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SUSTAINABLE ECONOMIC DEVELOPMENT AND THE ENVIRONMENT: THEORY AND EVIDENCE

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Abstract

The relationship between growth and pollution is studied through a vintage capital model, where new technologies are more environmentally friendly. We find that once the optimal scrapping age of technologies is reached, an economy may achieve two possible cases of sustainable development, one in which pollution falls and another in which it stabilizes, or a catastrophic outcome, where environmental quality reaches its lower bound. The outcome will depend on countries' investment path and their propensity to innovate in environmentally clean technologies, both of which are likely to differ across economies. Empirical results using long time series for a number of developed and developing countries indeed confirm heterogenous experiences in the pollution-output relationship.

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1 Introduction

Since the seminal paper by Grossman and Kruger (1991) there has been considerable academic interest in the relationship between economic development and environmental pollution. Importantly the authors have shown empirically that the link between these follows an inverted U-shaped pattern, now commonly referred to as the Environmental Kuznets Curve (EKC). This suggests that lower income regions are 'too poor to be green', but as countries become richer they will naturally reduce their generation of pollution. Several recent studies, however, have put the existence and the exact shape of an EKC into question (Stern, 2004). In view of the recent policy developments, resolving this issue seems of particular importance. More precisely, the recent Kyoto Protocol has set reduction targets for pollutant emissions to which developed countries are expected to commit themselves to, but from which developing countries are at the first instance exempt. This would suggest that policymakers are of the view that wealth on its own does not result in a - possibly sufficient - reduction in pollution, a stance which as of date has not yet been substantiated in the academic literature.

Arguably one of the main reasons for the lack of consensus on the existence of an EKC can be attributed to the fact that the number of theoretical underpinnings is relatively sparse and hence that the mechanisms underlying the link between pollution and development are probably not yet well understood (Dasgupta et al., 2002). The existing papers have borrowed from a broad range of theoretical frameworks to demonstrate the existence of the EKC. For example, Selden and Song (1995) show an inverted U-shaped relationship between pollution and output in a strictly neo-classical framework. Similarly, Brock and Taylor (2004)demonstrate by adding abatements to the standard Solow model that there will be an EKC. John and Pecchenino (1994) and John and al. (1995), in contrast, use overlapping generation models to highlight the same result. In their models, environmental quality declines when consumption levels are low, but given sufficient returns to environmental maintenance, environmental quality eventually improves. Building also on an overlapping generations political ecnomy framework,

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Jones and Manuelli (2001) have characterized the logistics of the EKC by modeling pollution as an externality where citizens choose between different policy instruments to limit it. Arguably the use of endogenous growth models may be particulary relevant to the understanding of the pollution-output link, since it allows one to lay down the conditions of sustainable economic development. Notably in this regard, Stokey (1998) uses an Ak model in order to introduce pollution in an endogenous growth framework and finds that inevitably an EKC will arise. Importantly, however, all of the existing models do not consider the decision of when to replace obsolete with newer technologies and how this may affect the pollution output relationship, but instead consider technological adoption to be exogenous. Clearly though, if one assumes, as would be more realistic in most cases, that older technologies are more environmentally unfriendly, then the decision when to scrap these is likely to be an important determinant of the extent of pollution generation.

In the current paper we thus explicitly model how the decision to scrap obsolete technologies affects the relationship between economic development and pollution. In order to do so we build on the Schumpeterian framework of Aghion and Howitt(1998) by introducing a vintage capital structure, where the law of motion of environmental quality will depend on the pollution flow and some upper limit on environmental quality that takes into account the exhaustibility of resources.[1] In this context, we diverge from the existing literature on the pollution-output relationship by making the explicit distinction between environmental quality and pollution. Arguably it is important to do so since the very notion of sustainable development refers to some self regeneration capacity of ecosystems, as originally defined by Daly (1990, 1991) and now commonly used by the World Bank (1991a and 1991b). Finally, we explicitly assume that new technologies are more environmentally friendly, allowing us to shed light on the mechanisms through which the environmental quality affects growth performance following technological adoption.

Using our model we show that a reduction in environmental pollution during the industrialization process is only possible when the optimal rate of technological adoption has been reached. However, reaching this point will not necessarily guarantee that pollution decreases. Rather, we identify the three possible outcomes concerning the relationship between pollution

[1] The use of vintage capital models, which were launched in the early 1960s' formalize Schumpeter's idea of "creative destruction", have become increasingly popular in the economics literature.

and economic development, where these depend on the rate of growth of investment relative to the rate of growth of environmental friendliness of technological improvement. First, there is the case that we term *weak sustainable development* where investment, consumption, and output increase at a constant rate, the level of pollution stabilizes, but environmental quality improves. Second an economy may achieve *strong sustainable development*, where investment, consumption, and output improve at a constant, but lower rate than under the former scenario, while pollution is decreasing. This latter case is what constitutes the EKC. Finally, there may be the case where pollution increases unboundedly and environmental quality reaches its lower bound in finite time, which we refer to as the *catastrophic development*.

Our theoretical predictions have potentially important empirical implications in terms of seeking evidence for the EKC. For one, they suggest that there could be considerable heterogeneity across countries in their pollution-output relationship experience, depending on their relative investment growth rates and the rate at which the environmental friendliness of their technology improves. More preciselys, countries may not only differ in the rate and when they reach the point along their development path at which they could potentially reduce their pollutant emissions, but this reduction is not guaranteed. Thus, the shape of the pollution-output relationship can differ widely across countries, so that the use of cross-country panel data sets to seek evidence for the existence of an EKC - a now common practice in the literature - may be flawed. Instead it may be more insightful to study the pollution-outcome link by examining countries individually. Additionally, if one wants to capture the full pattern of how industrialization affects environmental quality in individual countries, one is likely to require long time series data, since the possibility of achieving a reduction in pollution may feasibly happen at a very early stage of economic development. As a first attempt in this direction, we thus here use individual long time series on carbon dioxide emissions and an indicator of economic development for a number of developed and developing countries and rely on a nonparametric kernel regression estimator, which places little restriction on the functional form of the relationship between pollution and output. Our results do indeed provide evidence of heterogeneous experiences across the countries examined.

The rest of the paper is organized as follows. A vintage capital model is presented in Section 2. In particular, we proof the existence of a balanced growth path, and show that it can be reached in finite time. In section 3, the long time series data, the empirical framework, and the econometric results are displayed. A general discussion and conclusions are provided in Section

4.

2 The model

In this section, we first present a standard vintage capital model, where we add an equation of motion representing environmental quality. We then derive the transition dynamics and the conditions under which a balanced growth path exists. In particular, we are able to fully characterize the optimal scrapping path, which is usually not the case in these types of models.

2.1 A vintage capital structure

Consider an economy with a constant population level, where the labor market is perfectly competitive, and the production sector produces only one final good, which can be assigned to consumption or investment and plays the role of the numeraire.

Production Sector At time $t > 0$, per capita output $y(t)$ is assumed to follow a vintage capital rule

$$y(t) = \int_{t-T(t)}^{t} i(z)dz. \tag{1}$$

where $0 < T(t) < \infty$ represents the vintage of the oldest machine in use, and $i(z)$ is per capita investment in a machine of age z. Define the life expectancy of a machine as $J(t) = T(t + J(t))$, i.e., the expected life of a machine at time t is equal to the scrapping time $T(\cdot)$, evaluated at $t + J(t)$, which corresponds to the time when this new machine will be scrapped in the future.

As can be seen from (1), we, in contrast to Stokey (1998), do not consider the level of pollution as an input in the production sector. Instead, we allow pollution to enter consumers' utility function. Thus we are assuming that although the firm has the right to pollute, consumers also have the right to refuse buying goods from 'dirty' industries. Consequently, if a good is produced in such an industry, returns to capital will decrease with the employed technology. Hence, the firm is forced to scrap the old dirty machines and replace them by new cleaner ones, which in turn can be considered as an endogenous progress.

Environmental Sector In this economy, household agents care not only about their per capita consumption level $c(t) > 0$, but also pay attention to environmental quality. Following Aghion and Howitt (1998, Chap.5), we assume that there is an upper limit to environmental quality, denoted by $\overline{E}$. We measure $E(t)$ as the difference between the actual quality and this upper limit. Thus, environmental quality will always be negative. The equation of motion of environmental quality is given by

$$\dot{E}(t) = -qE(t) - \int_{t-T(t)}^{t} i(z)e^{-\gamma z}dz, \tag{2}$$

where $q > 0$ is the maximum potential rate of recovery of environment, $\gamma > 0$ is the rate at which technology's environmental friendliness improves, and $P(t) = \int_{t-T(t)}^{t} i(z)e^{-\gamma z}dz$ measures pollution.[2] One should note that from equation (2) pollution is a side-product of investment $i(z)$ in the production sector. Implicit in equation (2) is the assumption that new machines are less polluting than older ones.[3] Using a newer vintage leads henceforth to reduced pollution per input.

Furthermore, since our main point in this paper is sustainable economic development, we assume that environmental quality also has a lower limit, which we will refer to as the *catastrophic threshold*. This, in turn, implies that the optimal growth path, if it exists, will be constrained as follows

$$\underline{E} \leq E \leq 0.$$

Finally, per capita output $y(t)$ can be consumed, $c(t)$, or invested in a vintage capital good, $i(t) \geq 0$,

$$y(t) = c(t) + i(t). \tag{3}$$

[2]Here we use the concept of a *"cleaner" technological progress* instead of *abatement*. Copeland and Taylor (2003, Chap.2) however show that the two approaches are identical. Note also that in our framework, environmental quality is not just the inverse of pollution, given we introduce q, which is the self regeneration rate of nature. As an example of the self regeneration process, it has for instance been shown that in the case of carbon dioxide, in European forests, carbon uptake ranges up to 6.6 tonnes of carbon per hectare per year, according to the type of tree and the climate (for more details, see Valentini et al., 2000).

[3]Grossman (1995) already noticed the effect of economic growth on the quality of the environment, since wealthier countries can afford to spend more on research and development, and thus, substitute dirty technologies with cleaner ones.

Central Planner The central planner's objective function will entail per capita consumption and environmental quality. More particularly, the planner will choose the paths of consumption and environmental quality in order to maximize the instantaneous utility of the infinitely lived representative household,

$$\max_c \int_0^\infty U(c,E)\; e^{-\rho t}dt = \max_c \int_0^\infty [\beta c(t) + (1-\beta)E(t)]e^{-\rho t}dt, \tag{4}$$

subject to (2), (3), and

$$J(t) = T(t + J(t)), \tag{5}$$

where $\rho > 0$ is the constant time preference, $0 < \beta \leq 1$ is a weight parameter between consumption goods and environmental quality, and $i(z)$, $z \leq 0$ and $E(0)$ are given functions. Furthermore we assume that $0 < \gamma < \rho < 1$, which are necessary and sufficient conditions for the existence of a balanced growth path in an exogenous growth model.[4]

2.2 Optimal Scrapping Rule

This section investigates the transitional dynamics from any initial investment profile and environmental condition towards the balanced growth path (BGP), if it exists. The BGP is defined as the path along which consumption, investment, output, and environmental quality grow at constant rates, while the scrapping age T and optimal life expectancy J are finite constants. We proceed as follows. First, we assume there exists a finite time $0 \leq t^* < \infty$, such that the interior solutions begin at t^*, and we derive optimal conditions that should be verified whenever we reach t^*. Second, we prove the existence of t^*. Third, we compute the transition dynamics during period $0 \leq t < t^*$, and characterize the optimal conditions on investment and output, given the scrapping age and the BGP.

After changing the order of integrals and rearranging the terms, first order conditions with respect to $i(t)$ and $J(t)$ are given by

$$\beta e^{-\rho t}\left(\frac{1-e^{-\rho J(t)}}{\rho} - 1\right) = e^{-\gamma t}\int_t^{t+J(t)} e^{-\rho z}\mu(z)dz; \tag{6}$$

[4]In order to obtain explicit solutions, we avoid more general utility functions. While general utility functions would allow us to write down optimal conditions as in Ramsey type models, the equilibrium conditions for such an economy would give rise to a mixed-delay differential equation system with endogenous leads and lags (see Boucekkine et al., 1997).

$$\mu(t) = \beta e^{\gamma(t-T(t))}. \tag{7}$$

The co-state variable of $E(t)$ satisfies

$$\dot{\mu}(t) = (\rho + q)\mu(t) - (1 - \beta), \tag{8}$$

and the transversality condition is

$$\lim_{t\to\infty} e^{-\rho t}\mu(t)E(t) = 0.$$

Equation (8) together with its transversality condition is Tobin's q in the sense of environmental quality, which describe the shadow value of environmental quality. As in the optimal investment profile, this shadow value determines the optimal investment strategy (6), and the optimal scrapping rule (7).

Equation (6) states that the optimal investment strategy should be such that at time t the discounted marginal productivity during the whole lifetime of the capital acquired in t exactly compensates for both its discounted operation cost and its discounted environmental shadow value. The first term on the left hand side is the discounted marginal productivity during the whole lifetime of the capital acquired in t, and the second term is the marginal purchase cost at t normalized to one. The right hand side is the discounted environmental shadow value at t.

The optimal scrapping rule (7) shows that a machine should be scrapped as soon as its operation cost with respect to consumption no longer covers its market value of environmental quality.

2.2.1 Balanced growth path

The BGP is defined by a constant optimal scrapping age and constant rates of growth for the other endogenous variables.

Substituting (7) into (6), we obtain straightforwardly

$$e^{-\rho t}\left(\frac{1 - e^{-\rho J(t)}}{\rho} - 1\right) = e^{-\gamma t}\int_t^{t+J(t)} e^{-\rho z} e^{\gamma(z-T(z))} dz.$$

Deriving with respect to t, using (5) and rearranging terms, it follows that

$$e^{-\gamma T(t)} = 1 - \rho + \gamma - \frac{\gamma}{\rho} + \frac{\gamma}{\rho} e^{-\rho J(t)}. \tag{9}$$

Theorem 1 *(Proof: see Boucekkine et al. (1997)) With $0 < \gamma < \rho < 1$, for $t > t^*$, the unique differential interior solutions of $T(t)$ and $J(t)$ are given by*

$$J(t) = T(t) = T^*,$$

where T^* is the positive fixed-pointed of function $F(\cdot) : R_+ \to R_+$, with $R_+ = \{x \geq 0\}$, and for any $x \geq 0$,

$$F(x) = -\frac{1}{\gamma} \ln \left(1 - \rho + \gamma - \frac{\gamma}{\rho} + \frac{\gamma}{\rho} e^{-\rho x} \right).$$

One should note that while the optimal scrapping age does not depend on the weight between consumption goods and environmental quality, it does depend on consumers' time preference and on the technology program. Thus, different economies may highlight different optimal paths. Moreover the above parameters and technological progress do not guarantee that a BGP can be reached. In the following, we are going to deduce the conditions, under which an optimal BGP could be reached.

Suppose investment grows at a constant rate g, with investment level $\bar{i}$, i.e. $i(t) = \bar{i}e^{gt}$. From this we can easily see that investment, consumption, and output grow at the same constant rate. Reconsidering equation (2), and using basic ordinary differential equation techniques, we obtain that, for $t > t^*$,

$$E(t) = E(t^*)e^{-qt} - e^{-qt} \int_{t^*}^{t} e^{qs} \int_{s-T^*}^{s} i(z)e^{-\gamma z} dz ds. \qquad (10)$$

For a more explicit form of (10), see Appendix.

From (1) and (10), it follows,

Theorem 2 *Suppose $0 < \gamma < \rho < 1$, and let $t > t^*$. (a) If furthermore $\gamma < \frac{\rho}{2}$, there is a BGP, where investment, consumption, and output grow at constant rate γ, the growth rate of environmental quality is $q > 0$, and pollution levels are stable. Furthermore, sustainable growth is guaranteed and environmental quality will permanently improve, though never reach its upper bound. (b) When $g > \gamma$, there is no BGP and the economy converges towards the catastrophic outcome in finite time. We refer to this case as the over-investment case. (c) If $g < \gamma$, output, investment, and consumption grow at rate g, where g will be either $0 < g < \min\{\gamma, 1 - e^{-gT^*}\}$, or $g = 0$. In this case, environmental quality will constantly improve and tend to the upper bound in the long run, but not at a constant rate of growth. Pollution is always decreasing at rate $\gamma - g$. We call this case the under-investment case.*

In point (a), condition $\gamma < \frac{\rho}{2}$ ascertains that an interior solution of consumption is achieved.[5] The statement about the catastrophic outcome in point (b) directly results from the assumption concerning a lower bound in environmental quality. In other words, the environment can not infinitely worsen. The intuition for this is obvious. Consider simultaneously consumption and environmental quality. If the constant scrapping time T^* is reached, the investment growth rate should be the same as the technological progress rate in order to keep sustainable growth of output, while environmental cleaning is done by nature's self regeneration ability. However, this self regeneration will never allow environmental quality to reach its upper bound (point (a)). In the case of over-investment in newer technologies, i.e., $g > \gamma$, the environment will be totally destroyed in finite time (catastrophic case, point (b)). Finally, if keeping investment and consumption at a steady state level (i.e., $g = 0$), since cleaner machines are contiguously employed, it is obvious that the environment will improve (point (c)).

One should note that although T^* is reached does not imply that the cleanest machine is found. New techniques always appear, which are more environmental friendly. However, scrapping the old machines earlier or later than T^* always worsens either consumption or environmental quality, or both.

2.2.2 Transition dynamics and optimal scrapping time

Two cases can be distinguished, corresponding to different levels of development. The first case corresponds to a situation where countries scrap too fast, i.e., $T(0) < T^*$. Intuitively, one could think of the *developed country* case, where economies start with a relatively high stock of machines. Conversely, the *developing country* case would correspond to the case where economies have initially a relatively low stock of machines.

With the following Assumption 1, in the Appendix, we show the following result

Assumption 1. $e^{-\gamma T(0)} > \frac{1-\beta}{\beta(\rho+q)}$.

Theorem 3 *Given an investment profile of a country, if initially $T(0) < T^*$, then this economy should instantaneously jump to the optimal scrapping*

[5] It can easily be shown that along the BGP, $c(t) = y(t) - i(t) = \bar{i}r^{\gamma t}\left[\left(1-e^{-\gamma T^*}\right)/\gamma - 1\right] > 0$, implying $1 - e^{-\gamma T^*} > \gamma$, where γ is the growth rate of investment. Given (9), it follows that $1-e^{-\gamma T^*} = \rho-\gamma+\frac{\gamma}{\rho}[1-e^{-\rho T^*}] > \gamma$. A sufficient condition for this inequality to hold is $\rho > 2\gamma$.

path. In this case, $t^* = 0$. Conversely, if $T(0) > T^*$ and Assumption 1 hold, there exists a time t^0, t^1, such that, $0 < t^0 < t^1 < \infty$. Moreover,

$$T(t) = \begin{cases} t - \dfrac{\rho+q}{\gamma}t - \dfrac{1}{\gamma}\ln\left(e^{-\gamma T(0)} - \dfrac{1-\beta}{\beta(\rho+q)}\left(1 - e^{-(\rho+q)t}\right)\right), 0 \le t < t^1, \\ T^*, \quad t \ge t^1, \end{cases}$$

which is decreasing with time t, if $t^0 \le t < t^1$, and $t^* = t^1$.

Remark 1. Under this kind of vintage capital setting, it is the first time to our knowledge that a clear and explicit transition dynamic has been defined. For this linear utility function, the immediate jump corresponds to the case of consuming all output for some while, whereas the other case would correspond to investing all output, until scraping age T^*. That is, in finite time the corner solutions converge to interior solutions.

Intuitively, since the endogenous scrapping time $T(t)$ is increasing with the initial scrapping time $T(0)$, if an economy starts with a relatively high stock of machines, and scraps too fast, it is impossible, for any positive t, that $T(t)$ reaches T^*, the optimal path, given the endogenous scrapping program is decreasing with time. Henceforth, the only way to reach the optimal path is to immediately jump to this optimal path. Aghion and Howitt (1998, Chap.5) developed this idea under a Schumpeterian framework. However, they only show that there is some initial value of capital for this to happen, while we provide the explicit conditions under which this jump could indeed occur.

For the developing economy case, the instantaneous jump to the optimal path could be impossible (even starting from a corner solution, i.e., zero consumption and all output invested in physical capital). Instead of an immediate technology adoption, which would compensate for the initial low level of vintage physical capital, the new technology is supposed to be costly, implying the existence of time delays of adoption. For relatively poor economies, older and relatively environmental unfriendly machines still need to be employed for a certain period, until the optimal path is reached.

2.3 The link between pollution and output

As mentioned earlier, when $T(0) > T^*$, the economy starts with a relatively low stock of capital. Then in order to reach the interior solution (and thus the optimal path if there is one) as quickly as possible, one possibility is to invest all output as mentioned in Remark 1. In this case, starting from a corner solution, the economy's subsequent pollution, when $0 < t < t^*$, will be

$$P(t) = \int_{t-T(t)}^{t} y(z)e^{-\gamma z}dz.$$

Indeed, pollution increases with the accumulation of output $y(\cdot)$ during all periods in which the machine is in use. Moreover, there is also a *delay effect* on pollution coming from output.

If $t > t^*$, that is, the optimal scraping age is reached, then three different cases may occur.

If one were along the balanced growth path, i.e., the growth rate of investment is the same as the rate at which environmental friendliness of technology improves, it follows

$$y(t) = \frac{\bar{i}e^{\gamma t}}{\gamma}(1 - e^{-\gamma T^*}), \quad P(t) = \bar{i}T^*.$$

In this case, pollution is independent of output and time, but output is increasing with time t.

However, if one is not on the balanced growth path, it follows that

$$P(t) = \int_{t-T^*}^{t} \bar{i}e^{(g-\gamma)z}dz = \frac{\bar{i}}{g-\gamma}e^{(g-\gamma)t}(1 - e^{-(g-\gamma)T^*}),$$

and

$$\frac{P(t)}{y(t)} = \frac{g(1 - e^{-(g-\gamma)T^*})}{(g-\gamma)(1 - e^{-\gamma T^*})}e^{-\gamma t}.$$

It is easy to see that in this case of under-investment, where the investment rate is lower than the rate at which environmental friendliness of technology improves, pollution is decreasing over time due to the fact that $g < \gamma$. However, for the case of over-investment, the investment rate is higher than the rate at which environmental friendliness of technology improves, and it follows that pollution is increasing with time, while the pollution-output ratio is always positive and decreasing over time.

Theorem 4 *Suppose that* $0 < \gamma < \frac{\rho}{2}$.

(i) For any $t > 0$*, the pollution-output ratio is decreasing over time.*

(ii) For $0 < t \leq t^*$*, during the transition, pollution is increasing with respect to output.*

(iii) If $t > t^*$*,*

- *and if the BGP is reached, pollution is independent of output and time, and only depends on the optimal scrapping age and the turning point of investment in the economy [weak sustainable development];*
- *and we are in the under-investment case mentioned in Theorem 2, then pollution is decreasing with time [strong sustainable development];*
- *and we are in the over-investment case, pollution will be increasing over time [catastrophic development].*

The assertion of a decreasing pollution-output ratio in statement (i) is proved in the Appendix.

Contrary to previous studies, our analysis arguably allows for a more intricate understanding of the link between output and pollution generation. The three possible cases once the BGP is reached (i.e., $g = \gamma$ and $T = T^*$) can be easily illustrated with the help of Figure 1. Accordingly, pollution may remain at the level $P(t^*)$, generating a flat relationship between output and pollution, although environmental quality improves due to nature's self-regeneration ability [weak sustainable development]. There is also the possibility that the investment rate is lower than the rate at which environmental friendliness of technology improves, so that pollution decreases and environmental quality converges towards its upper bound [strong sustainable development]. Lastly, it may be that after having reached the optimal scrapping age, pollution continues to increase and environmental quality reaches its lower bound in finite time [catastrophic development]. This case arises whenever the investment rate outpaces the rate at which environmental friendliness of technology improves.

3 Empirical analysis

Our theoretical model suggests three potential scenarios that the output-pollution relationship may take after the economy has reached the optimal scrapping age t^*, where the trajectory will depend on the investment growth rate and the rate at which environmental friendliness of technology improves. Arguably, in the real world, these are likely to differ across countries at least to some extent, and thus, one would not necessarily expect countries to follow the same output-pollution path.

3.1 Data and econometric specification

Our theoretical model shows that there may be a possible change in the link between pollution and output once an economy has reached the optimal age of changing technology, t^*. This in turn means that our data has to cover the periods before and after t^* in order to capture a possible EKC. Most existing cross-country empirical studies on the EKC are, however, based on data after WWII on sulfur and carbon dioxide emissions stemming from the Historical Global Sulfur Emissions database (Lefohn et al., 1999), and the World Resource Institute (People and Ecosystems CD-rom). Arguably in the context of our model, this is a strong limitation, since it seems reasonable to assume that many developed countries have attained the path of optimal scrapping age, as we define it, some time before WWII. Indeed, as highlighted by Comin and Hohijn (2004), the rate of adoption of new technologies is linked to higher levels of income per capita, human capital, openness, which are all features shared by developed countries.

We thus, in the present study, instead use long historical series (up to 250 years) to study the output-pollution relationship. Although this restricts the number of countries that can be examined to 26, of which 19 are developed, one can be more confident that in at least the individual series of developed countries one is able to capture periods before and after the potential turning point. In this regard we use data on carbon dioxide from the Carbon Dioxide Information Analysis Center compiled by Marland et al. (2003), where coverage goes as far back as 1751 for some, but no later than 1901 for others, and extends to up until 2000. The data constitutes total national carbon dioxide emissions from fossil-fuel burning, cement manufacture, and gas flaring. In order to get carbon dioxide per capita figures, we divided these series by population data from the Maddison (2001, 2003) database. The same source was also used for country measures of GDP/capita, except for the US and the UK, where we have used GDP data from Johnston and Williamson (2003), respectively Clark (2004) and Maddison (2001, 2003).[6]

In order to allow for the possible non-linearity in the pollution-output relationship we implemented a kernel regression estimator

$$p(t) = g[y(t)] + u(it) \tag{11}$$

where $p(.)$ stands for pollution per capita, $y(.)$ for per capita output, and $u(it)$ is a disturbance term. Accordingly, if we allow $g(.)$ to be a smooth

[6] We, as in previous studies on the pollution-output relationship, use per capita measures in order to neutralize for size effects.

and continuous, possibly non-linear, function of $y(.)$, then the estimation of $g[y(.)]$ can be made by

$$\hat{g}[y(t)] = \hat{m}_p[y(t)]$$

where $\hat{m}_p[y(.)]$ is the nonparametric Nadaraya-Watson estimate (Nadaraya (1964) and Watson (1964)) of $E[p(.)/y(.)]$, such that, for a given continuous, bounded, and real shape function, $K_h()$, that integrates to one with a smoothing parameter h, $\hat{m}_p[y(.)]$ is defined as

$$\hat{m}_p[y(.)] = n^{-1}\frac{\sum_{i=1}^{n} K_h(y-y_i)\,p_i}{\sum_{i=1}^{n} K_h(y-y_i)}.$$

The appeal of this estimator lies in its very flexible approach to nonlinearity by allowing the relationship between pollution and output to vary over all values of per capita output. In our context this is arguably particularly important since we have no priors about the shape of the curve for individual countries. Moreover, our model does not provide any structural equation or a reduced form that could be straightforwardly confronted by our data.[7]

In implementing (11) on our data we used a Gaussian kernel and an optimal bandwidth for h (see Fox (1990)). Finally, one should note that, given the nonparametric nature of the estimator, the estimate of the relationship cannot be subjected to the kind of standard statistical tests (such as an F-test or a t-test) of parametric regressions. However, it is possible to calculate upper and lower point-wise confidence intervals, as suggested by Haerdle (1990). We depict these at the 1st and 99th percentiles distribution of GDP per capita values and at every fifth percentile in between these points. This depiction is convenient for gauging how the density of the sample affects the approximation bias, since these are inversely related.

3.2 Econometric results

In line with our earlier argument we proceeded to estimate equation (11) for the countries in our sample individually. We first depict results for the US and the UK for which we have the longest time series (201 and 250 years, respectively) in Figures 2 and 3, respectively. These, as can be seen from the

[7] Further studies having used semi and non-parametric estimation techniques measuring the EKC include Azomahou et al. (2006), Bertinelli and Strobl (2005) and Millimet et al. (2003) among others.

tightness of the confidence bands around the estimated curve, are relatively precisely estimated. In terms of their actual shape one finds that after a steep increase, the pollution-output relationship flattens in both cases. Importantly, however, it is clear in both cases that there is no evidence of an EKC. One may also take note that the turning point occurs for both countries well before WWII - between the second half of the 19th century and WWI for the US, and around the industrial revolution for the UK. This would seem to substantiate our argument for using long time series when examining the output-pollution relationship for countries individually.

We also estimated equation (11) for our other 17 developed countries for which data for a shorter time, but at least 100 years, was available.[8] Results for these are shown in Figure 4. Accordingly, one obtains for many of these roughly a similar picture as for the US and UK cases, i.e., an upward sloping part that flattens out at some point. For Australia and New Zealand the curve seems, in contrast, to steadily increase. A similar statement can be made, although much more cautiously given that their confidence bands are relatively wide, for Norway as well as Spain and Portugal. Finally, Germany, and to some extent France, Belgium, and Sweden, seem to be characterized by a more inverted U-shaped relationship between output and pollution, although again, for the three latter countries the confidence bands suggest relatively imprecise estimates.

While this observed heterogeneity in the pollution-output relationship is consistent with our theoretical predictions, in our model such heterogeneity would crucially hinge on cross-country differences in terms investment and environmental soundness of technologies. As noted earlier, however, actual data on investment and environmental soundness of technologies for long enough time periods does not exist. Nevertheless, one can use proxies constructed from the existent limited data to gauge to a very rough extent whether the heterogenous experiences of the countries is consistent with regard to these two parameters. In this regard, we use data on the share of pollution abatement costs in GDP for a set of OECD countries, as published in Linster and Zegel (2003), as an indicator of the environmental friendliness of technologies employed in individual countries.[9] Given the rather

[8] The average number of years of observations was 134 years. Details by country can be gathered in Table 2 in the Appendix.

[9] Pollution Abatement and Control expenditure are defined as purposeful activities aimed directly at the prevention, reduction and elimination of pollution or nuisances arising as a residual of production processes or the consumption of goods and services. It comprises the flow of investment, internal current expenditure, subsidies and fees that is directly aimed at pollution abatement and control, and which is incurred by the public

patchy nature of the data, we computed average figures of these shares for the period 1990-1999. Data on investment rates was taken from Heston et al. (2002) and to be consistent we used these to calculate country averages over the same period. In order to derive some relative comprehensive measure we normalised the abatement and investment figures by their overall cross-country mean, and then calculated the ratio of these normalised values as depicted in the third column of Table 1, alongside a visual evaluation of the slope of the right part of each country's pollution-output curve. One should note in this regard that values of the ratio less than one indicate that abatement expenditures were low relative to investment, whereas values above the mean indicate the contrary. Thus for the latter, according to our theoretical model, one would expect a relatively more positive slope in the pollution-output relationship than for the former.

As can be seen from Table 1, one finds that amongst the nine countries with values below one, six experienced a rise in the curve, one a decrease, while for the remainder the right hand part of the pollution-output relationship flattened out. In contrast, of those seven with values greater than one, no country is characterised by a rising right hand side portion of their curve. Rather, three experienced a fall, while for the remainder the curve flattened out. Thus, one can conclude that our simple calculations are mostly supportive of the theoretical predictions of our model.

We also depict our Kernel regression estimates for a number of developing countries in Figure 5. For these one finds that, except for Argentina, all are characterized by a continuously upward sloping pollution-output curve. According to our theoretical model, two explanations for this are plausible. Either these countries have not yet reached their optimal scrapping age, so that there continues to be an increasing pollution-output relationship, or it could be that the optimum scrapping age has been reached but the rate of investment growth is higher than the rate at which technology improves in terms of environment. This latter explanation is unlikely to be realistic, however, since generally developing countries have relatively (to developed countries) low rates of investment. For instance, in 2000, low income countries had rates of investment less than half compared to that of high income countries (Heston et al., 2002). A more likely explanation would instead be the former one, i.e., the actual scrapping age is not yet the optimal one. This is consistent with findings by Comin and Hohijn (2004), who note that "most of the technologies that we consider originate in advanced economies and are adopted there first. Subsequently, they trickle down to

sector, the business sector, private households and specialised producers of PAC services.

countries that lag economically". Moreover, it is well known that much of the technology imported into developing countries are through second hand machinery. For example, growth in the market for the resale of capital goods has recently been in the two digit figures and represents currently about 150 billion dollars annually (Janischweski et al., 2003). Notable cases include India where the ratio of used goods is about 75 per cent of all capital goods imports. The technologies embedded in imported secondhand machinery, however, tend to be much older than the state of the art and often have a dubious environmental record. As a matter of fact, it has been estimated that the export of second-hand cars to developing countries and emerging markets world-wide (approximately 3 million units a year) will create additional pollution of 1.8 million tonnes of carbon dioxide (Janischweski et al. (2003), Fig.5.4).

4 Conclusion

The continuing debate concerning the link between economic development and pollution, in particular with regard to the possible existence of an EKC, demonstrates that this issue is still of considerable interest to both academics and policymakers. However, while there is an abundance of empirical studies, generally generating mixed results, theoretical investigations have remained relatively scarce. In the present contribution, we shed new light on this debate by providing parameter conditions for an EKC.

Our theoretical model, which is particularly adapted to the kind of issue treated here since it allows for the possibility for newer technologies to be cleaner, points towards several major conclusions. First, an important distinction is made between pollution and environmental quality. While in general the EKC literature considers these two measures to be roughly the inverse of each other, we take account of nature's self regeneration capacity. This has important consequences for the interpretation of results in empirical studies using data on pollution given that stable pollution levels are not necessarily incompatible with sustainable economic development. Second, we are able to derive explicit conditions for the existence of a bell-shaped EKC in terms of countries' investment growth rates, and the rate at which their technologies improve in terms of environmental friendliness. Since these two parameters are in reality likely to be very different from country to country, it is thus important from an empirical point of view to examine countries individually, unless one can explicitly control for all the determinants of these two variables. Last, when studying the relationship between pollution and output our model demonstrates that it is important to distinguish between periods before and after the optimal scrapping age has been reached. While the link is always increasing before the stationary state, thereafter it will depend on countries' investment rates and willingness to improve technologies in terms of environmental friendliness. If one, as we argue above, examines countries individually, then one must necessarily use long time series since many countries are likely to have reached their optimal scrapping age considerable time ago.

With these points in mind we carried out an empirical study of a number of countries using long time series and find evidence that points towards very different experiences. Not only do our results suggest that some developed countries may have experienced their potential turning point well before the starting period of most current empirical analysis, but that their relationship between output and pollution thereafter has been fairly heterogenous - some rising, some falling, and others remaining fairly flat. As predicted in our model we find, in contrast, that for almost all developing countries in our sample the relationship is always upward sloping, potentially suggesting that these may have not yet reached the point at which an EKC may occur.

Although our analysis has highlighted a number of new aspects in terms of theoretical and empirical strategies, several issues remain unexplained in the present study. While we get clear cut parameter conditions determining the shape of the EKC once the optimal scrapping age has been reached, these parameters are assumed to be exogenous in our model. In terms of policy implications, however, it clearly would be worthwhile having more insight into whether, for instance, regulatory measures concerning the environment can be implemented in order to influence the output-pollution relationship. Alternatively, it may be interesting to investigate whether this could be done by providing incentives to invest in the environmental quality of technology. Moreover, the fact that for almost all developing countries studied the pollution-output relationship is increasing, thus suggesting that these have not yet reached the optimal scrapping age, raises a number of questions which would have important policy implications. In how far do imports of older technologies slow down the process to reach a level of *clean* development? Would it be possible to supporting these countries in leapfrogging the adoption of older technologies in order to fasten the pace towards cleaner development? A vintage capital structure, as introduced here, may provide an ideal framework to address all of these issues.

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5 Appendix

5.1 Explicit solution of the environmental equation (10)

Equation (10) can be rewritten

$$E(t) = \begin{cases} \xi(t^*) + \dfrac{\chi}{\theta\,(q-\theta)}\left[e^{-\theta t} - e^{-(q\tau+\theta t^*)}\right], \text{ if } \ 0 < g \neq \gamma, g \neq \gamma - q; \\ \xi(t^*) + \dfrac{\chi}{\theta} e^{-qt}\tau, \text{ if } \ 0 < g = \gamma - q; \\ \xi(t^*) + \dfrac{\psi}{-\gamma\,(\gamma - q)}\left[e^{-\gamma t} - e^{-(q\tau+\gamma t^*)}\right], \text{ if } \ g = 0, \ q \neq \gamma; \\ \xi(t^*) + \dfrac{\psi}{\gamma} e^{-qt}\tau, \text{ if } \ g = 0, \ q = \gamma; \\ \xi(t^*) + \dfrac{\bar{i}T^*}{q}\left[1 - e^{q\tau}\right], \text{ if } \ 0 < g = \gamma. \end{cases} \tag{12}$$

where $\xi(t^*) = E(t^*)e^{-qt}$, $\chi = \bar{i}(1 - e^{-(g-\gamma)T^*})$, $\psi = \bar{i}(1 - e^{\gamma T^*})$, $\theta = \gamma - g$, and $\tau = t - t^*$.

5.2 Proof of Theorem 3: Explicit solution for $T(t)$

In this appendix, we deduce the explicit form of $T(t)$, given the initial $T(0)$, and the optimal conditions (7) and (8).

Noting that equation (8) is a first order linear differential equation with initial condition $\mu(0) = \beta e^{-\gamma T(0)}$, we get

$$\mu(t) = e^{(\rho+q)t}\left[\beta e^{-\gamma T(0)} - \frac{1-\beta}{\rho+q}\left(1 - e^{-(\rho+q)t}\right)\right].$$

Combing this result of $\mu(t)$ with equation (7), we have

$$e^{-\gamma T(t)} = e^{(\rho+q-\gamma)t}\left[e^{-\gamma T(0)} - \frac{1-\beta}{\beta(\rho+q)}\left(1 - e^{-(\rho+q)t}\right)\right].$$

Hence,

$$T(t) = T(t; T(0)) = t - \frac{\rho+q}{\gamma}t - \frac{1}{\gamma}\ln\left(e^{-\gamma T(0)} - \frac{1-\beta}{\beta(\rho+q)}\left(1 - e^{-(\rho+q)t}\right)\right).$$

We can easily check that

$$\frac{\partial T(t; T(0))}{\partial T(0)} = \frac{e^{-\gamma T(0)}}{e^{-\gamma T(0)} - \frac{1-\beta}{\beta(\rho+q)}\left(1 - e^{-(\rho+q)t}\right)} > 0,$$

and

$$T'(t) = 1 - \frac{\rho + q}{\gamma} + \frac{1}{\gamma} \frac{\frac{1-\beta}{\beta} e^{-(\rho+q)t}}{e^{-\gamma T(0)} + \frac{1-\beta}{\beta(\rho+q)} \left(1 - e^{-(\rho+q)t}\right)}.$$

Notice that in the above equation, the last term on the right hand side is positive, decreasing with time t and converges to zero, but the first two terms on the right hand side are negative constant (due to $0 < \gamma < \rho < 1$). Therefore, there exists time t^0, such that, $T'(t^0) = 0$, and for $t > t^0$, we have $T'(t) < 0$. Hence in finite time t^1, $T(t^1) = T^*$. That complete the proof. $\diamondsuit$

5.3 Proof of Theorem 5: Pollution-output decreasing ratio

Denote

$$R(t) = \frac{P(t)}{y(t)} = \frac{\int_{t-T(t)}^{t} y(z) e^{-\gamma z} dz}{\int_{t-T(t)}^{t} y(z) dz}.$$

The derivative of $R(t)$ with respective to t is,

$$\begin{aligned} R'(t) &= \frac{1}{y^2(t)} \Bigg[y(t) \left(\int_{t-T(t)}^{t} y(z) dz e^{-\gamma t} - \int_{t-T(t)}^{t} y(z) e^{-\gamma z} dz \right) \\ &\quad - y(t - T(t))(1 - T'(t)) \Bigg(\int_{t-T(t)}^{t} y(z) dz e^{-\gamma(t-T(t))} \\ &\quad - \int_{t-T(t)}^{t} y(z) e^{-\gamma z} dz \Bigg) \Bigg] \\ &= \frac{1}{y^2(t)} \Bigg[y(t) \int_{t-T(t)}^{t} y(z) \left(e^{-\gamma t} - e^{-\gamma z} \right) dz \\ &\quad - y(t - T(t))(1 - T'(t)) \int_{t-T(t)}^{t} y(z) \left(e^{-\gamma(t-T(t))} - e^{-\gamma z} \right) dz \Bigg] \\ &< 0, \end{aligned}$$

where the last inequality comes from the fact that $T'(t) < 0$, and the fact that for $t - T(t) < z < t$, we have $e^{-\gamma t} < e^{-\gamma z} < e^{-\gamma(t-T(t))}$. $\diamondsuit$

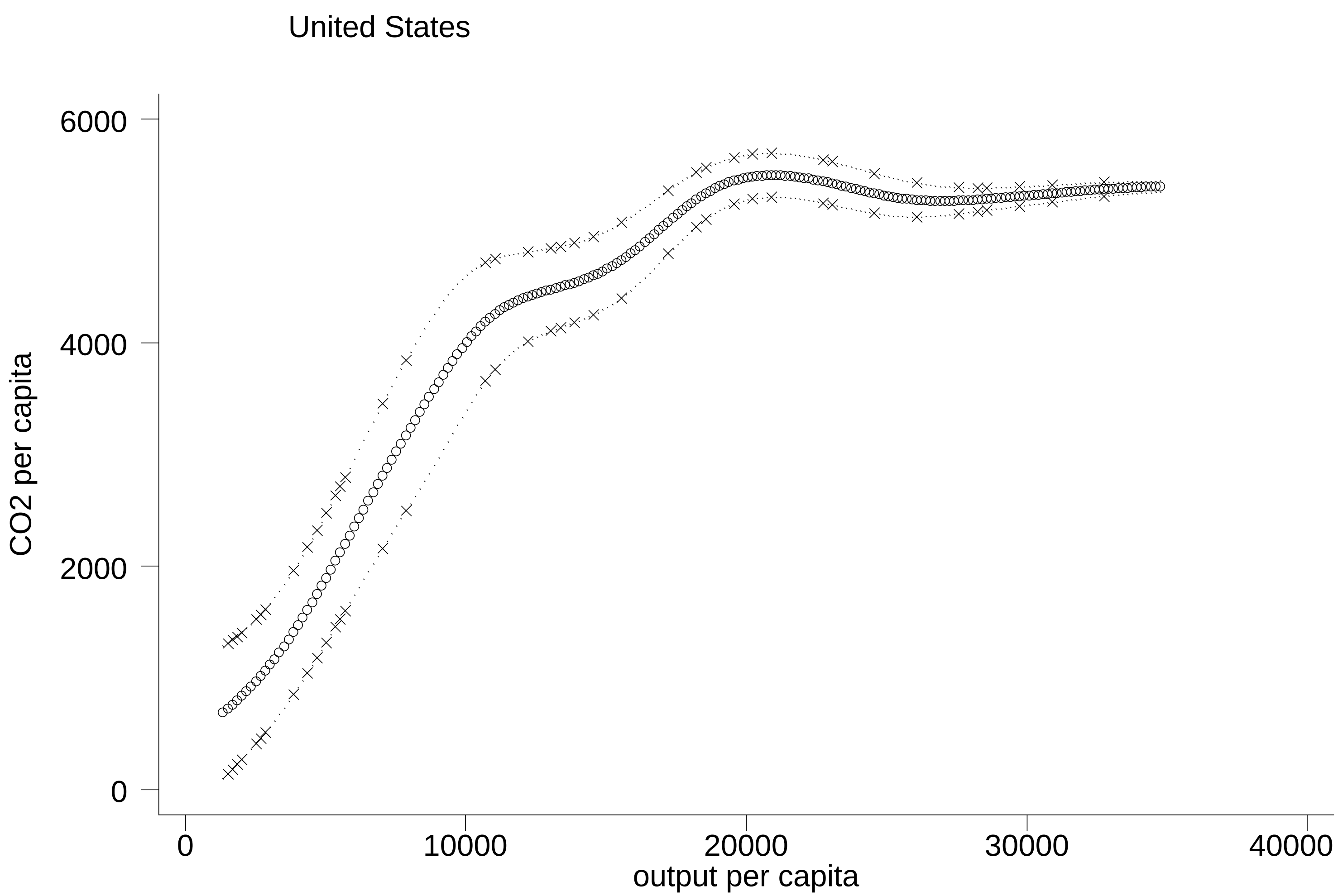

Fig. 2 - Non-parametric results, United States sample

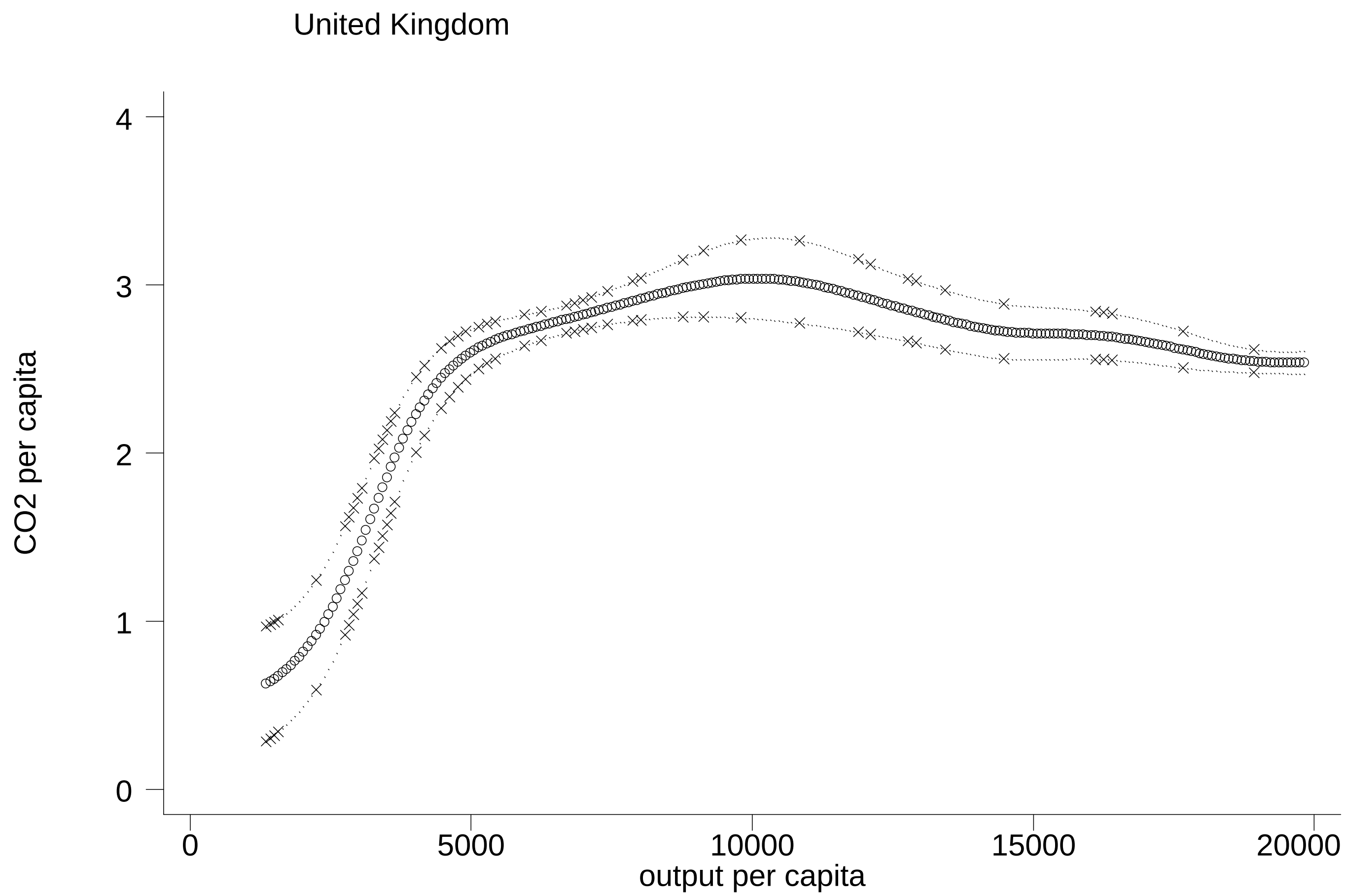

Fig. 3 - Non-parametric results, United Kingdom sample

Developed Countries

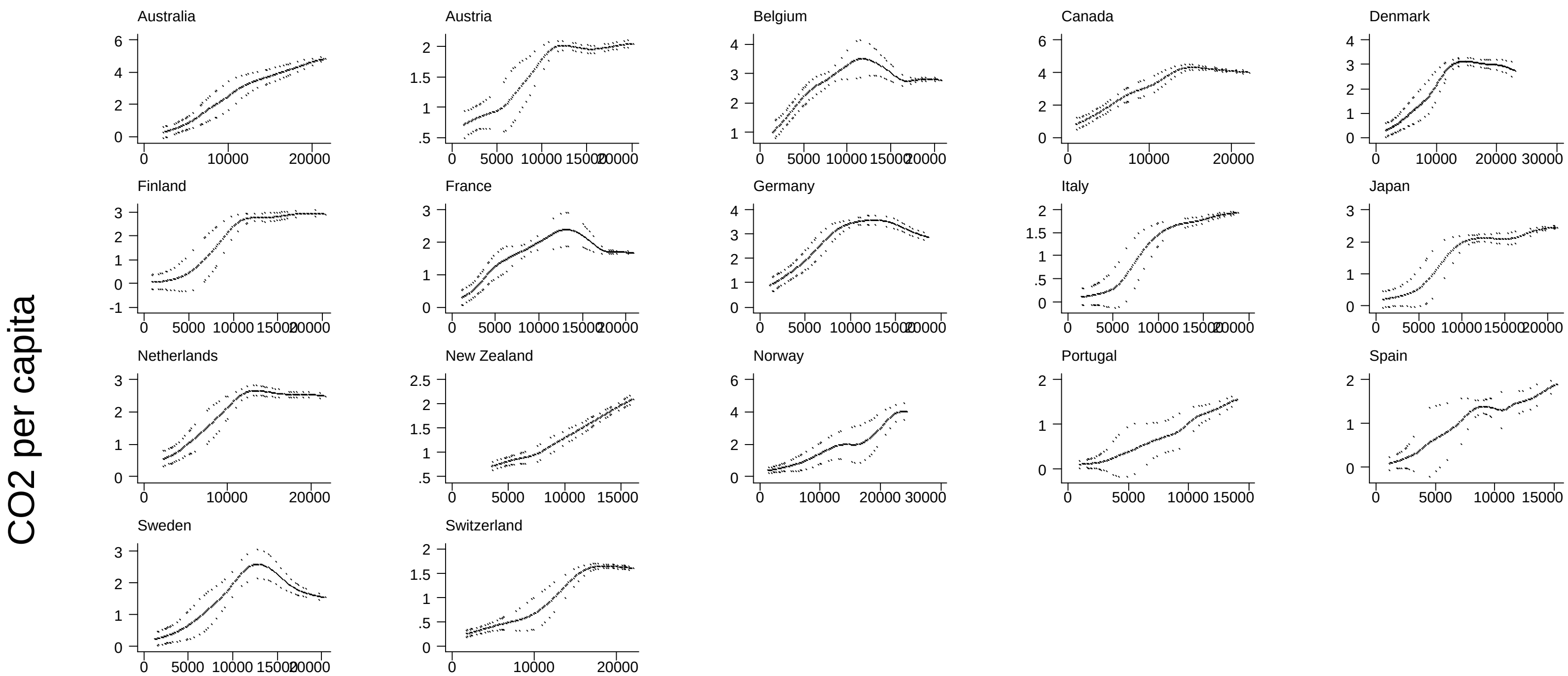

Fig. 4 - Non-parametric results, developed countries sample

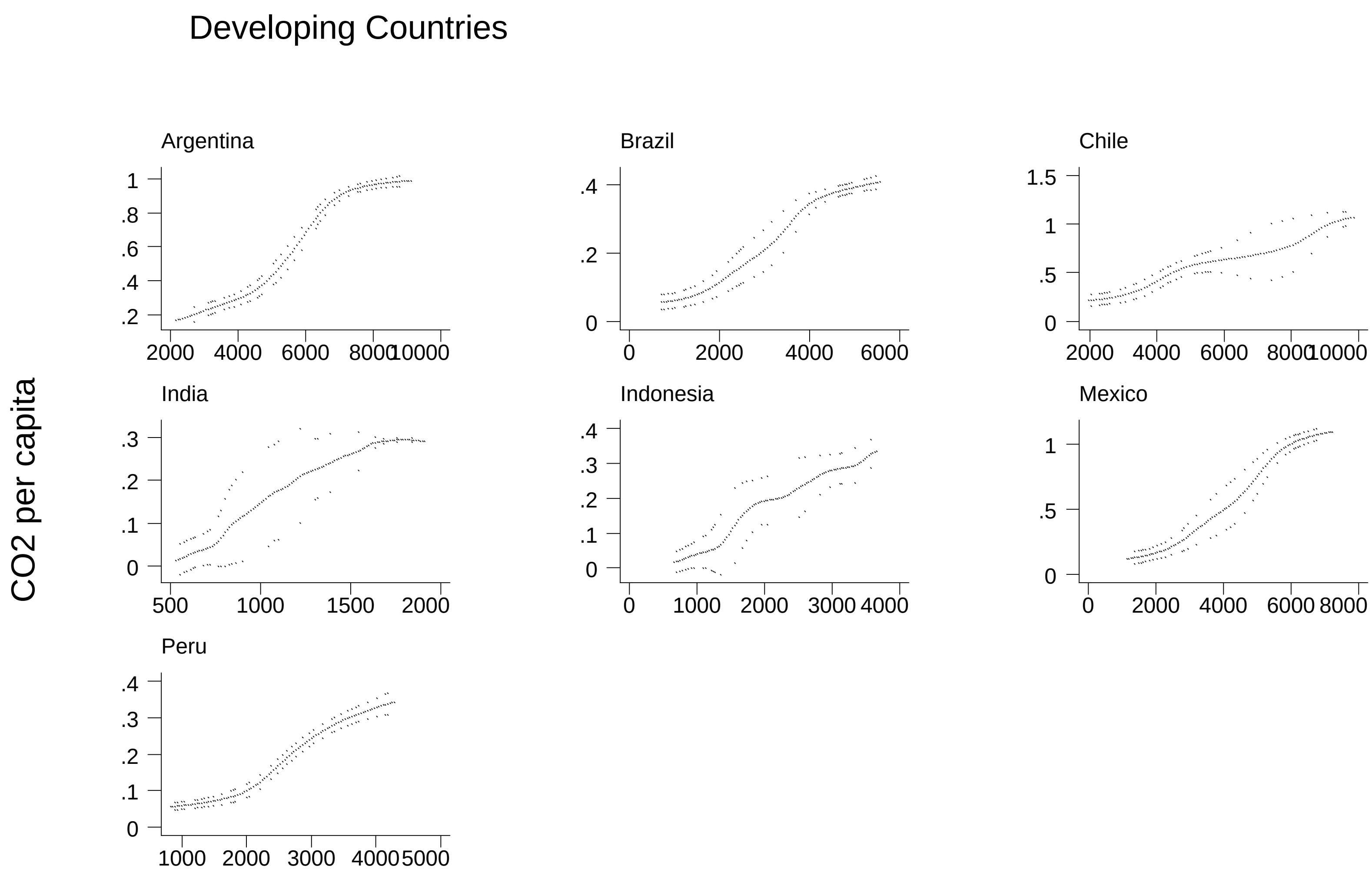

Fig. 5 - Non-parametric results, developing countries sample

Table 1 : Pollution abatement and investment shares of GDP in developed countries

	Pollution abatement and control expenditure as a percentage of GDP	Investment share of GDP (real shares in constant prices)	Ratio of normalized abatement on normalized investment	Slope of EKC according to econometric results
	Average 1990-1999			
Portugal	0.61	1.01	0.60	↑
Australia	0.62	0.98	0.63	↑
Italy	0.63	0.89	0.71	↑
United Kingdom	0.58	0.78	0.74	→
Japan	1.04	1.37	0.75	↑
Norway	0.95	1.13	0.84	↑
Finland	0.83	0.95	0.88	→
Sweden	0.75	0.84	0.89	↓
Canada	0.93	1.03	0.90	→
France	1.07	0.99	1.08	↓
Belgium	1.08	0.99	1.10	↓
Switzerland	1.26	1.14	1.11	→
Germany	1.24	1.01	1.23	↓
United States	1.18	0.88	1.34	→
Netherlands	1.50	0.94	1.59	→
Austria	1.73	1.07	1.61	→

Note: The last column of the table reports approximately to the slopes of the EKC in Figure 4, after countries have potentially reached their optimal scrapping age. (arrows refer to increasing, flattening or decreasing slopes)

Sources: Pollution Abatement and Control expenditure: Linster and Zegel (2003). Investment (PPP): Heston et al. (2002).

Table 2: Number of observation in the non-parametric estimations

	Number of years available per country
Argentina	*102*
Australia	*150*
Austria	*136*
Belgium	*156*
Brazil	*100*
Canada	*136*
Chile	*101*
Denmark	*158*
Finland	*141*
France	*181*
Germany	*153*
India	*117*
Indonesia	*105*
Italy	*140*
Japan	*131*
Mexico	*102*
Netherlands	*155*
New Zealand	*123*
Norway	*137*
Peru	*101*
Portugal	*131*
Spain	*151*
Sweden	*163*
Switzerland	*143*
UK	*250*
USA	*201*