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Environmental Kuznets Curves for Carbon Emissions: A Critical Survey

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Abstract
The empirical finding of an inverse U-shaped relationship between per capita income and pollution, the so-called Environmental Kuznets Curve (EKC), suggests that as countries experience economic growth, environmental deterioration decelerates and thus becomes less of an issue. Focusing on the prime example of carbon emissions, the present article provides a critical review of the new econometric techniques that have questioned the baseline polynomial specification in the EKC literature. We discuss issues related to the functional form, heterogeneity, "spurious" regressions and spatial dependence to address whether and to what extent the EKC can be observed. Despite these new approaches, there is still no clear-cut evidence supporting the existence of the EKC for carbon emissions.

JEL classifications: C20; Q32; Q50; O13

Keywords: Environmental Kuznets Curve; Carbon emissions; Functional form; Heterogeneity; "Spurious" regressions; Spatial dependence.

1. INTRODUCTION

The relationship between economic development and environmental quality has been extensively explored since Grossman and Krueger (1991) finding of an inverse U-shaped relationship between per capita income and pollution, the so-called Environmental Kuznets Curve (EKC). The EKC suggests that as countries experience economic growth, environmental deterioration decelerates and thus becomes less of an issue. With more or less success a large number of econometric studies have documented the existence of an EKC for pollutants such as sulfur dioxide (SO_2), nitrogen oxide (NO_x) and suspended particulate matter (*SPM*).[1] Apart from some exceptions, however, most of the EKC literature is statistically weak. The baseline models estimated in the literature are linear polynomial models that include quadratic (and sometimes also cubic) terms of income as explanatory variables. Recently, these models have been criticized of being too restrictive and alternative more flexible econometric techniques have been proposed.

Focusing on the prime example of carbon dioxide (CO_2) emissions, the present article provides a critical review of the new econometric techniques used. In particular, we discuss issues related to the functional form, the heterogeneity of income effects across countries (regions), "spurious" EKC regressions and spatial dependence in emissions across countries. To my best knowledge, no one has yet attempted to give an overview of the recent influential contributions and to determine whether and to what extent the EKC is robust to the new econometrics approaches employed.

[1] Although it is essentially an empirical finding, some papers have also derived the EKC theoretically. See for example, Stokey (1998) and Jones and Manuelli (2001), among others. Levinson (2002) provides a review of the theoretical as well as the empirical literature.

On the functional form issue, some studies have addressed the non-linearity of the income-emissions relationship by using a spline (piecewise linear) function. The spline model has the advantage over the polynomial specification in that the approximation error is generally smaller. Others papers have considered Weibull distributions and smooth transition regression models as alternative, and more flexible specifications, to the polynomial model. The non-parametric models, which do not require the specification of a functional form, constitute one of the latest econometric tools used. Yet, these new econometric approaches have not yielded conclusive results regarding the existence of the EKC for carbon emissions. Another important issue in panel data studies is the underlying assumption of homogeneity of income effects across countries (regions). As some studies show not all countries display the same relationship between emissions and income. This is particularly true when developed and developing countries are compared, with the EKC holding for some developed countries only. A further econometric criticism of the EKC concerns the issue of "spurious" regressions. As the model includes potentially non-stationary variables such as emissions and GDP, one can only rely on EKC results that exhibit the co-integration property. The test for unit roots finds that carbon emissions and GDP per capita are integrated variables, although not always co-integrated, what casts doubt on the validity of the EKC. Finally, recent studies allow for spatial dependence in emissions across countries to account for the possibility that countries' emissions are affected by emissions in neighbouring countries. The results so far support the use of spatial econometric models over the polynomial EKC specification.

The main reason for studying carbon emissions is that they play a focal role in the current debate on environmental protection and sustainable development. CO_2 is a major determinant of the greenhouse gas implicated in global warming. While the physical effects of local pollutants such as sulphur dioxide or nitrogen oxide are conspicuous and can be accounted for by only domestic activity, the effects of carbon dioxide are far-reaching and cause an international externality. Thus the incentives to abate carbon emissions are clearly undermined by the free-rider problem, what makes the study of CO_2 emissions particularly interesting. Another reason is that CO_2 emissions are directly related to the use of energy, which is an essential factor in the world economy, both for production and consumption. Therefore, the relationship between carbon emissions and economic growth has important implications for environmental and economic policies.

The paper is organized as follows. Section 2 summarizes the basic idea of the emission-income relationship and surveys the first studies on the EKC. Section 3 discusses the standard polynomial specification and the reviews the studies using this methodology for carbon emissions. The new econometric techniques are presented in Section 4, while Section 5 discusses the policy implications emerging from the literature on the EKC. Finally, Section 6 concludes.

2. EKC: BACKGROUND IDEA

The basic idea of the EKC is that environmental degradation increases with income up to a threshold income level beyond which environmental quality improves as income continues to grow. This relationship is summarized by an inverted U-shaped curve (see Figure 1). It is known as the Environmental Kuznets Curve due to its resemblance to Kuznets's inverted U relationship between income inequality and economic growth (Kuznets, 1955). There are three main forces behind the EKC. First, growth exerts a

scale effect on the environment: a larger scale of economic activity leads to increased environmental degradation as more energy is used. Second, income growth can have a positive impact on the environment through a **composition effect**: as a country grows and develops, the structure of its economy changes from a manufacturing based economy towards an information intensive and services based economy, and so increasing the share of cleaner activities in its GDP. Finally, as countries become richer, environmental awareness increases, and so does the demand for environmental regulations. This will generally lead to the substitution of obsolete and dirty technologies for cleaner ones, improving the quality of the environment. This is known as the **induced technique effect** of growth. The negative impact on the environment of the scale effect tends to prevail in the initial stages of countries' growth, but that it is eventually outweighed by the positive impact of the composition and induced technique effects that tend to lower emission levels.

The EKC concept emerged during the early 1990s with three studies that appeared independently. Grossman and Krueger (1991) in an NBER working paper, published later in 1993 (Grossman and Krueger, 1993), tested the EKC hypothesis in the context of the much-debated North American Free Trade Agreement (NAFTA). At the time, many people feared that by opening the markets with Mexico companies would rush across the border to escape the stricter environmental standards of Canada and the United States. The authors already find an inverted-U relationship between pollutants such as sulphur dioxide or smoke and per capita income for the US previous to NAFTA. The emission-income relationship was also discussed by Shafik and Bandyopadhyay (1992) in the World Bank's inquiry into the growth and environment relation for the Bank's 1992 *World Development Report*. The authors argued that ‘‘the view that greater economic activity inevitably hurts the environment is based on static assumptions about technology, tastes, and environmental investments'' and that ''as incomes rise, the demand for improvements in environmental quality will increase, as will the resources available for investment." The EKC was further popularized by Panayotou (1993) in a Development Discussion paper as part of a study for the International Labour Organisation. Panayotou was the first to name the relationship as the Environmental Kuznets Curve.

3. ECONOMETRIC METHODOLOGY

3.1 BASELINE MODEL

The most prominent single-equation approach to the EKC is the estimation of linear polynomial models including quadratic (and sometimes also cubic) terms of income as explanatory variables. The standard quadratic polynomial model is given by[2]

$$p_{it} = \mu_i + \varphi_t + \beta_1 y_{it} + \beta_2 y_{it}^2 + u_{it} \quad i = 1,...,N\,;\; t = 1,...,T \tag{1}$$

where $p_{it} = \ln(P_{it})$ is the logarithm of per capita emissions in region (country) i in year t, $y_{it} = \ln(Y_{it})$ is the logarithm of per capita GDP in region (country) i in year t, $\beta \equiv (\beta_1, \beta_2)'$ is the parameter vector and u_{it} is an error term.[3] If the coefficient on income, β_1, is positive and the coefficient on income squared, β_2, is negative, the relationship between income and emissions is not monotonic but displays an inverse-U shape. The term μ_i is a region-specific effect, which controls for unobserved factors that affect emissions at the regional level. The model accounts for heterogeneity in a limited way though. Although the level of emissions per capita may differ across

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[2] The popular quadratic model appears to be due to Holtz-Eakin and Selden (1995), whereas Grossman and Kruger (1995) use a cubic polynomial model.

[3] The functional form takes typically either a log-linear or linear form, with a number of studies considering both. In general, the results are qualitatively the same.

regions, the income elasticity is assumed to be the same in all regions at a given income level. The time-specific (or year-specific) intercepts φ_t may reflect changes over time in relevant factors common across regions such as macroeconomic factors and stochastic shocks. In addition, φ_t may reflect common changes over time in the technology used as well as in the environmental policies and standards adopted. Some papers include a time trend, instead of year-fixed effects, in order to estimate a more parsimonious model. In this case, all years have an equal effect on emissions.

Some studies also control for other possible determinants of emissions such as trade openness and measures of international mobility of factors to account for the so-called "pollution haven hypothesis" (Grossman and Krueger, 1991, 1993, Jaffe et al., 1995, Janicke et al., 1997, Suri and Chapman, 1998, Cole and Elliott, 2003, Cole 2004). The "pollution heaven hypothesis" argues that heavy polluters move from high-income countries with strict environmental regulations to low-income countries with weaker environmental regulations. So, the shape of the EKC is a consequence of high-income countries "exporting" their pollution to low-income countries. Other studies have included measures of income inequality (Torras and Boyce, 1998, Magnani, 2000, Bousquet and Favard, 2005) and measures of corruption (Lopez and Mitra, 2000, Fredriksson et al., 2004, Cole, 2007). The reason for the inclusion of income inequality is that inequality may reduce a country's willingness to pay for environmental regulation and abatement, while corruption presumably reduces the stringency of environmental policy and, therefore, is likely to have a negative impact on the environment as well.

The turning point or threshold level of income, where emissions are at a maximum is calculated by taking the derivative of $E(p_{it})$ in Eq. (1) with respect to y_{it}, setting it equal to zero and solving for y_{it} (or Y_{it})

$$Y^* = \exp(-\frac{\beta_1}{2\beta_2})$$

Estimation of the polynomial specification in Eq. (1) can be carried out by fixed effects (within-group estimator) or random effects (feasible generalised least squares). The fixed effects estimator treats the μ_i and φ_t terms as regression parameters, whereas the random effects estimator treats them as components of the error term u_{it}. The random effects estimator is more efficient than the fixed effects estimator. The important consideration here is whether μ_i and φ_t are correlated with per capita income. If they are, the random effects model yields inconsistent estimates and only the fixed effects estimator should be used. Many studies perform a Hausman test to choose between the fixed effects and random effects estimators.

3.2 EMPIRICAL FINDINGS

Although evidence of an EKC has been found for several pollutants, these findings are not unanimously accepted in the literature. The case of CO_2 emissions is a good example. In this section we survey the early EKC literature using the polynomial model to study the carbon emissions-income relationship.[4] Table 1 summarizes the studies of

[4] The list of references cited in this section is by no means exhaustive. For more general discussions, also on other pollutants, see the special issues of the Environmental and Development Economics (1997) and Ecological Economics (1998). See also the surveys of Stern (1998, 2004), Panayotou (2000), Dasgupta et al. (2002), Levinson (2002), Cole (2003), Copeland and Taylor (2004) and Dinda (2004).

carbon emissions, listed in chronological order. In early work, Shafik (1994) fits a country fixed effects model with a time trend for a panel of 149 countries over the period 1960-1990 and finds that carbon emissions do not improve with rising income, as the linear model has virtually all the explanatory power.[5] Holtz-Eakin and Selden (1995) estimate a quadratic polynomial model with country and year fixed effects for a panel of 130 countries during 1951-1986 and obtained some support for an EKC. However, their estimated turning point occurs at a very high level of per capita income ($35,428 in per capita 1986 dollars). An EKC model for CO_2 emissions is also estimated by Tucker (1995) on a cross-section of 131 countries for each year during the period 1971-1991. An inverted-U curve rises in statistical significance over time, and mainly during the 1980s. In particular, the coefficient of the linear income term is always positive and significant, while that of the quadratic income term is significant in 13 years out of 21, negative in 11 of those years, and becomes more negative and significant as time goes by.

Cole et al. (1997) examine the EKC relationship for a wide range of environmental indicators using panel datasets. The study focuses on a quadratic polynomial model with country fixed effects estimated in both linear and log-linear versions. As in Holtz-Eakin and Selden (1995) they obtain an EKC relationship with significant income parameters but the turning points fall well outside the observed income range, and in the log-linear model the standard errors of the turning point are large. This implies that the estimates of the CO_2 turning point are quite unreliable, casting doubt on the possible downturn of CO_2 emissions. In general, their results suggest that a meaningful EKC exists only for local air pollutants.

[5] This paper was originally a background paper (Shafik and Bandyopadhyay, 1992) for the World Bank's inquiry into growth and environment relationships (see the 1992 *World Development Report*).

In Hill and Magnani (2002) the EKC for carbon emissions is found to be highly sensitive to the dataset used. They use data for 156 countries and three separate years: 1970, 1980 and 1990. Cross-section estimation supports the EKC hypothesis for all three cross-sections, though the turning point is very high and near the upper end of the income distribution. However, when countries are split into low, middle and high income, carbon emissions seem to increase with income for all three groups of countries. The authors also test for omitted variables and find that openness, inequality and education are significant determinants of CO_2 emissions.

Other papers have focused on individual countries. de Bruyn et al. (1998) argue that the estimation of the EKC from panel data can not capture the dynamics of the relationship between income and emissions. By using a dynamic model and including energy prices to account for the intensity of use of raw materials, they consider an emission-income relationship separately for the Netherlands, the UK, the US and West Germany over the period 1961-1990. Their results show that economic growth has a positive direct effect on emissions and that emission reductions may be achieved as a result of structural and technological changes in the economy. In the context of a small open economy, Friedl and Getzner (2003) estimate an EKC for Austria over the period 1960-1999. They obtain the so-called N-shaped or cubic relationship, which exhibits the same pattern as the inverted-U curve initially, but beyond a certain income level the relationship between emissions and income is positive again (see Figure 2). The existence of an N-shaped curve suggests that at very high income levels, the scale effect of economic activity becomes so large that its negative impact on environment can not be counterbalanced by the positive impact of the composition and induced technique effects mentioned above. Lantz and Feng (2006) look at the EKC relationship for carbon emissions in Canada using a region-level panel dataset (5 regions) with region fixed effects for the period 1970-2000. Their results show that carbon emissions are unrelated to GDP. Interestingly, they find an inverted U-shaped relationship between CO_2 emissions and population, and a U-shaped relationship between CO_2 emissions and technology.

On the whole, the variability of the empirical findings discussed leads to the conclusion that the standard polynomial model may not be the most adequate to capture the relationship between carbon emissions and income.

4. ECONOMETRIC ISSUES REGARDING THE ESTIMATION OF EKC

In this section we provide a critical review of the new econometric techniques recently used in the EKC literature. Table 2 summarizes the studies focusing on carbon emissions and listed in chronological order.

4.1 NEW FUNCTIONAL FORMS

Given the restrictiveness of the polynomial model in Eq. (1), alternative more flexible functional forms have been proposed. For instance, Schmalensee et al. (1998) use a spline (piecewise linear) function, which is a linear approximation to a non-linear function. The number of splines is based on a test, with the final model having 10-segment splines, each containing an equal number of observations. The spline model has the advantage over the polynomial specification in that the approximation error is generally smaller. Schmalensee et al. (1998) find evidence of an EKC for CO_2

emissions, with a within-sample turning point, for a dataset of 141 countries over the period 1950–1990.[6]

Galeotti et al. (2006) propose a Weibull functional form to estimate an EKC. The choice of the Weibull distribution is based on its easily interpretable parameters. The regression model is given by

$$\ln(P_{it}) = \mu_i + \varphi_t + (\alpha - 1)\ln\left(\frac{Y_{it} - \gamma}{\beta}\right) - \left(\frac{Y_{it} - \gamma}{\beta}\right)^{\alpha} + \delta\left(\frac{Y_{it} - \gamma}{\beta}\right)^{-\alpha} + u_{it}$$

where the shape parameter α governs the curvature of the function, while the scale parameter β is related to the height of the function, and therefore with the maximum level of emissions at the turning point, if the latter exists. Furthermore, the location parameter γ controls for the position of the function and, therefore, implies the turning point of income. As for δ, this parameter gives added flexibility to the model by allowing for different patterns in the shape of the function. The model is estimated by maximum likelihood (ML) on carbon emissions for 125 countries. The results are mixed. There is evidence of an EKC with reasonable turning point during 1960-1997 for OECD countries, while a concave pattern with no reasonable turning point is obtained for non-OECD countries over the period 1971-1997.

Aslanidis and Xepapadeas (2006) propose a 2-regime smooth transition regression (STR) model which is an even more flexible parametric specification, and as they show the quadratic polynomial model is just the linearized version of the STR. The STR model is given by

$$p_{it} = \mu_i + \varphi_t + (\beta_1 + \beta_2 F(y_{it}))\, y_{it} + u_{it}$$

[6] They use an extension of the Holtz-Eakin and Selden (1995) dataset.

$F(y_{it})$ is the transition function, in this case depending on income, which is assumed to be continuous and bounded between 0 and 1; y_{it} is the transition variable-income. An EKC exists if $\beta_1 > 0$ and $\beta_1 + \beta_2 < 0$. In words, emissions increase with income up to some threshold level of income after which they are reduced with further growth. To complete the model, consider the following logistic functional form for the transition function

$$F(y_{it}) = (1 + \exp(-\gamma(y_{it} - c)))^{-1}$$

where the parameter c is the threshold between the two regimes. The slope parameter γ gives flexibility to the model by determining the smoothness of the change in the value of the logistic function and thus the speed of the transition from one regime to the other. For instance, when $\gamma \to \infty$, $F(y_{it})$ becomes a step function and the transition between regimes is abrupt. Estimation of the STR is carried out by non-linear least squares (NLS). Aslanidis and Iranzo (2009) applied this methodology to CO_2 emissions from 77 non-OECD countries over the period 1971-1997. Although there is no evidence of EKC, they find two regimes; a low-income regime where emissions accelerate with economic growth and a middle-to high-income regime associated with a deceleration in environmental degradation.

The semi and non-parametric models constitute one of the latest econometric tools used to test for the EKC hypothesis. These models are appealing as they impose no parametric restrictions on the form of the relationship. For instance, the semi-parametric model considered by Millimet et al. (2003) is written as

$$p_{it} = \mu_i + \varphi_t + G(y_{it}) + u_{it}$$

where $G(y_{it})$ is an unknown function of income, which *a priori* $G(.)$ can take any functional form. The estimation methods are based on standard kernel regressions.

Taskin and Zaim (2000) estimate a non-parametric model for some measures of environmental efficiency. On the basis of cross-sectional data for carbon emissions, they compute environmental efficiency indices and show evidence of EKC for a panel of 52 countries over the period 1975-1990. However, other studies that use semi and non-parametric specifications obtain mixed results. For example, using a panel of 122 countries, Bertinelli and Strobl (2005) can not reject a linear (positive) relationship between per capita income and carbon emissions during 1950–1990. Azomahou et al. (2006) carry out an extensive analysis on a panel of 100 countries during 1960-1996 and find that the linear (positive) relationship between carbon emissions and GDP can not be rejected either. They formally test this hypothesis by performing a monotonicity test within their non-parametric framework. Moreover, they test and reject the polynomial functional form in favour of the non-parametric model. As shown from the previous studies, the use of a particular functional form does not yield conclusive results either.

4.2 HOMOGENEITY ACROSS COUNTRIES

Besides the functional form, another important restriction of the polynomial model is the imposed homogeneous income effect across regions (or countries). List and Gallet (1999), Martinez-Zarzoso and Bengochea-Morancho (2004), and Dijkgraaf and Vollebergh (2005), among others, have relaxed such assumption.[7] The homogeneity assumption implies that except for the fixed (scale) effect all regions exhibit on average the same emission-income pattern. More precisely, all regions share the same turning point though the peak emission level may differ across regions via the individual

[7] As mentioned before, de Bruyn et al. (1998) criticize the estimation of the EKC from panel data and argue for country-specific models. Effectively they are also challenging the homogeneity assumption.

specific effects (see Figure 3). This assumption is too restrictive for large panels of heterogeneous regions. Regions (or countries) vary in terms of resource endowments, infrastructure, public pressure, economic, social and political factors, etc., and thus so might vary their income-pollution relationship.

Using a panel of US state-level data on SO_2 and NO_x emissions List and Gallet (1999) address the homogeneity issue by allowing for different income slopes across states.[8] They use a polynomial seemingly unrelated regressions (SUR) model, which appears appropriate for long time series data (their sample period is 1929–1994). Their results reject the homogeneity assumption and provide some evidence of the EKC being robust across US states.

Martinez-Zarzoso and Bengochea-Morancho (2004) analyse carbon emissions for 22 OECD countries during 1975-1998. They employ a pooled mean group estimator that allows for slope heterogeneity across countries in the short run, while imposing restrictions in the long run. These long-run restrictions are tested and supported by the data. The results show a great deal of heterogeneity across countries, and in most cases an N-shaped relationship emerges.

In a similar spirit, Dijkgraaf and Vollebergh (2005) argue that even a cursory comparison of per capita CO_2 and GDP plots for Japan and France casts serious doubts on the homogeneity assumption. Using data for 24 OECD countries for the period 1960-1997, the authors fit polynomial and spline models to test the null hypothesis that income coefficients are the same for all countries. The homogeneity assumption is clearly rejected. When individual country time series models are estimated, only 11 out of 24 cases show a statistically significant turning point and confirm the EKC hypothesis.

[8] This is the same data used by Millimet et al (2003) and Aslanidis and Xepapadeas (2006).

The firm rejection of the homogeneity assumption raises doubts not only on the homogeneous polynomial model but, insofar as they assume common income effects, also on the more flexible specifications discussed in the previous section.

4.3 "SPURIOUS" REGRESSIONS

Another important issue that still remains unsolved is that of possible "spurious" EKC relationships. The early literature completely neglects the fact that the EKC regressions involve potentially non-stationary variables such as emissions and GDP.[9] We can only rely on results from regressions that contain non-stationary variables if these variables exhibit the co-integration property, that is, if there is a long-run equilibrium relationship between them.

The econometrics literature has extended non-stationarity (unit root) tests to panel data. Let x_{it} denote the variable on which we want to test for a unit root; in our case, emissions or income. In general, the panel unit root tests consider the following regression model

$$x_{it} = \mu_i + \varphi_t + \rho_i x_{it-1} + u_{it}$$

where u_{it} is a stationary process.[10] Under the null hypothesis, there is a unit root in x_{it}, i.e., $H_0 : \rho_i = 1$ for all $i = 1,...,N$. On the other hand, the alternative hypothesis can take two forms depending on whether there are restrictions on the autoregressive coefficients ρ_i across cross-sections (regions). First, one can assume that the autoregressive coefficients are common across cross-sections. This gives rise to the homogeneous alternative of stationarity $H_a^{Homo} : \rho_i = \rho < 1$ for all *i.* A popular unit root test with

[9] In the macroeconometrics literature there is a lot of evidence that GDP series in particular are non-stationary.
[10] Note that region-specific time trends instead of the time-specific fixed effects can be included.

homogenous alternative is the test of Levin et al. (2002) (*LL*), which is a modified augmented Dickey-Fuller (ADF) test. Alternatively, one can allow ρ_i to vary across cross-sections. This gives rises to the heterogeneous alternative of stationarity

$$H_a^{Hetero}:\begin{cases}\rho_i < 1 & for\ i = 1,...,N_1\\ \rho_i = 1 & for\ i = N_1+1,...,N\end{cases}$$

for some N_1 such that $\lim_{N\to\infty} N_1/N > 0$. The heterogeneous alternative is more flexible than the homogeneous one in two ways. First, it allows for some cross-sections to be non-stationary also under the alternative and, second, it does not restrict the autoregressive coefficient to be identical under the alternative hypothesis. Popular unit root tests with heterogeneous alternative are the two tests developed by Im et al. (2003). One of these tests is essentially a group-mean of individual ADF statistics (IPS) test and the other is a group-mean Lagrange multiplier (IPS-LM) test. Another popular panel unit root test with a heterogeneous alternative is the test proposed by Maddala and Wu (1999) (MW). The idea is based on Fisher's results to derive tests that combine the *p*-values from individual unit root tests. The MW test is flexible in that it can be applied to any type of unit root test.

If the null hypothesis of non-stationarity of emissions and GDP is not rejected, the next step is to test whether these variables are co-integrated using the recently developed co-integration tests for panel data.[11] Pedroni (2004) proposes seven co-integration tests which have become very popular in empirical work. All these tests are unit root tests performed on the residuals of the EKC regression. If carbon emissions and GDP are co-integrated, the residual process will be stationary. As in unit root tests, the co-integration tests can take two forms depending on whether there are restrictions on the autoregressive coefficients across cross-sections.

[11] A comprehensive survey is given in Breitung and Pesaran (2008).

Wagner and Müller-Fürstenberger (2004) use the aforementioned panel unit root and co-integration tests to study the polynomial EKC. Their analysis is based on carbon emissions and GDP data for 107 countries over the period 1986-1998. Because of the short time span, they resort to both classical as well as bootstrap inference. Their results are mixed. Although, for carbon emissions there is clear evidence for non-stationarity, the test for GDP is not clear-cut. As for co-integration, results are not conclusive either. They depend upon the choice of the unit root and co-integration test, and also on whether one uses bootstrap or classical inference.[12]

The above panel integration and co-integration tests assume that the order of integration of a stochastic process can take on only integer values. This knife-edge distinction between, say, a stationary I(0) (integrated of order 0) and a non-stationary I(1) (integrated of order 1) process is too restrictive. Galeotti et al. (2009) challenge this assumption and consider tests of fractional integration and co-integration for panels. Fractionally differenced processes are flexible as the order of integration does not need to be an integer but can take any value between zero and one. Also, the order of integration is allowed to differ across cross sections. This framework gives flexibility to the EKC model as it allows for more possibilities for emissions and income to be co-integrated if they are non-stationary. The authors use a panel of 24 OECD countries over the period 1960-2002. The fractional integration tests find evidence of non-stationarity for the carbon emissions and GDP processes. Regarding co-integration, using a value of the (estimated) integration parameter of 0.5 as a threshold for fractional co-integration, the EKC hypothesis is supported in only 5 out of 24 countries. Overall, their results cast doubt on the validity of the EKC.

[12] Similar mixed results are also reported by Müller-Fürstenberger and Wagner (2007). They use the same data but focus on the IPS and IPS-LM tests.

4.4 SPATIAL DEPENDENCE

Most papers estimating the EKC implicitly assume that regions' (countries') emissions are unaffected by the emissions in neighbouring regions. This assumption has recently been challenged in papers using spatial econometric techniques (Maddison, 2006, Auffhammer and Carson, 2009).[13] There are several reasons why spatial relationships may be present in the income-pollution relationship. First, according to the "pollution haven hypothesis", and given that distance and common land borders may be important factors in increasing trade and investment, poor regions close to rich ones would be more likely to host the dirty activities of firms of developed countries and thus to have higher emissions. Second, the literature on the international diffusion of technology suggests that this is geographically localized, so that the R&D spillovers decline with geographical distance (Keller, 2004). Therefore, if there is technological progress that reduces emissions, it is reasonable to consider spatial relationships in emissions. Third, CO_2 emissions are strongly correlated with industrial activity. As economies are becoming increasingly linked over time so do their industrial activities, which in turn implies a stronger spatial relationship in emissions. Finally, governments often mimic each other environmental policies in order to reduce the costs of decision making and to legitimize their actions (Fredriksson and Millimet, 2002).

Auffhammer and Carson (2009) explore spatial econometric models to provide out-of-sample forecasts of China's aggregate emissions. Their analysis is based on province-level panel data of carbon emissions for 30 Chinese provinces over the period 1985-2004. The spatial econometric model considered by the authors is the following

$$p_{it} = \mu_i + \varphi_t + G(y_{it}) + G(y_{it-1}) + \pi p_{it-1} + \rho\left(\sum_{j=1}^{k} w_{ij} p_{jt-1}\right) + u_{it}$$

[13] Maddison (2006) use a country-panel of sulphur dioxide, nitrogen oxides, volatile organic compounds and carbon monoxide emissions for only 2 years of data (1990 and 1995). His methodology consists in a standard quadratic model augmented by spatial dependence. The results do not give support to the existence of an EKC while reveal significant spatial effects across countries.

where $\left(\sum_{j=1}^{k} w_{ij} p_{jt-1}\right)$ are spatial lags which capture spillover effects across provinces and w_{ij} are the spatial weights given to previous year's CO_2 emissions by its k neighbouring provinces. In words, carbon emissions at a particular Chinese province are partially determined by a spatially weighted average of emissions of the neighbouring provinces. In principle, the model is semi-parametric as $G(.)$ has an unknown functional form which models the (possibly) non-linear relationship between emissions and GDP.[14] Moreover, the authors propose a dynamic model in order to take into account the partial adjustment of capital due to technological progress. For this, they include lagged emissions, p_{it-1}, as a regressor. In its most general form, the model allows for different speeds of adjustment across provinces π_i and this makes the technique even more flexible.

Their results support the use of the spatial model. In particular, the fit improves substantially with the inclusion of spatial lags. Moreover, the model clearly outperforms the static quadratic EKC specification on the basis of in-sample evaluation criteria. As for forecasting, the results point to a notable increase in carbon emissions in China during the current decade.

Summing up, these findings are encouraging for the use of spatial econometrics techniques and it rests for future research to see whether they can provide similar results for other datasets as well as for other types of pollutants.

[14] In practice, Auffhammer and Carson search over three functional forms, that is, polynomial, spline and non-parametric, and finally settle with the spline model.

5. POLICY IMPLICATIONS

The shape of the relationship between carbon emissions and income has critical policy implications. An inverse U-shaped relationship seems to suggest that as countries experience economic growth, environmental deterioration eventually decelerates and thus becomes less of an issue. Therefore, taking these results for their face value would imply that growth is the "cause" and the "cure" of enviromental degradation. The problem would then be how to best accelerate growth to surpass the income threshold (turning point) as soon as possible. However, the survey carried out here shows that there are reasons to question this conclusion.

First, the EKC is not a structural model capturing the interrelations between technology, the composition of economic output, environmental policy and their effects on emissions, but a reduced form model. As such, it has the advantage that it is easily estimated. However, the observed relation between income and pollution reflects a correlation rather than a causal relationship. Furthermore, the EKC does not answer the question whether the reduction in emissions is achieved by more ambitious environmental policies (that may even be unrelated to economic growth) or by exogenous structural and technological changes. But, more fundamentally, the evidence presented in this survey suggests that the econometric foundations of the EKC are, in fact, weak and cast doubt on the generalization of the EKC to the majority of countries.

The failure to accept the EKC gives rise to radically different policy implications regarding environmental policy, with particularly dramatic consequences for developing countries. In effect, the environmental conditions in which the less advanced economies are developing today are much different from the ones faced by the developed countries in the past. The stock of greenhouse gases inherited by today's developing countries is certainly higher than that encountered by the developed countries in the early stages of their development. It is this stock, rather than the current flow of carbon emissions, that contributes mostly to global warming and its damages. For this reason, a policy of "accelerating growth in order to surpass the income threshold" based on a naïve interpretation of the EKC may have serious negative effects on the environment in the future.

This argument affects particularly the developing countries currently on the upward part of the curve. There is a good reason to believe that these countries may not be able to follow the same path as the developed countries. For instance, according to the "pollution heaven hypothesis" the EKC may be the result of environmental effects being displaced from developed countries (with stricter environmental regulations) to developing countries (with weaker environmental regulations), rather than reduced overall emissions. This implies that, without the implementation of the appropriate environmental policies, developing countries would not be able to find in turn some other countries to which "export" their pollution-intensive industries.

6. CONCLUSION

The empirical research on the relationhship between CO_2 emissions (a major greenhouse gas) and economic growth is continuously spurred by the renewed attention of scientists, policy-makers and the public opinion to the issue of climate change. A remarkable large number of recent contributions have investigated this relationship, correcting for some of the drawbacks of the early studies using the baseline polynomial model. In this survey we highlight the econometric issues related to functional forms, heterogeneity of income effects across countries, "spurious" EKC regressions and spatial dependence in emissions across regions.

With respect to functional forms, new parametric (e.g., spline, Weibull and smooth transition regression) and the non-parametric forms have been proposed as alternative and more flexible specifications to the baseline polynomial model. Despite these more sophisticated approaches, there is still no clear-cut evidence supporting or rejecting the existence of the EKC for carbon emissions. As for the assumption of homogeneous income effects across regions (countries), there is an aggreement in the literature rejecting such assumption. This is particularly clear when developed and developing countries are compared, with the EKC holding for some developed countries only.

With regard to the possible "spurious" EKC relationship, we reviewed studies adopting the recently developed unit root and co-integration tests for panel data. Overall, they find that carbon emissions and GDP per capita are integrated variables, although not always co-integrated, what casts doubt on the validity of the EKC. Finally, some recent studies have allowed for spatial dependence in emissions across regions, which is intuitively appealing as regions' emissions are likely to be affected by emissions in neighbouring regions. The results, so far, are encouraging in the sense that the spatial econometric models clearly outperform the baseline polynomial EKC specification.

Other issues that, in our view, remain unresolved are the possible structural breaks in the EKC and contemporaneous feedback effects from emissions to GDP.[15] So far little work has addressed these issues. Azomahou et al. (2006) looks at the first issue, and find no evidence of structural shifts in the (monotonic) relationship between CO_2 emissions and GDP. As for simultaneity, the results in Holtz-Eakin and Selden

[15] Regarding the latter, it is worth mentioning that the environment is a major factor of production as many countries heavily rely on natural resources to grow. At the same time, environmental degradation (e.g., high pollution levels) may reduce worker productivity as well as compromise potential growth.

(1995) reject the existence of contemporaneous feedback effects. However, the evidence is still sparse and more work needs to be done in this direction. [16]

[16] For instance, one could investigate a VAR-type model for CO_2 emissions and GDP, and to analyse the long-run and short-run effects of GDP.

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Table 1: CO_2 EKC studies using polynomial model

Author (s)	**Country/Time effects**	**Data sample**	**Time period**	**Shape of EKC**
Shafik (1994)	Fixed country effects/Time trend	149 countries	1960-1990	Linear (positive) relationship
Holtz-Eakin and Selden (1995)	Fixed country/Time effects	130 countries	1951-1986	Inverse U-shaped (but turning point is too high)
Tucker (1995)	Cross-section regressions for each year	131 countries	1971-1991	Inverse U-shaped (stronger over time)
Cole et al. (1997)	Fixed country effects	7 world regions	1960-1991	Inverse U-shaped (but turning point is too high)
de Bruyn et al. (1998)	Time series regressions	4 OECD countries	1961-1990	Linear (positive) relationship
Hill and Magnani (2002)	Cross-section regressions for each year	156 countries	1970, 1980, 1990	Inverse U-shaped (but highly sensitive to dataset and turning point is too high)
Friedl and Getzner (2003)	Time series regressions	Austria	1960-1999	N-shaped
Lantz and Feng (2006)	Fixed region effects	5 Canadian regions	1970-2000	CO_2 is unrelated to income. Inverse U-shaped with population and U-shaped with technology

Table 2: CO_2 EKC studies using new econometric techniques

Author (s)	Econometric issue addressed	Technique	Data sample	Time period	Shape of EKC
Schmalensee et al. (1998)	Functional form	Spline model	141 countries	1950–1990	Inverse U-shaped
Taskin and Zaim (2000)	Functional form	Non-parametric models	52 countries	1975-1990	Inverse U-shaped
Martinez-Zarzoso and Bengochea-Morancho (2004)	Heterogeneity	Pooled mean group estimator	22 OECD countries	1975-1998	N-shaped for majority of countries
Wagner and Müller-Fürstenberger (2004)	"Spurious" EKC relationship	Panel unit root & cointegration tests	107 countries	1986-1998	Results are mixed
Bertinelli and Strobl (2005)	Functional form	Non-parametric models	122 countries	1950–1990	Linear (positive) relationship
Dijkgraaf and Vollebergh (2005)	Heterogeneity	Polynomial & spline models	24 OECD countries	1960-1997	Inverse U-shaped in 11 out of 24 countries
Azomahou et al. (2006)	Functional form	Non-parametric models	100 countries	1960-1996	Linear (positive) relationship
Galeotti et al. (2006)	Functional form	Weibull model	125 countries	1960-1997 (OECD) 1971–1997 (non-OECD)	Inverse U-shaped for OECD Concave (but with no reasonable turning point) for non-OECD
Aslanidis and Iranzo (2009)	Functional form	Smooth transition regression models	77 non-OECD countries	1971–1997	Positive but at a slower rate after some income threshold
Auffhammer and Carson (2009)	Spatial dependence	Spline model augmented with spatial dependence	30 Chinese provinces	1985-2004	Linear (positive) relationship
Galeotti et al. (2009)	"Spurious" EKC relationship	Fractional panel unit root & cointegration tests	24 OECD countries	1960-2002	Inverse U-shaped in 5 out of 24 countries

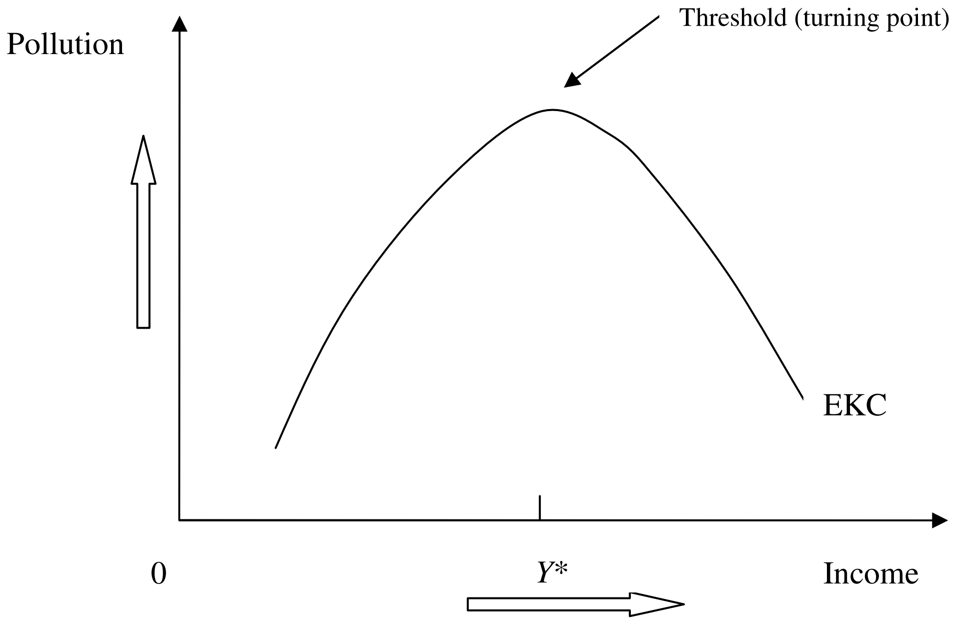

Figure 1: Environmental Kuznets Curve (inverse U-shaped relationship)

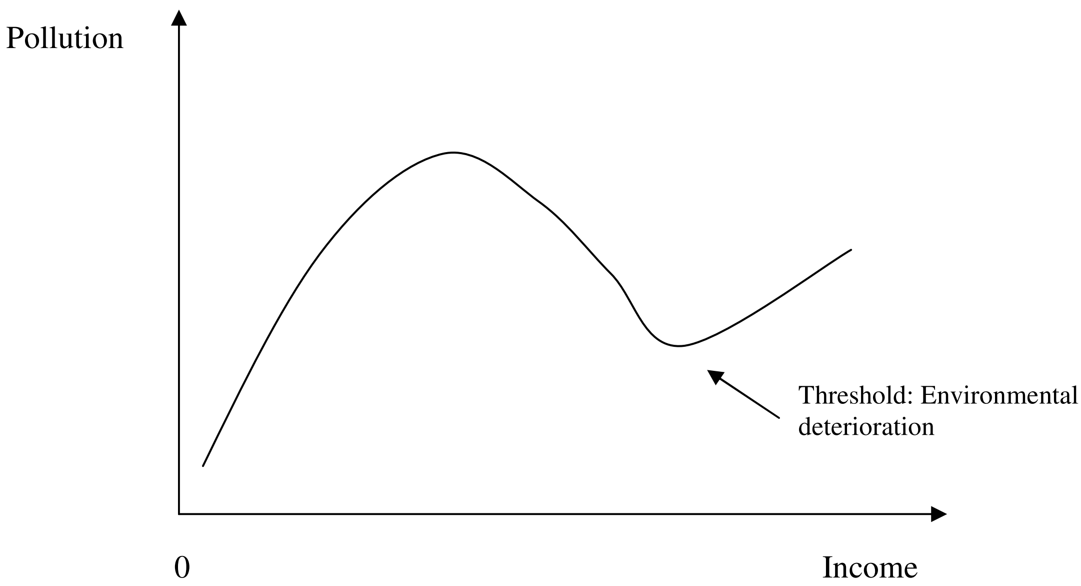

Figure 2: N-shaped relationship

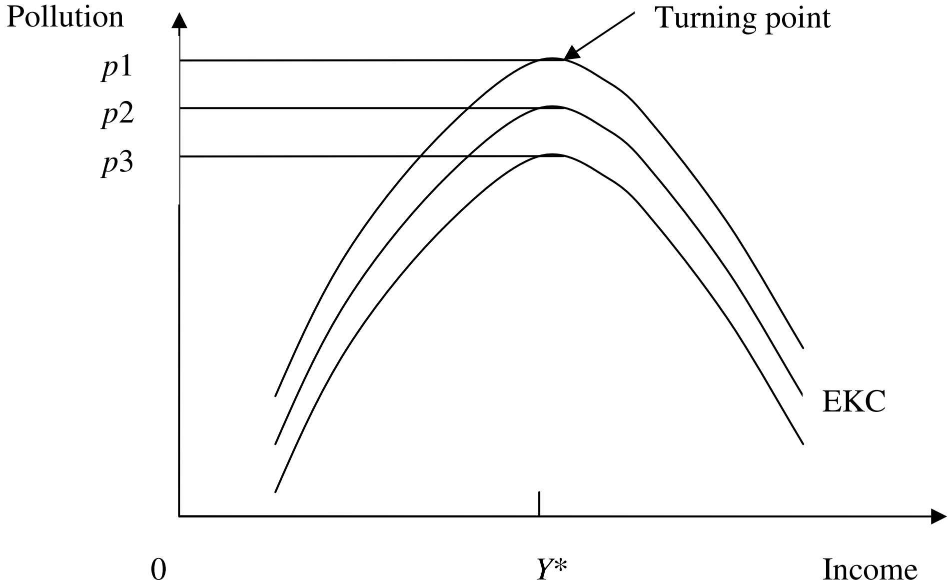

Figure 3: Environmental Kuznets Curve: Slope Homogeneity