

Assumption 2. *$f(k) : \mathbb{R}^+ \rightarrow \mathbb{R}^+$ is $\mathcal{C}^2$. $\forall k > 0$, $f(k) > 0$, $f'(k) > 0$, $f''(k) < 0$.*

Capital depreciates at a constant rate $\delta < 1$. Profit maximization yields:

$$w_t = f(k_t) - k_t f'(k_t) \tag{5}$$

$$r_t = f'(k_t) - \delta \tag{6}$$

with w_t the wage rate and r_t the real rental rate of capital.

2.3 The households

We consider an infinite horizon economy composed of finite-lived agents. A new generation is born in each period $t = 1, 2, ...$, and lives for two periods: youth and old age. There is no population growth and the size of a generation is normalized to one. The young agent born in period t is endowed with one unit of labor, which is supplied inelastically to firms for a real wage w_t. She allocates this wage to savings s_t and maintenance m_t.[2][3] When retired, the agent supplies her savings to firms and earns the return of savings $R_{t+1}s_t$ (with $R_{t+1} = 1 + r_{t+1}$ the interest factor). Her income is entirely devoted to the consumption c_{t+1}. The two budget constraints respectively write:

$$w_t = s_t + m_t \tag{7}$$

$$c_{t+1} = R_{t+1}s_t. \tag{8}$$

The preferences of the agent born at date t are defined on old age consumption and environmental quality. They are described by the utility function $U(c_{t+1}, Q_{t+1})$.

Assumption 3. *$U(c, Q) : \mathbb{R}^+ \times]-\infty, \bar{Q}] \to \mathbb{R}$ is $\mathcal{C}^2$ with: $U_1 \geq 0$, $U_2 \geq 0$, $U_{11}, U_{22} \leq 0$. The cross derivative is positive $U_{12} \geq 0$.[4] We further assume that $\lim_{c \to 0} U_1(c, Q) = +\infty$.*

Following John and Pecchenino [1994] and John *et al.* [1995], polluting emissions E_t are imputed to the consumption c_t and contribute to the accumulation of pollutant stock. It is possible to control the level of emissions and to improve environmental quality through the maintenance m_t. Real emissions are represented by the following linear function: $E_t = \beta c_t - \gamma m_t$ with $0 \leq \beta, \gamma < 1$. In the presence of human activity, the dynamics of environmental quality then becomes:[5]

$$Q_{t+1} = N(Q_t) - E_t. \tag{9}$$

In this framework, households typically face an intergenerational externality. When the agent consumes, she does not take into account the negative repercussions of her choice on the environmental quality bequeathed to future generations. In the same way, when the young agent

---

[2] It is possible to reinterpret m_t as a tax levied by a one period-lived government in order to finance the abatement activity, for the benefit of agents living during its period of office (John *et al.* [1995]).

[3] Note that there is no first period consumption. This simplifying assumption allows us to focus on the crucial trade-off between final good and environmental good consumptions (see, next page, the representative agent problem). In any event, adding a first period consumption would not change the qualitative results.

[4] This assumption expresses the existence of a complementarity between consumption and environmental quality in the agent's utility. An increase in environmental quality enhances the marginal utility of consumption and implies that the agent has a greater desire to consume. The alternative assumption $U_{12} < 0$ reflects, on the contrary, that the two goods are substitutes.

[5] It is worth noting that the main difference with John and Pecchenino (1994)'s setting precisely resides in those dynamics since they use the following specification: $Q_{t+1} = (1 - \Gamma)Q_t - \beta c_t + \gamma m_t$ where $0 \leq \Gamma < 1$ represents the constant rate of assimilation.

decides her maintenance effort, she only cares about the environment she will enjoy in old age. But the agent ignores the future benefits of her "green" investment. The potential irreversibility of pollution strengthens the intergenerational dimension compared with John and Pecchenino [1994]. Indeed, due to the present generations' decisions, future generations will likely suffer from an irrevocably degraded environment.

The representative agent born at date t divides her first period income between savings (which determines the consumption of the final good) and maintenance (which influences the "consumption" of the environmental good) in order to maximize her lifetime utility. Taking prices and environmental quality at the beginning of period t as given, the problem is written as:

$$\max_{s_t, m_t, c_{t+1}} U(c_{t+1}, Q_{t+1})$$

subject to,

$$\begin{cases} w_t = s_t + m_t \\ c_{t+1} = R_{t+1} s_t \\ Q_{t+1} = N(Q_t) - E(c_t, m_t) \\ m_t \geq 0. \end{cases}$$

The first order condition (FOC) reads:

$$-R_{t+1} U_1(c_{t+1}, Q_{t+1}) + \gamma U_2(c_{t+1}, Q_{t+1}) + \mu = 0 \tag{10}$$

with $\mu \geq 0$ the Lagrange multiplier that satisfies

$$\mu m_t = 0. \tag{11}$$

The next section is devoted to the study of the competitive equilibrium. The non-negativity constraint on m_t requires to distinguish the case where abatement is working *i.e*, $m_t \geq 0$, from the one where the agents do not maintain the environment *i.e*, $m_t = 0$. Moreover, each part of this study must also be divided in two subcases depending on whether or not, environmental quality has reached the irreversibility threshold $\bar{Q} - \bar{P}$.

3 The competitive equilibrium

Prior to the equilibrium analysis, it is important to define the two frontiers delimiting the four possible cases enumerated above.

3.1 The frontier case

We first provide a general definition of the frontiers. Next, a brief discussion is conducted on the issue of the admissibility of equilibria.

Imposing $m_t = \mu = 0$ in the FOC (10) yields:

$$R(w(k_t))U_1(c(w(k_t)), N(Q_t) - \beta c(k_t)) - \gamma U_2(c(w(k_t)), N(Q_t) - \beta c(k_t)) = 0. \tag{12}$$

This equation implicitly defines Q_t as a monotonically increasing function of k_t: $Q_t = Q^f(k_t)$ with $Q^{f\prime}(k_t) \geq 0$.[6]

Definition 1 *In the $k - Q$ space, the first frontier, delimiting irreversible pollution levels from reversible ones, corresponds to the irreversibility threshold: $Q_t = \bar{Q} - \bar{P}$. The second frontier $Q^f(k_t)$, thereafter called the indifference frontier, represents the set of points (k_t, Q_t) where the agents are indifferent to whether or not they invest in depollution. When the system is located in the region above this manifold, environmental quality is sufficiently high and/or wealth is so low that maintenance is nil, while in the opposite situation, it is operative.*

Analyzing the admissibility problem boils down to investigating the location of different equilibria with respect to the two frontiers separating, on the one hand, the interior space ($m_t \geq 0$) from the corner one ($m_t = 0$) and, on the other hand, the irreversible pollution space from the reversible zone.

This section addresses the existence of equilibria in the four regions of the $k - Q$ space. Now, assume that, for each dynamical system, there exists at least one stable steady state. Admissibility refers to the following reasoning: it is possible, during the convergence toward a stable solution of a determined zone, that the equilibrium path crosses one or the other frontier before reaching the steady state. But as soon as the trajectory goes through a frontier, the system is governed by new dynamics totally different from the ones valid in the previous region. In other words, the stable solution in consideration is not admissible since, once the frontier is crossed, the economy will converge to another stable solution associated with the new significant dynamics.

3.2 Zero maintenance equilibrium

The first part of the analysis deals with the case where the non negativity constraint on maintenance is binding *i.e*, $m_t = 0$. A justification of this study is based on the observation that less developed economies may not be concerned with the protection of the environment and favor

---

[6] Total differentiation of (12) gives

$$Q^{f\prime}(k) = \frac{R'w'U_1 + Rc'w'U_{11} - \beta c'U_{12} - \gamma c'(w'U_{12} - \beta U_{22})}{N'(\gamma U_{22} - RU_{12})}$$

and, under our assumptions, this ratio is positive.

wealth accumulation instead. In other words, these economies, in the first stages of development, may be too poor to have the incentive to abate polluting activities (Dasgupta *et al.* [2002]).

In this context, the representative agent does not face any trade-off since she allocates her entire first period income to savings $w_t = s_t$. The intertemporal equilibrium defines as follows:

Definition 2 *A zero maintenance (or corner) equilibrium with perfect foresight is given by the sequence of per capita variables* $\{c_t, s_t\}$, *the sequence of aggregate variables* $\{L_t, K_t, Q_t\}$ *and the sequence of prices* $\{R_t, w_t\}$ *such that:*

i/ the households save their income: $w_t = s_t$ *and, the two conditions (5)-(6), for profit maximization, hold,*

ii/ all markets clear: $L_t = N = 1$ *on the labor market and* $k_{t+1} = s_t$ *on the capital market,*

iii/ the budget constraints (7)-(8) are satisfied,

iv/ the dynamics of environmental quality are given by (9).

Equilibrium dynamics are derived from the combination of (5)-(8), (9) and the capital market clearing condition for capital:

$$\begin{cases} k_{t+1} = f(k_t) - k_t f'(k_t) \\ Q_{t+1} = N(Q_t) - E(k_t) \end{cases} \tag{13}$$

and, one may note that capital accumulation is independent of environmental quality. Emissions amount to a share β of the consumption: $E(k_t) = \beta c(k_t)$ with,

$$c(k_t) = (1-\delta)k_t + k_t f'(k_t). \tag{14}$$

Before studying the existence of solutions to the system (13), let us define capital's share of output and the elasticity of substitution between capital and labor as follows:

$$s(k_t) = \frac{k_t f'(k_t)}{f(k_t)} \tag{15}$$

$$\sigma(k_t) = -\frac{(1-s(k_t))f'(k_t)}{k_t f''(k_t)} \tag{16}$$

In the remainder of the paper, the following conditions are supposed to hold:

Assumption 4. *The technology satisfies:*

$$\lim_{k_t \to 0} \frac{f(k_t) - k_t f'(k_t)}{k_t} > 1 \tag{17}$$

$$\sigma(k_t) \geq 1 - s(k_t) \tag{18}$$

Condition (17) is analogous to the *no catching point* condition, presented in De La Croix and Michel [2002], according to which the first unit of capital must be sufficiently efficient, in terms of labor productivity (recall that the numerator in (17) corresponds to the wage $w(k_t)$), to avoid the trivial equilibrium associated with $k = 0$. This assumption guarantees that stationary maintenance is positive in the neighborhood of zero. The second inequality (18) states that the elasticity of substitution between capital and labor is higher than the labor share of output.[7] It is a sufficient condition to ensure that the consumption function is increasing in k.

The first proposition states the existence conditions of corner steady states by paying particular attention to the level of environmental quality compared with the irreversibility threshold.

For the sake of simplicity, the analysis for both types of equilibrium (corner and interior) will be conducted for a capital stock belonging to the specific interval $[0, \bar{k}]$, where $\bar{k}$ is defined as follows:[8]

$$\bar{k} = \inf \{k \in [0, +\infty[\ / \ w(k) = k\}$$

Proposition 1 *i/ there is no steady state associated with irreversible pollution,*

ii/ there exists a corner steady state that exhibits a level of environmental quality above $\bar{Q} - \bar{P}$ *if and only if*

$$\max_{P \in [0, \bar{P}]} \Gamma(P) \geq E(\bar{k}). \tag{19}$$

Furthermore, if the inequality in (19) is strict, exactly two solutions exist.

Proof. See the appendix A.2.1. ■

The lack of steady state characterized by the irreversibility of pollution is explained by the environment's inability to stabilize to a constant long run level. In fact, when agents do not depollute, environmental quality perpetually deteriorates since the assimilation capacity of Nature is exceeded and there is no force able to compensate for the polluting emissions. The only means to stop the degradation is to cease consuming and, when capital is essential to production, to furthermore stop all productive activity. But, under the assumptions made on preferences, this limit case can be excluded. In terms of dynamics, it implies that if the economy is located in this subspace, the equilibrium path will necessarily cross the indifference frontier to reach the region where the agents have the incentive to maintain the environment.

Condition (27), for a solution with reversible pollution, corresponds to a rewriting, in our general equilibrium framework, of the condition used by Tahvonen and Withagen [1996]. It conveys the idea that the maximum potential of natural assimilation is intrinsically higher than the stationary level of emissions. In contrast to the previous situation, this condition ensures that

---

[7] These conditions are notably satisfied by the CES technologies, $F(K, L) = (\alpha K^{-\rho} + (1 - \alpha)L^{-\rho})^{-\frac{1}{\rho}}$, when $\rho \in (-1, 0]$. In addition, the second one seems quite reasonable since most of the estimations of labor's share of output and the elasticity of substitution give values respectively comprised in the range $[0.6, 0.7]$ and close to 1.

[8] The reason why this restriction is imposed will be discussed in the next subsection.

environmental quality will reach, in the long run, a constant level when stationary emissions will be entirely absorbed by Nature.

At the corner steady state, the level of capital coincides with the upper bound of the interval $[0, \bar{k}]$. In addition, if the inequality in (19) is strict, then the two steady states are associated with levels of environmental quality that are located on both sides of the striking value $\bar{Q} - \tilde{P}$ (such that $N'() = 1$). Now, according to the definition of $\bar{k}$ and the properties of $N(Q)$, the steady state with the highest environmental quality is locally stable while the other is unstable (see the appendices A.1 and B.1). Finally, by construction, reversible steady states satisfy the admissibility condition concerning their location with respect to the irreversibility threshold.

Thereafter, the focus is put on the very distinct features of the positive maintenance equilibrium.

3.3 Positive maintenance equilibrium

When households are sufficiently wealthy and/or suffer from high environmental damages, they decide to engage in maintenance: $m_t \geq 0$. In this case, their optimization problem admits an interior solution and the FOC (10) rewrites:

$$R_{t+1} U_1(c_{t+1}, Q_{t+1}) = \gamma U_2(c_{t+1}, Q_{t+1}) \tag{20}$$

This condition expresses the trade-off inherent in the maintenance decision at period t. An increase in the effort m_t is a means to improve environmental quality and thus to enhance welfare (RHS of (20)). However, it also implies a fall in the non-environmental component of welfare (LHS) since both savings and old age consumption decrease. Consequently, the agent chooses m_t to equate the marginal benefit of maintenance to its marginal cost.

The definition of the equilibrium is modified and the variable m_t now plays an active role:

Definition 3 *A competitive equilibrium is a sequence of per capita variables $\{c_t, m_t, s_t\}$, a sequence of aggregate variables $\{L_t, K_t, Q_t\}$ and a sequence of prices $\{R_t, w_t\}$ such that:*
i/ condition (20), for households, and conditions (5)-(6), for profit maximization, hold,
ii/ all markets clear: $L_t = N = 1$ on the labor market and $k_{t+1} = s_t$ on the capital market,
iii/ budget constraints (7) and (8) are satisfied,
iv/ the dynamics of environmental quality are given by (9).

The equilibrium analysis consists of considering the system of equations (5)-(9), *(*20) and the market clearing conditions. Combining these equations yields the expression of the maintenance decision as a function of the capital stock

$$m_t = f(k_t) - k_t f'(k_t) - k_{t+1} \tag{21}$$

and, since consumption is still given by (14), the emissions function E_t rewrites:

$$E(k_t, k_{t+1}) = \beta \left((1-\delta)k_t + k_t f'(k_t)\right) - \gamma \left(f(k_t) - k_t f'(k_t) - k_{t+1}\right). \tag{22}$$

By substituting equations (6) and (14) into the FOC (20), we get the following equation,

$$R(k_{t+1})U_1(c(k_{t+1}), Q_{t+1}) - \gamma U_2(c(k_{t+1}), Q_{t+1}) = 0 \tag{23}$$

which implicitly defines an equilibrium relation, valid for any t, between Q_t and k_t:

$$Q_t = Q^e(k_t). \tag{24}$$

It is worth noting that this increasing[9] relation governs the dynamics in the whole positive maintenance space.

Finally, the substitution of equation (22) into the law of motion for the environment (9), together with (23), completely characterizes the equilibrium dynamics:

$$\begin{cases} R(k_{t+1})U_1(c(k_{t+1}), Q_{t+1}) - \gamma U_2(c(k_{t+1}), Q_{t+1}) = 0 \\ Q_{t+1} = N(Q_t) - E(k_t, k_{t+1}) \end{cases} \tag{25}$$

The existence conditions of interior steady states are summarized in the following propositions. Two distinct cases are envisioned depending on whether or not environmental quality has exceeded the irreversibility threshold. The analysis is restricted to the interval $[0, \bar{k}]$. This choice is dictated by the fact that stationary maintenance is necessarily non negative on this range (see appendix A.1).[10]

Proposition 2 *When capital is not essential to production ($f(0) > 0$), there exists a steady state with irreversible pollution. Let us now consider the case where capital is essential to production ($f(0) = 0$). Then, there exists an irreversible steady state if*

$$\lim_{k \to 0} E'(k) < 0 \tag{26}$$

Proof. See appendix A.2.1 ■

In both cases, stationary emissions $E(k)$ are negative in the neighborhood of zero. Considering negative emissions boils down to assuming that there exists a man-made environment. This

---

[9] Total differentiation of (23) gives:

$$Q^{e\prime}(k_t) = -\frac{R'U_1 + Rc'U_{11} - \gamma c'U_{12}}{RU_{12 - \gamma}U_{22}}$$

and, under our hypothesis, this derivative is positive.

[10] This restriction does not weaken our study since the equation $w(k) = k$ admits a unique solution for the class of CES technologies.

situation, reported by Forster [1975] among others, is all the more likely in our model since the impact of an increase in k on maintenance exceeds its repercussions on consumption.[11] When $\beta > \gamma$, it also supposes that the difference between the parameters of emissions diffusion β and maintenance efficiency γ is relatively tight.

Note that this property guarantees the stabilization of environmental quality to a constant level since emissions will cancel (each others) for a level of capital in $[0, \bar{k}]$. But it certainly does not mean that, during the transitional dynamics, emissions $E(k_t, k_{t+1})$ can be negative.

Let (k_i^*, Q_i^*) be a steady state with irreversible pollution. The admissibility of irreversible steady states (thereafter ISS) requires $Q_i^* \leq \bar{Q} - \bar{P}$, which is equivalent to $k_i^* \leq \underline{k}$ with $\underline{k} = (Q^e)^{-1}(\bar{Q} - \bar{P})$. In the next step of the analysis, we refer to this condition to prove the existence of reversible steady states.

Proposition 3 *i/ Assume first that all ISS are admissible (*$\sup\{k_i^*\} \leq \underline{k}$*) or that* $\underline{k}$ *is comprised between two successive, odd then even, levels* k_i^* *(*$\underline{k} \in [k_i^{*a}, k_i^{*a+1}]$*, with* a *an odd number). Then there exists a reversible steady state if:*

$$\max_{P \in [0,\bar{P}]} \{\Gamma(P)\} \geq \max_{k \in [0,\bar{k}]} \{E(k)\} \tag{27}$$

and,

$$Q^e(\bar{k}) \geq \bar{Q} - \tilde{P}. \tag{28}$$

ii/ Suppose next that no ISS is admissible ($\inf\{k_i^*\} > \underline{k}$*) or that* $\underline{k}$ *belongs to an interval whose bounds correspond to two successive, even then odd, levels* k_i^* *(*$\underline{k} \in [k_i^{*b}, k_i^{*b+1}]$*, with* b *an even number). Then there exists a reversible steady state if (28) holds and if:*

$$\max_{P \in [0,\bar{P}]} \{\Gamma(P)\} \leq \max_{k \in [0,\bar{k}]} \{E(k)\} \tag{29}$$

Proof. See appendix $A.2.3$. ■

In the first case *i/*, condition (27) states that the maximum potential of assimilation is higher than the maximum volume of emissions on the significant domains of variation of k and Q. It is similar to the necessary and sufficient condition (19), used to show the existence of corner steady states, since, in the positive maintenance space, emissions reach their maximum when

---

[11] If one refers to the Cobb-Douglas example (obtained by letting $\rho \to 0$ in the CES), it is easy to show that

$$\lim_{k \to 0} \frac{c'(k)}{m'(k)} < \frac{\alpha}{1-\alpha}$$

with $\alpha \in (0,1)$ the capital's share of output.

Therefore, under the common assumption that $\alpha < 1/2$, an increase in k has a stronger impact on $m()$ than on $c()$ in the neighborhood of zero.

the depollution effort vanishes, that is, at the upper bound $\bar{k}$. In addition, (28) is a technical condition that ensures some correspondence between these domains.

In the second configuration *ii/*, the sense of the inequality in (29) is reversed. This alternative is considered by Tahvonen and Salo [1996] in their optimal control model with irreversible pollution. In contrast to (27), it implies that the transgression of the irreversibility threshold is most likely to occur.

By construction, reversible steady states also satisfy the admissibility condition imposing $Q^* > \bar{Q} - \bar{P}$. And one may note that in both cases the three types of equilibrium thus far discussed can exist simultaneously (in the appendix, see the representation of the phase diagram).

A synthesis of equilibrium properties[12] shows that a first implication of the inverted U-shape decay function is the existence of multiple steady states. These equilibria have very distinct features since some of them exhibit a safe environment while others are associated with irreversible pollution. The coexistence of these two types of interior solutions challenges John and Pecchenino [1994]'s result that maintenance is a "sufficient" condition for improving environmental quality. Indeed, it appears that maintaining the environment does not necessarily ensure its improvement and, furthermore, does not protect Nature against irrevocable degradation.

The existence of multiple equilibria with irreversible pollution already has been shown, notably by Tahvonen and Withagen [1996], in partial equilibrium models with infinitely-lived agents. The original result here resides in the consequence of the interaction between capital and environmental quality. The analysis of interior solutions reveals that a process of unregulated growth[13] can drive the economy toward a poverty trap. Poverty traps correspond precisely to irreversible steady states. In fact, such a long-run state is first an ecological trap since environmental quality is below the irreversibility threshold $\bar{Q} - \bar{P}$. But it is also an economic trap because the level of wealth, measured by capital stock, is lower than the level reached at any reversible (corner or interior) solution.

More precisely, the main feature of the model is that ecological poverty generates economic poverty. The general thinking that explains the emergence of economic poverty is the following. In the "irreversible" region, pollutant concentration is such that, on the one hand, nature no longer assimilates pollution and, on the other, households suffer from the damages caused by pollution. It is worth noting here that agents continue maintenance acitivites despite the irreversibility of pollution. Indeed, the maintenance effort is the only means to slow down the accumulation of pollution and to limit the disutility it causes. In order to control this damage, they have no other option than to devote a sizeable share of their resources to maintenance. This decision is detrimental to consumption (that always remains positive according to preferences) and savings.

---

[12] The analysis of local stability is performed in appendix B.2.

[13] Or, if we consider John *et al.* [1995]'s approach instead, a process of growth where the regulation of emissions is a myopic government's responsibility.

A new stage of economic recession occurs since the agents' reaction to environmental degradation causes a break in capital accumulation. As the opportunity cost of maintenance becomes more and more severe, the economy

fails to artificially restore environmental quality. Finally, it manages to stabilize to a steady state with a constant, but irrevocably degraded, environment and a very low level of wealth.

This result contributes to the growing literature on poverty traps. Since the seminal paper of Azariadis and Drazen [1990], numerous studies have tried to determine the factors explaining the emergence of such states (see, among others, Xepapadeas [1997], Azariadis [2000]). Among the arguments frequently invoked is an insufficient investment in human capital or the existence of threshold externalities affecting production or education technologies. These externalities imply that the production of education, for instance, first exhibits decreasing returns to scale for low levels of human capital. Then, above a critical value of the stock, there is a change in the technology and the returns to scale become constant and even increasing. In this context, the country that does not reach the critical level of human capital is doomed to remain in a poverty trap while the country that accumulates knowledge to a level above the threshold can experience sustained growth.

Here, the new mechanism proposed is also based on the notion of threshold effects but it comes from the environmental side of the system instead. To summarize, economic activity, through the polluting emissions it creates, can lead to the exceeding of the ecological threshold beyond which the natural assimilation capacity vanishes. This, in turn, causes a stage of economic recession that drives the economy into a poverty trap.

Whether the economy will be dragged down into the poverty trap or if, to the contrary, it will enjoy a stage of economic growth combined with an increase in environmental quality obviously depends on its initial location. Any economy with initially low levels of wealth and environmental quality would probably have the greatest difficulties in escaping from this impoverishment region. The final part of the paper deals with this issue. This section performs numerical simulations intended to illustrate the most striking equilibrium trajectories. Particularly, a discussion on the possible emergence of an Environmental Kuznets Curve, in our setting, will be conducted.

4 Dynamic Analysis: the Degenerated EKC

The aim of this section is to isolate the impact of an inverted U-shaped decay function on environmental and economic dynamics. The key question is whether or not the potential irreversibility of pollution challenges the main result of John and Pecchenino [1994], that is, the existence of the EKC. To answer this question, the following functional forms are used:

For $P_t \geq 0$, the decay function is given by a function defined piecewise:

$$\Gamma(P_t) = \begin{cases} \theta P_t(\bar{P} - P_t) & \forall P_t < \bar{P} \\ 0 & P_t \geq \bar{P} \end{cases}$$

the volume of pollution assimilated is first increasing in the stock until the level $\bar{P}/2$, it then is decreasing. Beyond the critical threshold $\bar{P}$, the natural capacity to absorb pollution vanishes.

Following John and Pecchenino [1994], we use a Cobb-Douglas technology:

$$Y_t = AK_t^{\alpha} L_t^{1-\alpha}$$

with $\alpha \in (0,1)$ and $A > 0$ a scale parameter.

The household's preferences are characterized by a separable utility function.[14] This function is growing and concave in consumption and the environment (for $Q \leq \bar{Q}$):

$$U(c_{t+1}, Q_{t+1}) = \log c_{t+1} - \frac{1}{2}(\bar{Q} - Q_{t+1})^2.$$

Numerical simulations are performed for the following set of parameters:

$$\left\{A = 2.52, \theta = 0.09, \gamma = 0.2, \beta = 0.3, \alpha = 0.3, \delta = 0.6, \bar{P} = 5, \bar{Q} = 7\right\}.$$

It is possible to show only two admissible steady states exist.[15] Both solutions are located in the positive maintenance space. The first is associated with reversible pollution while the other exhibits irreversibility.

Figure 2 first represents the attraction basins of each solution. The partition of the $k - Q$ space is straightforward: starting from any point (K_0, Q_0) located in the upper and dark (resp. lower and bright) area, the economy reaches, in the long run, the reversible (resp. irreversible) steady state. Therefore, when Q_0 is lower than the critical level $\bar{Q} - \bar{P}$, the dynamics lead the economy with certainty into the environmentally poor steady state. On the contrary, an economy initially endowed with a sufficient amount of environmental quality will enjoy, in the long run, a safe environment.

More importantly, it is worth noting that the set of initial points characterized by reversible pollution and associated with a convergence toward the irreversible state is not empty. These initial conditions belong to the lower basin, on the left of the indifference frontier (see figure 3). It means that an economy may be attracted to this kind of steady state despite its relatively high endowment in environmental quality.

We now focus on the equilibrium trajectories' properties. By analogy with John and Pecchenino [1994], the simulations start from initial conditions in the zero maintenance region. In

---

[14] The results do not depend on the (simplifying) assumption of separability.

[15] Parameter restrictions and equilibrium properties, for the numerical example, are summarized in appendix D.

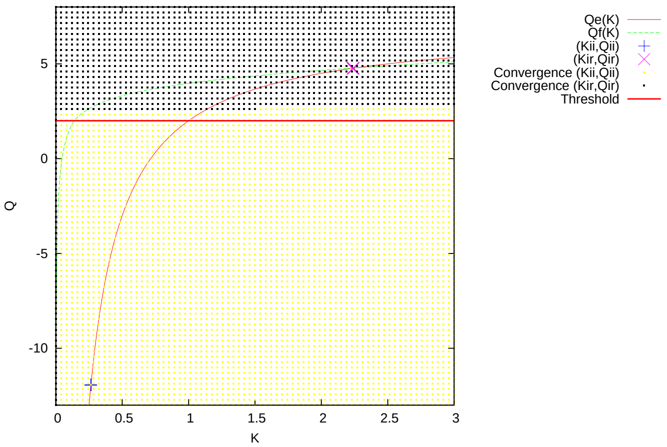

Figure 2: The attraction basins. The figure contains the equilibrium relation $Q^e(k_t)$ the indifference frontier $Q^f(k_t)$ and the threshold $\bar{Q} - \bar{P} = 2$. The two steady states are located on $Q^f(k_t)$. Symbol "+" (*resp.* "x") represents the irreversible (*resp.* reversible) steady state.

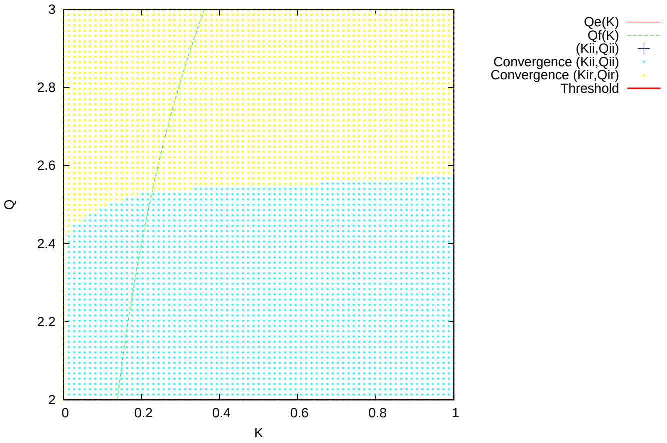

Figure 3: Set of initial reversible conditions converging toward the irreversible state.

addition, the only initial states (k_0, Q_0) considered are reversible. The dynamics exhibit very distinct features compared with John and Pecchenino [1994].[16] Indeed, the analysis reveals that the EKC is no longer the rule and points instead to the following trajectories.

The first trajectory (see figure 4), with Q_0 closed to the upper bound $\bar{Q}$, corresponds to a monotonically decreasing convergence toward the reversible steady state. The initial endowment Q_0 is such that the economy remains in the zero maintenance area during almost all the transitional dynamics.Agents do not allocate any resources to maintenance and the economy enjoys a phase of sustained growth. In turn, the quality of the environment continuously declines. The degradation is first relatively slow but, as soon as capital approaches its stationary level, polluting emissions cause a severe fall in environmental quality (until its stabilization). When the indifference frontier $Q^f(k_t)$ is crossed, the economy starts to abate. However, this effort does not allow a stop to environmental deterioration.

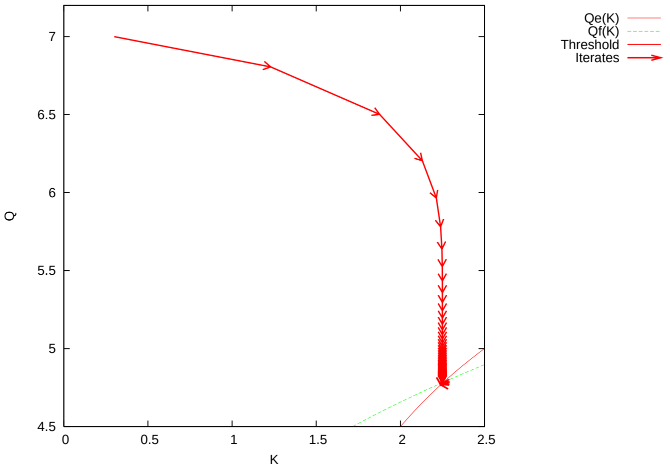

Figure 4: Equilibrium trajectory leading to the reversible steady state

The other striking trajectory, with diametrically opposite properties, is detected for an initial conditions with low, but still higher than the threshold, levels of environmental quality (see figure 5). This trajectory illustrates the case where the economy is dragged down into the ecological and economic poverty trap. The intuition behind the emergence of the degenerated EKC is the following. Starting from an initial state with relatively low levels of capital and environmental quality, there first is a stage of economic development accompanied by (slowly) worsening of

---

[16] The authors detect a V-shaped relation between capital and environmental quality during the convergence toward the interior steady state. This EKC is the result of a break in maintenance. Starting from a point located in the zero maintenance region, agents first have no incentive to invest in maintenance and capital accumulation is accompanied by environmental degradation. When pollution emissions are sufficiently damaging (or equivalently, once the trajectory has crossed the frontier $Q^f(k_t)$), agents decide to engage in maintenance. In this second phase, environmental quality increases with capital until the positive maintenance steady state is reached. Finally, by combining these two different development stages, the authors obtain a sort of EKC.

environmental quality. During this phase, agents benefit from a sufficient environment and choose not to abate their activities. They favour consumption and wealth accumulation instead. The economy becomes rich but also accumulates an ecological debt that will be the responsibility of future generations. However, since agents do not take into account intergenerational externalities, this debt will exceed the gains from higher wealth. In fact, once the trajectory crosses the indifference frontier, maintenance becomes positive and the second development stage begins. During this second phase, agents are willing to devote a share of their resources to maintenance to control the damages arising from pollution. However, due to their limited budget and the need to consume, they cannot allocate enough resources to maintenance and fail to compensate for the harmful effect of polluting emissions, which is exacerbated by the weakness of the natural regeneration capacity.[17] Thus, environmental quality does not stop deteriorating. Moreover, this effort is made to the detriment of savings. The resulting break in capital accumulation is revealed in the fact that, at each date, the stock of capital will set up at a lower level.

This impoverishment mechanism finally re-occurs, from period to period. Its main implication resides in the exceeding of the irreversibility threshold. In this context, the economy is unable to stop the fall in environmental quality. This, in turn, causes a phase of economic recession since agents devote increasing amounts of resources to maintenance in order to limit the disutility of the unbroken rise in emissions. In the very long run, the economy reaches the steady state characterized by both a level of capital almost nil and a negative environmental quality.

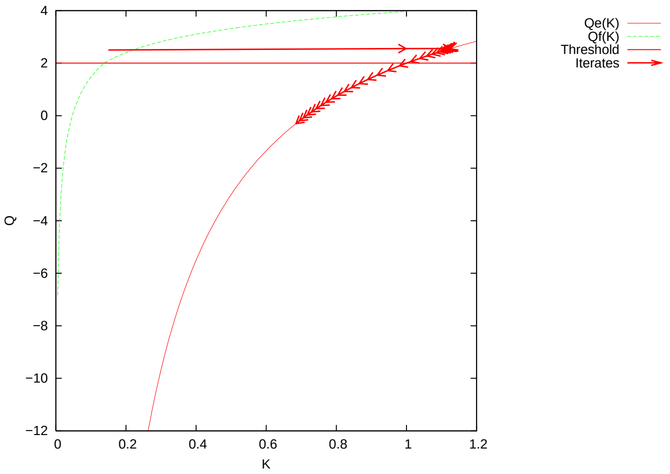

Figure 5: Equilibrium trajectory: the degenerated EKC

The qualitative properties of this trajectory confirm Dasgupta and Mäler [2002]'s warning against any hasty interpretation of the EKC. Under the assumption of a constant rate of decay, the economy can pollute with complete impunity since it always will be able to reverse the trend by compensating for past environmental damage, with the support of an increasing natural

---

[17] Here, the economy is located in the region where the assimilation function is decreasing in pollution.

assimilation of the pollution stock. If, on the contrary, the potential irreversibility of pollution is taken into account then the exceeding of critical ecological thresholds implies that the economy can not depend on the natural regeneration process anymore. Ultimately, it fails to absorb on its own the environmental debt accumulated from past polluting activities. The economy is then doomed to suffer irreparable degradation of the environment.

5 Conclusion

The purpose of this study is to confront the notion of irreversibility of pollution with the environmental Kuznets curve (EKC). Our analysis is intended to challenge the conclusions of John and Pecchenino [1994], who highlight an equilibrium relationship between growth and environmental quality that has the same characteristics as the EKC. The emergence of the EKC in their overlapping generations model is based on a break in abatement activity. A possible interpretation of this result is that it will always be possible to remedy the damage caused by pollution in the first stages of economic development, provided that the economy devotes, once the need arises, a sufficient amount of resources to maintenance. In this paper, we seek to discover the extent to which John and Pecchenino [1994]'s result is submitted to the assumption of a constant rate of pollution assimilation. Our approach echoes Dasgupta and Mäler [2002]'s statement that the concept of the EKC, and its interpretation given above, must be rejected once one admits the potential irreversibility of environmental damages.

To answer our question, their framework is extended by considering an inverted U-shaped assimilation function (similar to the one used by Forster [1975]) rather than a constant rate of pollution assimilation. The equilibrium analysis reveals three important features of the model. First, there exist multiple equilibria with diametrically opposite properties. Some are associated with irreversible pollution although the abatement activity is operative. The major implication of this result lies in the fact that an economy, having vastly impaired the environment by placing greater importance on economic growth, may be unable to reverse the trend. In other words, the simple fact of engaging in maintenance may not suffice to avoid the convergence toward a long term state with the characteristics of an ecological poverty trap. Second, ecological poverty creates economic poverty in turn. Therefore, these steady states also correspond to poverty traps in terms of wealth. Finally, noteworthy equilibrium trajectories are illustrated with numerical simulations. Our intuition that the EKC, as it is depicted by John and Pecchenino [1994], is no longer the rule when the possibility of irreversibility is taken into account, is confirmed. The convergence toward a poverty trap makes appear a sort of degenerated EKC instead.

The existence of such a long-term state legitimizes the intervention of public authorities in the management of pollution problems, and will lead us, in future research, to study more deeply the means and consequences of such intervention. Further developments of this paper may consist notably of assuming that pollution proceeds from production activity, and that it is controlled thanks to a pollution permit market. In this context, the question is first to identify under what conditions this system of regulation allows an economy to avoid a drifting towards a poverty trap. In addition, it should be interesting to assess the effects of a reform of the pollution permit system on the growth perspectives of an economy.

References

[1] Allais, M., 1947, *Economie et Intérêt*, Paris, Imprimerie Nationale.

[2] Andreoni, J. and A. Levinson, 2001, "The simple analytics of tyhe environmental Kuznets Curve", *Journal of Public Economics* **80**, 269-286.

[3] Azariadis, C. and A. Drazen, 1990, "Threshold externalities in economic development", *The Quaterly Journal of Economics*, vol. 105, p. 501-526.

[4] Azariadis, C., 2000, "Intertemporal Macroeconomics", Blackwell Publishers Ltd, chapter 14.

[5] Brock, W. and M. Taylor, 2004, "Economic growth and the environment: a review of theory and empirics", *NBER working paper series*, no. 10854.

[6] Carson, R.T., Y. Jeon and R. McCubbin, 1997, "The relationship between air pollution emissions and income: US data", *Environment and Development Economics* **2**, 433-450.

[7] Cesar, H. and A. de Zeeuw, 1994, "Substainability and the greenhouse effect: Robustness analysis of the assimilation function", dans *Control and Game Theoretical Models of the Environment* , J. Filar and C. Carraro Eds, Birkhäuser, Boston.

[8] Comolli, P., 1977, "Pollution control in a simplified general equilibrium model with production externalities", *Journal of environmental Economics and Management* **4**, 289-304.

[9] Copeland, B. and M. Taylor, 2003, "Trade, growth and the environment", *NBER working papers series*, no. 9823.

[10] Dasgupta, P., 1982, *The Control of Resources*, Basil Blackwell, Oxford.

[11] Dasgupta, P. and K-G Mäler, 2002, "The Economics of Non-Convex Ecosystems : Introduction", *Environmental and Resource Economics* **26**, 499-525.

[12] Dasgupta, S., B. Laplante, H. Wang and D. Wheeler, 2002, "Confronting the Environmental Kuznets Curve", *Journal of Economics Perspectives* **16**, no. 1, 147-168.

[13] De La Croix, D. and P. Michel, 2002, *A Theory of Economic Growth*, Cambridge University Press.

[14] Diamond, P.A, 1965, "National Debt in a Neoclassical Growth Model", *American Economic Review* **55**, no. 5, 1126-1150.

[15] Dinda, S., 2004, "Environmental Kuznets curve hypothesis: a survey", *Ecological Economics*, vol. 49, p. 431-455.

[16] Forster, B., 1975, "Optimal Pollution Control with Nonconstant Exponential Rate of Decay", *Journal of environmental Economics and Management* **2**, 1-6.

[17] Grossman, G. and A. Krueger, 1993, "Environmental Impacts of North American Free Trade Agreement", dans *The U.S-Mexico Free Trade Agreement*, P. Garber ed., MA: MIT Press, Cambridge.

[18] Grossman, G. and A. Krueger, 1995, "Economic Growth and the environment", *The Quaterly Journal of Economics*, 353-376.

[19] Holling, C., 1973, "Resilience and stability of ecological, systems", *Review of Ecological System* **4**, 1-23.

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

[21] John, A., R. Pecchenino, D. Schimmelpfennig and S. Schreft, 1995, "Short lived agents and long-lived environment", *Journal of Public Economics* **58**, 127-141.

[22] Jones, L. and R. Manuelli, 2001, "Endogenous Policy Choice: The Case of Pollution anbd Growth", *Review of Economic Dynamics*, vol. 4, p. 369-405.

[23] Keeler, E., M. Spence and R. Zeckauser, 1971, "The Optimal Control of Pollution", *Journal of Economic Theory* **4**, 19-34.

[24] Perman, R. and D. Stern, 2003, "Evidence from panel unit root and cointegration tests that the environmental Kuznets curve does not exist", *Australian Journal of Agricultural and Resource Economics.*

[25] Peterman, R., 1980, "Influence of ecosystem structure and perturbation history on recovery process" in *The Recovery Process in Damaged Ecosystems*, J. Cairns Jr ed., Ann Arbor Science, Michigan.

[26] Samuelson, P., 1958, "An exact consumption-loan model of interest with or without the social contrivance of money", *Journal of Political Economy* **66**, 467-482.

[27] Schmalensee, R., T.M Stocker and R.A Judson, 1998, "World carbon dioxyde emissions: 1950-2050", *Review of Economics and Statistics* **80**, 15-27.

[28] Selden, T.M and D. Song, 1995, "Neoclassical Growth, the J curve for Abatement and the Inverted U Curve for Pollution", *Journal of Environmental Economics and Management* **29**, 162-168.

[29] Smulders, S. and R. Gradus, 1993, "The Trade-off between Environmental Care and Long-term Growth: Pollution in three Prototype Growth Models", *Journal of Economics* **58**, 25-51.

[30] Stern, D., 1998, "Progress on the environmental Kuznets curve ?", *Environment and Development Economics*, vol. 3, p. 173-196.

[31] Stern, D., 2003, "The rise and fall of the environmental Kuznets curve", *Rensselaer working papers,* no. 0302.

[32] Stokey, N., 1998, "Are there limits to growth", *International Economic Rewiew* **39**, 1-31.

[33] Suri, V. et D. Chapman, 1998, "Economic growth, trade and energy: implications for the environmental Kuznets curve", *Ecological Economics*, vol. 25, p.195-208.

[34] Tahvonen, O. et S. Salo, 1996, "Non convexities in optimal pollution accumulation", *European Economic Review*, vol. 45, p. 1379-1398.

[35] Tahvonen, O. and C. Withagen, 1996, "Optimality of irreversible pollution accumulation", *Journal of Economic Dynamics and Control* **20**, 1775-1795.

[36] Toman, M. and C. Withagen, 2000, "Accumulative pollution, "clean technology", and policy design", *Resource and Energy Economics* **22**, 367-384.

[37] Van der Ploeg, F. and C. Withagen, 1991, "Pollution Control and the Ramsey Problem", *Environmental and Resources Economics* **1**, 215-236.

[38] World Bank 1992, *World Bank development report 1992 : Development and the Environment.*

[39] Xepapadeas, A., 1997, "Economic Development and Environmental Pollution: Traps and Growth", *Structural Change and Economic Dynamic*, vol. 8, p. 327-350.

[40] Yu, Z.H., 2005, “Environmental protection: A theory of direct and indirect competition for political influence", *Review of Economic Studies*, 72, p. 269-286.

Appendix

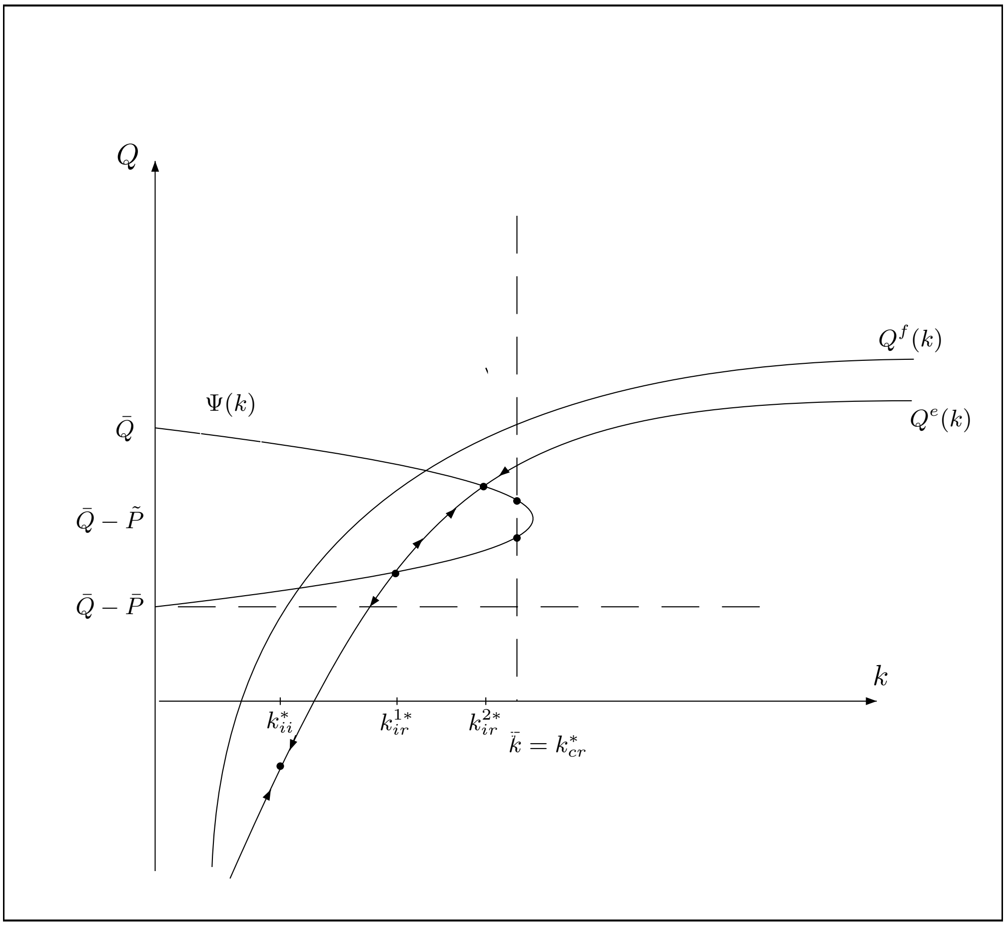

Figure 6: The Phase Diagram

Note that the function $\Psi(k)$, implicitly defined by the following equation,

$$\Gamma(\bar{Q} - Q) = E(k)$$

represents the second equilibrium relation between capital and environmental quality that holds at interior steady states (see appendix A.2.3).

A. Proof of propositions 1, 2 and 3

We first summarize the properties of functions that have a real influence on the study of existence. Next, we explicitly deal with the issue by analyzing separately the four possible cases.

A.1 Functions properties

The maintenance function is given by the difference between the wage and the level of capital:

$$m(k) = w(k) - k$$

By definition, the wage is a non negative and increasing function of k: $w(k) \geq 0$ and $w'(k) = -kf''(k) \geq 0 \ \forall k \in \mathbb{R}^+$. Under Assumption 2, we have $\lim_{k \to 0} w(k) = f(0)$ and $\lim_{k \to 0} kf'(k) = 0$. Furthermore, it satisfies $\lim_{k \to +\infty} w(k)/k = 0$. Thus, the wage function is located below the first bisectrix when capital tends towards infinity. If capital is not essential to production ($f(0) > 0$), then there exists an intersection between $w(k)$ and k and, consequently, a positive finite value k such that $m(k) = 0$. Otherwise, the previous property keeps holding if we impose : $\lim_{k \to 0} w(k)/k > 1$ (condition (17)).

Let us define $\bar{k}$ as follows:

$$\bar{k} = \inf\{k \in [0, +\infty[\ / w(k) = k\}$$

At this striking point, $w'(\bar{k}) < 1$ since the wage crosses the bisectrix from above.

Note that the condition $m(k) \geq 0$, for an interior solution, calls for a restriction of domain of variation of capital. Therefore, the study of existence will be restricted to the interval defined by the lower intersection point $\bar{k}$ since: $\forall k \in [0, \bar{k}], \ m(k) \geq 0$.[18]

The consumption function writes:

$$c(k) = (1 - \delta)k + kf'(k)$$

Under Assumption 2, $c(k) \geq 0 \ \forall k \in [0, \bar{k}]$. It is possible to compute its values at the bound of $[0, \bar{k}]$: $\lim_{k \to 0} c(k) = 0$ and $c(\bar{k}) = (1 - \delta)\bar{k} + \bar{k}f'(\bar{k}) > 0$. The first derivative is given by $c'(k) = 1 - \delta + f'(k) + kf''(k)$ and we impose the following condition (assumption (18)):

$$\sigma(k) \geq 1 - s(k) \leftrightarrow f'(k) + kf''(k) \geq 0$$

with $\sigma(k)$, the elasticity of substitution, defined by (16) and $1 - s(k)$, the labor share of output (see (15)).

This assumption guarantees $c'(k) > 0$ on $[0, \bar{k}]$.

The emissions function:

---

[18] With CES technologies, the intersection $\bar{k}$ is unique.

At the corner stationary equilibrium, polluting emissions are simply given by $E(k) = \beta c(k)$ and this function has the same properties as $c(k)$.

At the interior equilibrium, they are defined as a function of capital:

$$E(k) = \beta c(k) - \gamma m(k)$$

The levels of emission corresponding to each bound of the interval $[0, \bar{k}]$ equal to: $\lim_{k \to 0} E(k) = -\gamma f(0) \leq 0$ and $E(\bar{k}) = \beta c(\bar{k}) > 0$. The first derivative is given by: $E'(k) = \beta c'(k) - \gamma m'(k)$. In addition, it is easy to prove that emissions reach their maximum at the upper bound $\bar{k}$: $E(\bar{k}) = \max\{E(k) \ / \ k \in [0, \bar{k}]\}$.

The environmental law of motion $N(Q)$ is defined piecewise on the interval $]-\infty, \bar{Q}]$ (the upper bound comes from the fact that we consider only non negative pollution levels):

$$N(Q) = \begin{cases} Q & \forall Q \leq \bar{Q} - \bar{P} \\ Q + \Gamma(\bar{Q} - Q) & \forall \bar{Q} - \bar{P} < Q \leq \bar{Q} \end{cases}$$

For any value of Q lower than the critical threshold (that is $Q \leq \bar{Q} - \bar{P}$), $N(Q)$ is simply linear. Thus, we have $N(0) = 0$, $N(\bar{Q} - \bar{P}) = \bar{Q} - \bar{P}$ and $N'(Q) = 1 \ \forall Q \leq \bar{Q} - \bar{P}$.

Once the irreversibility frontier $\bar{Q} - \bar{P}$ is crossed, the natural regeneration process is effective and the law of motion becomes: $N(Q) = Q + \Gamma(\bar{Q} - Q)$. From the properties of the decay function $\Gamma(.)$, we know that $N(Q) > 0 \ \forall Q \in]\bar{Q} - \bar{P}, \bar{Q}]$, $\lim_{Q \to \bar{Q} - \bar{P}} N(Q) = \bar{Q} - \bar{P}$ and $N(\bar{Q}) = \bar{Q}$. The derivative $N'(Q) = 1 - \Gamma'(\bar{Q} - Q)$ is positive $\forall Q \leq \bar{Q}$. Il also appears that $N'(Q) \geq 1 \leftrightarrow Q \leq \bar{Q} - \tilde{P}$. Finally, this function is concave since $N''(Q) = \Gamma''(\bar{Q} - Q) \leq 0$.

A.2 Steady State (SS) analysis

A.2.1 Existence of Corner SS (prop. 1)

A steady state solves the following system of equations:

$$\begin{cases} k = f(k) - kf'(k) \\ \Gamma(\bar{Q} - Q) = E(k) \end{cases} \tag{30}$$

If pollution is irreversible, then the second equation becomes:

$$E(k) = 0$$

From the definition of $E(k)$, its unique solution is $c(k) = 0$. But this limit case can be excluded according to the assumption $\lim_{c \to 0} U_1(c, Q) = +\infty$. There is no corner SS that exhibits irreversible pollution.

In the reversible case, for $Q \in]\bar{Q} - \bar{P}, \bar{Q}]$, under assumption (17), there exists only one positive value of capital that solves the first equation on the interval $[0, \bar{k}]$. This solution exactly corresponds to the upper bound $\bar{k}$ (such that $m(k) = 0$): $k^*_{cr} = \bar{k}$. Now, the corresponding level of environmental quality is given by the following equation: $\Gamma(\bar{Q}-Q) = \beta c(\bar{k})$. Under the properties of $\Gamma(\bar{Q}-Q)$, we deduce from condition (19) that there exists one (or two if the inequality in (19) is strict) equilibrium value Q_{cr}^{*} associated with k_{cr}^{*}. The uniqueness of equilibrium implies that $Q_{cr}^{*} = \bar{Q} - \tilde{P} > \bar{Q} - \bar{P}$ otherwise, the ranking is such that $Q_{cr}^{*+} > \bar{Q} - \tilde{P} > Q_{cr}^{*-} > \bar{Q} - \bar{P}$.

A.2.2 Existence of Interior irreversible SS (prop. 2)

Evaluating (25) at an irreversible SS (thereafter ISS) yields:

$$\left\{ \begin{array}{l} R(k)U_1(c(k),Q) - \gamma U_2(c(k),Q) = 0 \\ E(k) = 0 \end{array} \right. \tag{31}$$

where emissions are now given by (22).

If k is not essential to production ($f(0) > 0$) then emissions are negative in the neighborhood of 0. If not, imposing $\lim_{k \to 0} E'(k) < 0$ (see condition (26) in proposition 2), is sufficient to prove that there exists a positive value of capital for which emissions are nil. From the properties of $E(k)$, the second equation admits an odd number of positive solutions k_{ii}^{*}[19] such that $E(k) = 0$.

According to (24), the first equation in (31) corresponds to the equilibrium relation $Q_t = Q^e(k_t)$ valid for all t. Substituting a solution k_{ii}^{*} in this equation gives the corresponding equilibrium value of environmental quality $Q_{ii}^{*} = Q^e(k_{ii}^{*})$.

There exists at least one SS associated with a positive maintenance and irreversible pollution. The admissibility of this solution, from the point of view of its location with respect to the critical level $\bar{Q} - \bar{P}$, requires $Q_{ii}^{*} \leq \bar{Q} - \bar{P}$, which is equivalent to $k_{ii}^{*} \leq \underline{k}$ with $\underline{k} = (Q^e)^{-1}(\bar{Q} - \bar{P})$ since the relation $Q^e(k_t)$ is invertible.

A.2.3 Existence of Interior reversible SS (prop. 3)

The system of equations (25) now writes:

$$\left\{ \begin{array}{l} R(k)U_1(c(k),Q) - \gamma U_2(c(k),Q) = 0 \\ \Gamma(\bar{Q} - Q) = E(k) \end{array} \right.$$

where the first equation still characterizes the equilibrium relation: $Q = Q^e(k)$.

Thus, the analysis of existence boils down to examine the solutions to the following equation,

$$\Gamma(\bar{Q} - Q^e(k)) = E(k) \tag{32}$$

and, considering the reversible pollution region impose to restrict the study to the interval $]\underline{k}, \bar{k}]$.[20]

---

[19] The index "i" (resp. "c") prevails for interior (resp. corner) solutions. The second subscript "i" (resp. "r") means that equilibrium pollution is irreversible (resp. reversible).

[20] It is worth noting that there *a priori* exists a problem concerning the domains of definition of these two functions. In fact, $E(k)$ depends on conditions on technology, preferences and the law of pollution diffusion. But, $G(k)$ is also and especially characterized by the properties of the assimilation function. Thus, nothing guarantees the non-emptiness of the studied interval $]\underline{k}, \bar{k}]$ and, we will have to set conditions that ensures its significance.

Let us note $G(k) = \Gamma(\bar{Q} - Q^e(k))$. $G(k)$ has the same qualitative behaviour as the assimilation function $\Gamma(\bar{Q} - Q)$ since $G'(k) = -Q^{e\prime}(k)\Gamma'(\bar{Q} - Q^e(k))$ with $Q^{e\prime}(k) \geq 0$. Thus, it is first increasing from $\underline{k}$ to $(Q^e)^{-1}(\bar{Q} - \tilde{P})$ and next, decreasing until $(Q^e)^{-1}(\bar{Q})$. We also have $G(k) \geq 0 \ \forall k \in]\underline{k}, (Q^e)^{-1}(\bar{Q})]$, $G(\underline{k}) = G((Q^e)^{-1}(\bar{Q})) = 0$ and $\max\{G(k) \ / \ k \in]\underline{k}, (Q^e)^{-1}(\bar{Q})]\} = G((Q^e)^{-1}(\bar{Q} - \tilde{P})) = \Gamma(\tilde{P})$.

In order to determine the ranking between the functions $G(k)$ and $E(k)$ at the lower bound $\underline{k}$, it is possible to refer to the admissibility condition, for ISS, that imposes $k_{ii}^* \leq \underline{k}$. Two cases possibly occur:

- Suppose first that all ISS are admissible ($\sup\{k_i^*\} \leq \underline{k}$) or that $\underline{k}$ is comprised between two successive, odd then even, levels k_i^* ($\underline{k} \in [k_i^{*a}, k_i^{*a+1}]$, with a an odd number). In these cases, the ranking in $\underline{k}$ is known: $E(\underline{k}) > G(\underline{k})$. If we further assume that[21]

$$\sup_{P\in[0,\bar{P}]} \{\Gamma(P)\} \geq \sup_{k\in[0,\bar{k}]} \{E(k)\}$$

and, $\bar{k} \geq \tilde{k}$ (see conditions (27) and (28) in proposition 3), then the interval $]\underline{k}, \bar{k}]$ is non empty and equation (32) admits a solution. In fact, under those conditions, the ranking is inverted at the noteworthy point $\tilde{k}$: $E(\tilde{k}) \leq G(\tilde{k})$, which means that there exists an intersection point between the curves $E(k)$ and $G(k)$ on $]\underline{k}, \bar{k}]$.

- Consider now that no ISS is admissible ($\inf\{k_i^*\} > \underline{k}$) or that $\underline{k}$ belongs to an interval whose bounds correspond to two successive, even then odd, levels k_i^* ($\underline{k} \in [k_i^{*b}, k_i^{*b+1}]$, with b an even number). If (28) holds, by symmetry, proving the existence of a reversible SS requires to reverse the inequality in (27).

Figure 7 illustrates how the interior SS are determined. The fonctional forms we consider are those used in section 4 for the numerical simulations.

B. Local Dynamics

B.1 Stability of corner SS

The Jacobian associated with a corner SS writes:

$$J = \begin{pmatrix} w'(k^*) & 0 \\ -\beta c'(k^*) & N'(Q^*) \end{pmatrix}$$

Stability requires that the two roots of the characteristic polynomial are located into the unit circle, all other configuration being unstable. We know that the trace corresponds to the sum of the (real parts) eigenvalues of J and, the determinant is the product, in modulus, of the eigenvalues. Here, the two eigenvalues are $\lambda_1 = w'(k^*)$ and $\lambda_2 = N'(Q^*)$. Thus, sufficient conditions for stability are:

$$w'(k^*) < 1 \tag{33}$$

---

[21] This condition is tantamount to (19) since $\max\{E(k)\} = E(\bar{k})$.

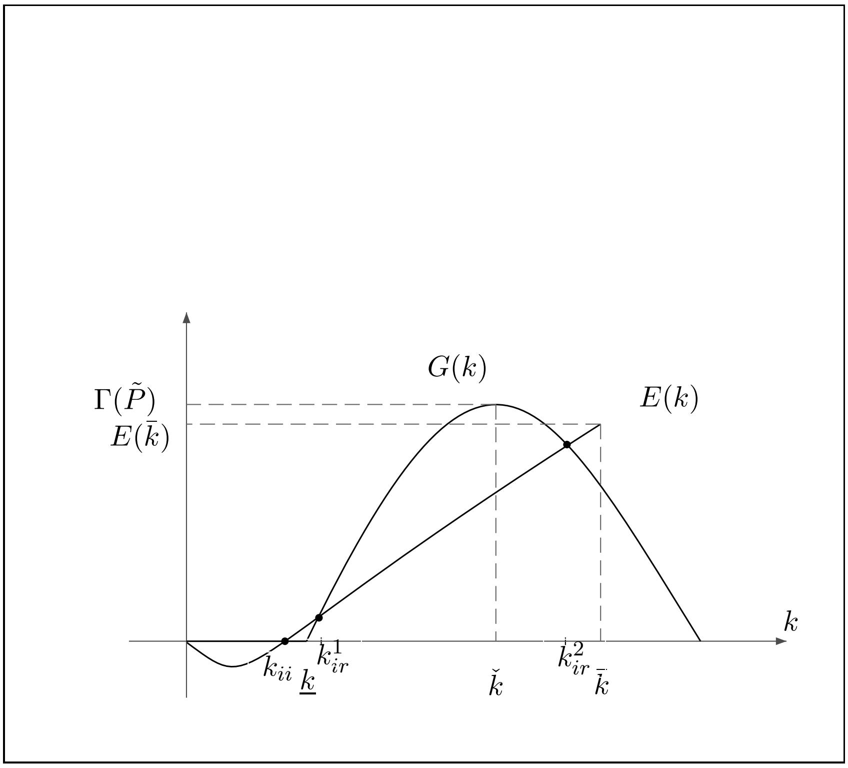

Figure 7: Existence Analysis: with $\check{k} = (Q^e)^{-1}(\bar{Q} - \tilde{P})$

$$N'(Q^*) < 1 \tag{34}$$

Condition (33) implies that the economy is able to absorb a capital shock whereas inequality (34) expresses the environment capacity to recover its original state when submitted to an exogenous perturbation.

The first condition is satisfied since $k_{cr}^* = \bar{k}$ and $w'(\bar{k}) < 1$. Moreover, if there exists a single solution, then $Q_{cr}^* = \bar{Q} - \tilde{P}$; now, we deduce from $N'(\bar{Q} - \tilde{P}) = 1$ that this steady state is unstable. As soon as there exists two solutions, considering their location with respect to $\bar{Q} - \tilde{P}$ ($Q_{cr}^{*1} > \bar{Q} - \tilde{P} > Q_{cr}^{*2}$), the "low" steady state is unstable (because $N'(Q_{cr}^{*2}) > 1$) while the other is locally stable ($N'(Q_{cr}^{*1}) < 1$).

B.2 Stability of interior SS

B.2.1 Reversible Pollution: linearizing the system (25) around a steady state (k^*, Q^*) yields:

$$\begin{cases} dQ_{t+1} = Q^{e\prime}(k^*)dk_{t+1} \\ dQ_{t+1} = N'(Q^*)dQ_t - (E'(k^*) - \gamma)dk_t - \gamma dk_{t+1} \end{cases} \tag{35}$$

From this system, we get the jacobian matrix:

$$J = \begin{pmatrix} -\frac{E'(k)-\gamma}{Q^{e\prime}(k)+\gamma} & \frac{N'(Q)}{Q^{e\prime}(k)+\gamma} \\ -\frac{(E'(k)-\gamma)Q^{e\prime}(k)}{Q^{e\prime}(k)+\gamma} & \frac{N'(Q)Q^{e\prime}(k)}{Q^{e\prime}(k)+\gamma} \end{pmatrix}$$

Now, it is clear that $det(J) = 0$. In fact, the studied dynamics boil down to a one dimensional system because of the existence of the equilibrium relation (24). Therefore, the first eigenvalue is nil $\lambda_1 = 0$ while the second is equal to the trace $\lambda_2 = tra(J)$ with,

$$tra(J) = \frac{N'(Q)Q^{e\prime}(k) - (E'(k) - \gamma)}{Q^{e\prime}(k) + \gamma}$$

We summarize all possible cases:

1/ if $(N'(Q) - 1)Q^{e\prime}(k) < E'(k) \leq \gamma + N'(Q)Q^{e\prime}(k)$ then $1 > tra(J) \geq 0$

The conditions $E'(k) \geq 0$ and $N'(Q) \leq 1$ (with one of the two inequalities being strict) suffice to satisfy the necessary stability condition $E'(k) > (N'(Q) - 1)Q^{e\prime}(k)$.

2/ if $\gamma + N'(Q)Q^{e\prime}(k) < E'(k) < 2\gamma + (1 + N'(Q))Q^{e\prime}(k)$ then $tra(J) < 0$ and $|tra(J)| < 1$.

Thus, the double condition

$$(N'(Q) - 1)Q^{e\prime}(k) < E'(k) < 2\gamma + (1 + N'(Q))Q^{e\prime}(k) \tag{36}$$

defines an interval of variation, for the emissions function derivative, on which local stability of any interior reversible steady state is guaranteed. More precisely, the convergence is monotonic in the first case whereas it is oscillatory in the second one.

B.2.1 Irreversible pollution: this case is obtained by fixing $N'(Q) = 1$. Following the same processes, the sufficient condition for stability writes:

$$0 < E'(k) < 2(\gamma + Q^{e\prime}(k)) \tag{37}$$

Note that Condition (36) imposes that the derivative of the emission function relative to capital is positive. It also supposes that the impact of a rise in capital on emissions is less than a bound defined particularly by its impact on environmental quality at equilibrium (measured by $Q^{e\prime}(k^*)$). This condition ensures that the economy is able to assimilate a capital shock and to recover in a few periods its original state. When the level of pollution is below the critical point $\bar{P}$, the condition (37) generalizes (36). We shall note that the inequality $N'(Q^*) \leq 1$ is sufficient to guarantee that the repercussions of a shock on environmental quality are absorbed from periods to periods.[22]

D. Simulations

Parameter restrictions:

---

[22] The linear formulation of environmental dynamics (see note 5) does not allow to catch this new effect. The specificity (and limits) of this approach lies in the fact that nature is always able to assimilate a shock on the environment which returns to its stationary level in a finite time. On the contrary, in our framework, if $N'(Q) > 1$ then, this shock echoes in a more than proportional manner and the stability property is lost.

We impose a restriction concerning the parameters of the technology and the emissions function: $\gamma(1-\alpha) - \beta\alpha \geq 0$. We also fix the domain of variation of the scale parameter: $A \in [\underline{A},\bar{A}]$ with

$$\underline{A} = \left(\frac{2}{\gamma \bar{P}}\right)^{1-\alpha} \frac{1}{1-\alpha}$$

and,

$$\bar{A} = \left(\frac{\theta \bar{P}^{2} (1-\alpha)}{4\beta((1-\delta)(1-\alpha)+\alpha)}\right)^{1-\alpha} \frac{1}{1-\alpha}$$

These conditions cover the whole of our assumptions made in the general setting.

Equilibrium properties:

In this framework, the equilibrium analysis reveals the following features. There exist five steady states:

- one interior irreversible locally stable solution,
- two interior reversible solutions, the "low" being unstable whereas the "high" is stable,
- two corner reversible solutions with the same configuration for stability.

It is possible to compute analytically the global dynamics characterizing the four possible regions.

Moreover, by using the following set of parameter values,

$$\left\{A = 2.52, \theta = 0.09, \gamma = 0.2, \beta = 0.3, \alpha = 0.3, \delta = 0.6, \bar{P} = 5, \bar{Q} = 7\right\}$$

we show that there exist only two steady states that satisfy the criterion of admissibility: the interior irreversible solution and the high interior reversible solution (constrained reversible solutions are inadmissible in the sense that they are located in the positive maintenance region).

NOTE DI LAVORO DELLA FONDAZIONE ENI ENRICO MATTEI

Fondazione Eni Enrico Mattei Working Paper Series

Our Note di Lavoro are available on the Internet at the following addresses:
http://www.feem.it/Feem/Pub/Publications/WPapers/default.htm
http://www.ssrn.com/link/feem.html
http://www.repec.org
http://agecon.lib.umn.edu
http://www.bepress.com/feem/

NOTE DI LAVORO PUBLISHED IN 2007

NRM	1.2007	*Rinaldo Brau, Alessandro Lanza, and Francesco Pigliaru*: How Fast are Small Tourism Countries Growing? The 1980-2003 Evidence
PRCG	2.2007	*C.V. Fiorio, M. Florio, S. Salini and P. Ferrari:* Consumers' Attitudes on Services of General Interest in the EU: Accessibility, Price and Quality 2000-2004
PRCG	3.2007	*Cesare Dosi and Michele Moretto*: Concession Bidding Rules and Investment Time Flexibility
IEM	4.2007	*Chiara Longo, Matteo Manera, Anil Markandya and Elisa Scarpa*: Evaluating the Empirical Performance of Alternative Econometric Models for Oil Price Forecasting
PRCG	5.2007	*Bernardo Bortolotti, William Megginson and Scott B.* Smart: The Rise of Accelerated Seasoned Equity Underwritings
CCMP	6.2007	*Valentina Bosetti and Massimo Tavoni*: Uncertain R&D, Backstop Technology and GHGs Stabilization
CCMP	7.2007	*Robert Küster, Ingo Ellersdorfer, Ulrich Fahl* (lxxxi): A CGE-Analysis of Energy Policies Considering Labor Market Imperfections and Technology Specifications
CCMP	8.2007	*Mònica Serrano* (lxxxi): The Production and Consumption Accounting Principles as a Guideline for Designing Environmental Tax Policy
CCMP	9.2007	*Erwin L. Corong* (lxxxi): Economic and Poverty Impacts of a Voluntary Carbon Reduction for a Small Liberalized Developing Economy: The Case of the Philippines
CCMP	10.2007	*Valentina Bosetti, Emanuele Massetti, and Massimo Tavoni*: The WITCH Model. Structure, Baseline, Solutions
SIEV	11.2007	*Margherita Turvani, Aline Chiabai, Anna Alberini and Stefania Tonin*: Public Policies for Contaminated Site Cleanup: The Opinions of the Italian Public
CCMP	12.2007	*M. Berrittella, A. Certa, M. Enea and P. Zito*: An Analytic Hierarchy Process for The Evaluation of Transport Policies to Reduce Climate Change Impacts
NRM	13.2007	*Francesco Bosello, Barbara Buchner, Jacopo Crimi, Carlo Giupponi and Andrea Povellato*: The Kyoto Protocol and the Effect of Existing and Planned Measures in the Agricultural and Forestry Sector in the EU25
NRM	14.2007	*Francesco Bosello, Carlo Giupponi and Andrea Povellato*: A Review of Recent Studies on Cost Effectiveness of GHG Mitigation Measures in the European Agro-Forestry Sector
CCMP	15.2007	*Massimo Tavoni, Brent Sohngen, and Valentina Bosetti*: Forestry and the Carbon Market Response to Stabilize Climate
ETA	16.2007	*Erik Ansink and Arjan Ruijs*: Climate Change and the Stability of Water Allocation Agreements
ETA	17.2007	*François Gusdorf and Stéphane Hallegatte*: Compact or Spread-Out Cities: Urban Planning, Taxation, and the Vulnerability to Transportation Shocks
NRM	18.2007	*Giovanni Bella*: A Bug's Life: Competition Among Species Towards the Environment
IEM	19.2007	*Valeria Termini and Laura Cavallo*: "Spot, Bilateral and Futures Trading in Electricity Markets. Implications for Stability"
ETA	20.2007	*Stéphane Hallegatte and Michael Ghil*: Endogenous Business Cycles and the Economic Response to Exogenous Shocks
CTN	21.2007	*Thierry Bréchet, François Gerard and Henry Tulkens*: Climate Coalitions: A Theoretical and Computational Appraisal
CCMP	22.2007	*Claudia Kettner, Angela Köppl, Stefan P. Schleicher and Gregor Thenius*: Stringency and Distribution in the EU Emissions Trading Scheme –The 2005 Evidence
NRM	23.2007	*Hongyu Ding, Arjan Ruijs and Ekko C. van Ierland*: Designing a Decision Support System for Marine Reserves Management: An Economic Analysis for the Dutch North Sea
CCMP	24.2007	*Massimiliano Mazzanti, Anna Montini and Roberto Zoboli*: Economic Dynamics, Emission Trends and the EKC Hypothesis New Evidence Using NAMEA and Provincial Panel Data for Italy
ETA	25.2007	*Joan Canton*: Redealing the Cards: How the Presence of an Eco-Industry Modifies the Political Economy of Environmental Policies
ETA	26.2007	*Joan Canton*: Environmental Taxation and International Eco-Industries
CCMP	27.2007	*Oscar Cacho and Leslie Lipper* (lxxxii): Abatement and Transaction Costs of Carbon-Sink Projects Involving Smallholders
CCMP	28.2007	*A. Caparrós, E. Cerdá, P. Ovando and P. Campos* (lxxxii): Carbon Sequestration with Reforestations and Biodiversity-Scenic Values
CCMP	29.2007	*Georg E. Kindermann, Michael Obersteiner, Ewald Rametsteiner and Ian McCallcum* (lxxxii): Predicting the Deforestation–Trend Under Different Carbon–Prices

CCMP	30.2007	*Raul Ponce-Hernandez* (lxxxii): A Modelling Framework for Addressing the Synergies between Global Conventions through Land Use Changes: Carbon Sequestration, Biodiversity Conservation, Prevention of Land Degradation and Food Security in Agricultural and Forested Lands in Developing Countries
ETA	31.2007	*Michele Moretto and Gianpaolo Rossini*: Are Workers' Enterprises Entry Policies Conventional
KTHC	32.2007	*Giacomo Degli Antoni*: Do Social Relations Affect Economic Welfare? A Microeconomic Empirical Analysis
CCMP	33.2007	*Reyer Gerlagh and Onno Kuik*: Carbon Leakage with International Technology Spillovers
CCMP	34.2007	*Richard S.J. Tol*: The Impact of a Carbon Tax on International Tourism
CCMP	35.2007	*Reyer Gerlagh, Snorre Kverndokk and Knut Einar Rosendahl*: Optimal Timing of Environmental Policy; Interaction Between Environmental Taxes and Innovation Externalitie
SIEV	36.2007	*Anna Alberini and Alberto Longo*: Valuing the Cultural Monuments of Armenia: Bayesian Updating of Prior Beliefs in Contingent Valuation
CCMP	37.2007	*Roeland Bracke, Tom Verbeke and Veerle Dejonckheere*: What Distinguishes EMAS Participants? An Exploration of Company Characteristics
CCMP	38.2007	*E. Tzouvelekas, D. Vouvaki and A. Xepapadeas*: Total Factor Productivity Growth and the Environment: A Case for Green Growth Accounting
CCMP	39.2007	*Klaus Keller, Louise I. Miltich, Alexander Robinson and Richard S.J. Tol*: How Overconfident are Current Projections of Anthropogenic Carbon Dioxide Emissions?
CCMP	40.2007	*Massimiliano Mazzanti and Roberto Zoboli*: Environmental Efficiency, Emission Trends and Labour Productivity: Trade-Off or Joint Dynamics? Empirical Evidence Using NAMEA Panel Data
PRCG	41.2007	*Veronica Ronchi*: Populism and Neopopulism in Latin America: Clientelism, Trade Union Organisation and Electoral Support in Mexico and Argentina in the '90s
PRCG	42.2007	*Veronica Ronchi*: The Neoliberal Myth in Latin America: The Cases of Mexico and Argentina in the '90s
CCMP	43.2007	*David Anthoff, Cameron Hepburn and Richard S.J. Tol*: Equity Weighting and the Marginal Damage Costs of Climate Change
ETA	44.2007	*Bouwe R. Dijkstra and Dirk T.G. Rübbelke*: Group Rewards and Individual Sanctions in Environmental Policy
KTHC	45.2007	*Benno Torgler*: Trust in International Organizations: An Empirical Investigation Focusing on the United Nations
CCMP	46.2007	*Enrica De Cian, Elisa Lanzi and Roberto Roson*: The Impact of Temperature Change on Energy Demand: A Dynamic Panel Analysis
CCMP	47.2007	*Edwin van der Werf*: Production Functions for Climate Policy Modeling: An Empirical Analysis
KTHC	48.2007	*Francesco Lancia and Giovanni Prarolo*: A Politico-Economic Model of Aging, Technology Adoption and Growth
NRM	49.2007	*Giulia Minoia*: Gender Issue and Water Management in the Mediterranean Basin, Middle East and North Africa
KTHC	50.2007	*Susanna Mancinelli and Massimiliano Mazzanti*: SME Performance, Innovation and Networking Evidence on Complementarities for a Local Economic System
CCMP	51.2007	*Kelly C. de Bruin, Rob B. Dellink and Richard S.J. Tol*: AD-DICE: An Implementation of Adaptation in the DICE Mode
NRM	52.2007	*Frank van Kouwen, Carel Dieperink, Paul P. Schot and Martin J. Wassen*: Interactive Problem Structuring with ICZM Stakeholders
CCMP	53.2007	*Valeria Costantini and Francesco Crespi*: Environmental Regulation and the Export Dynamics of Energy Technologies
CCMP	54.2007	*Barbara Buchner, Michela Catenacci and Alessandra Sgobbi*: Governance and Environmental Policy Integration in Europe: What Can We learn from the EU Emission Trading Scheme?
CCMP	55.2007	*David Anthoff and Richard S.J. Tol*: On International Equity Weights and National Decision Making on Climate Change
CCMP	56.2007	*Edwin van der Werf and Sonja Peterson*: Modeling Linkages Between Climate Policy and Land Use: An Overview
CCMP	57.2007	*Fabien Prieur*: The Environmental Kuznets Curve in a World of Irreversibility

(lxxxi) This paper was presented at the EAERE-FEEM-VIU Summer School on "Computable General Equilibrium Modeling in Environmental and Resource Economics", held in Venice from June 25th to July 1st, 2006 and supported by the Marie Curie Series of Conferences "European Summer School in Resource and Environmental Economics".
(lxxxii) This paper was presented at the Workshop on “Climate Mitigation Measures in the Agro-Forestry Sector and Biodiversity Futures”, Trieste, 16-17 October 2006 and jointly organised by The Ecological and Environmental Economics - EEE Programme, The Abdus Salam International Centre for Theoretical Physics - ICTP, UNESCO Man and the Biosphere Programme - MAB, and The International Institute for Applied Systems Analysis - IIASA.

2007 SERIES

CCMP	*Climate Change Modelling and Policy* (Editor: Marzio Galeotti)
SIEV	*Sustainability Indicators and Environmental Valuation* (Editor: Anil Markandya)
NRM	*Natural Resources Management* (Editor: Carlo Giupponi)
KTHC	*Knowledge, Technology, Human Capital* (Editor: Gianmarco Ottaviano)
IEM	*International Energy Markets* (Editor: Matteo Manera)
CSRM	*Corporate Social Responsibility and Sustainable Management* (Editor: Giulio Sapelli)
PRCG	*Privatisation Regulation Corporate Governance* (Editor: Bernardo Bortolotti)
ETA	*Economic Theory and Applications* (Editor: Carlo Carraro)
CTN	*Coalition Theory Network*