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Summary

Since its first inception in the debate on the relationship between environment and growth in 1992, the Environmental Kuznets Curve has been subject to continuous and intense scrutiny. The literature can be roughly divided in two historical phases. Initially, after the seminal contributions, additional work aimed to extend the investigation to new pollutants and to verify the existence of an inverted-U shape as well as assessing the value of the turning point. The following phase focused instead on the robustness of the empirical relationship, particularly with respect to the omission of relevant explanatory variables other than GDP, alternative datasets, functional forms, and grouping of the countries examined. The most recent line of investigation criticizes the Environmental Kuznets Curve on more fundamental grounds, in that it stresses the lack of sufficient statistical testing of the empirical relationship and questions the very existence of the notion of Environmental Kuznets Curve. Attention is drawn in particular on the stationarity properties of the series involved – per capita emissions or concentrations and per capita GDP – and, in case of unit roots, on the cointegration property that must be present for the Environmental Kuznets Curve to be a well-defined concept. Only at that point can the researcher ask whether the long-run relationship exhibits an inverted-U pattern. On the basis of panel integration and cointegration tests for sulphur, Stern (2002, 2003) and Perman and Stern (1999, 2003) have presented evidence and forcefully stated that the Environmental Kuznets Curve does not exist. In this paper we ask whether similar strong conclusions can be arrived at when carrying out tests of fractional panel integration and cointegration. As an example we use the controversial case of carbon dioxide emissions. The results show that more EKCs come back into life relative to traditional integration/cointegration tests. However, we confirm that the EKC remains a fragile concept.

Keywords: Environment, Growth, CO2 Emissions, Panel data, Fractional integration, Panel cointegration tests

JEL Classification: O13, Q30, Q32, C12, C23

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1. Introduction

The relationship between economic development and environmental quality is the subject of a long-standing debate. About thirty years ago a number of respected scholars, mostly social and physical scientists, attracted the public attention to the growing concern that the economic expansion of the world economy will cause irreparable damage to our planet. In the famous volume *The Limits to Growth* (Meadows, Meadows, Randers, and Behrens, 1972), the members of the Club of Rome ventilated the necessity that, in order to save the environment and even the economic activity from itself, economic growth cease and the world make a transition to a steady-state economy (see Ekins, 2000, for a more thorough discussion of this position).

In the last decade there has prevailed the economists' fundamental view about the relationship between economic growth and environmental quality: increase in the former does not necessarily mean deterioration of the latter; in current jargon, a de-coupling or de-linking is possible, at least after certain levels of income. This is the basic tenet at the heart of the so-called Environmental Kuznets Curve (EKC henceforth), the single most investigated topic in applied environmental economics.

About a decade ago a spat of initial influential econometric studies (Shafik and Bandyopadhyay, 1992; Grossman and Krueger, 1993, 1995; Panayotou, 1993; Shafik, 1994; Selden and Song, 1994) identified, mostly in the case of local air and water pollutants, a bell shaped curve of pollution plotted against GDP. This behavior implies that, starting from low per capita income levels, per capita emissions or concentrations tend to increase but at a slower pace. After a certain level of income (which typically differs across pollutants) – the "turning point" – emissions or concentrations start to decline as income further increases. It must be said that in the case of global pollutants like CO_2 the evidence however is less clear-cut.

Although many authors rightly warn against the non-structural nature of the relationship, if supported by the data, the inverted-U shape of the curve contains a powerful message: GDP is both the cause and the cure of the environmental problem. However, being based on no firm theoretical basis, the EKC is ill-suited for drawing policy implications. The inverted-U relationship between economic growth and the environment cannot be simply exported to different institutional contexts, to different countries with different degrees of economic development, not even to different pollutants. Particularly in the case of CO_2

emissions extreme caution and careful scrutiny are necessary. Indeed, the global nature of this pollutant and its crucial role as a major determinant of the greenhouse effect attribute to the analysis of the CO_2 emissions-income relationship special interest.

Much has been written on the growth-environment nexus and on the EKC. The literature has been mushrooming in the last decade and literature surveys are already numerous. Our updated list of overviews includes: Stern, Common, and Barbier (1996), Ekins (1997), Stern (1998), Stagl (1999), Panayotou (2000), de Bruyn (2000), Ekins (2000), Borghesi (2001), Dasgupta, Laplante, Wang, and Wheeler (2002), Levinson (2002), Harbaugh, Levinson, and Molloy Wilson (2002), Hill and Magnani (2002), Galeotti (2003), Yandle, Bhattarai, and Vijayaraghavan (2004). These papers all summarize the abundant empirical work done on the EKC.

Econometric analyses of the environment-growth relationship have been carried out for several measures of pollution over time and across countries.[1] Our reading of this literature distinguishes two phases. The first phase can be defined as that of enthusiasm, when the notion of EKC is essentially taken for granted, goes unquestioned. The efforts are concentrated on verifying the shape of the relationship, measuring the income value of the turning point(s), extending the investigation to other pollutants. The second phase witnesses the quest for robustness. The EKC is assessed and tested in various directions, including alternative functional forms, different econometric methods, inclusion of additional explanatory variables.

In the last couple of years the EKC has come under a more fundamental attack. One criticism involves the common practice of estimating the EKC on the basis of panel data with the implied homogeneity in the slope/income coefficients across individual units (countries, states, provinces, cities). A second aspect concerns the need to parametrize the EKC relationship prior to estimation. It is clear that any test on the shape of the EKC or any calculation of turning points are all conditional on the specific parametrization chosen. One way to overcome this problem is to use parametrizations as flexible as possible, another one is to use nonparametric or semiparametric regression techniques. But the most fundamental

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[1] The study of the impact of economic growth on the environment is a significant endeavor, the analysis of feedback effects of the environment on a country well being is even more challenging a task. These considerations help explain why this research field has been explored firstly on empirical grounds and only afterwards with the help of theoretical models.

criticism refers to the stationarity of the variables involved in EKC regressions. According to the theory of integrated time series it is well known that nonstationary series may or may not produce linear combinations that are stationary. If not, all inference on the EKC leads misleading results. Thus, even before assessing the shape or other features of the estimated EKC, the researcher should make sure that pollutant and income, if nonstationary, are cointegrated. It is therefore necessary to run tests of integration and cointegration to guarantee the existence of a well-defined EKC prior to any subsequent step. The evidence of panel integration/cointegration tests – a recent development in the econometrics literature – appears to lead to the conclusion that the EKC is a very fragile concept.

This paper takes up this last and more fundamental difficulty in the current EKC econometric practice. In particular it is noted that the aforementioned stationarity tests are the standard ones (though in a panel context) where the order of integration of time series is allowed to take on only integer values. So, for instance, a linear combination between pollutant and income gives rise (does not give rise) to a valid EKC only if it is integrated of order zero (one). As a matter of fact, recent progress in econometrics has led to the formulation of the notion and tests of fractional integration and cointegration according to which the order of integration of a series needs not be an integer. The consequence of this fact is that there is a continuum of possibilities for time series to cointegrate – and therefore for the existence of EKCs – thus overcoming the zero-one divide.

In this paper we carry out tests of fractional integration and of fractional cointegration extended to a panel context. We use as an example the case of carbon dioxide for 24 OECD countries over the period 1960-2002. The results show that more EKCs come back into life relative to traditional integration/cointegration tests. However, we confirm that the EKC remains a fragile concept.

The paper is organized as follows. Section 2 is devoted to a brief excursus of the literature. Section 3 carries out “traditional” tests of panel integration/cointegration on our sample of data. Section 4 introduces the reader to fractional integration and cointegration and shows the results of these tests. In the final section we draw a few conclusions and note that there remain other open questions.

2. A Subjective Reading of the Literature

Virtually all EKC studies are concerned with the following questions: (i) is there an inverted-U relationship between income and environmental degradation? (ii) if so, at what income level does environmental degradation start declining? The first wave of contributions to the EKC literature has typically focused upon the answer to these questions. Often out-of-sample projections of pollutant emissions or concentrations have also been a subject of interest.

It is to be noted that both questions have ambiguous answers. The main reason is that, in the absence of a single environmental indicator, the estimated shape of the environment-income relationship and its possible turning point(s) generally depend on the pollutant considered. In this regard, three main categories of environmental indicators are distinguished: air quality, water quality and other environmental quality indicators. In general, for indicators of air quality – such as SO_2, NO_x or SPM – there seems to be evidence of an inverted-U pattern. The case of CO_2 is more controversial. So is for deforestation. Aside from these cases, studies have found that environmental problems having direct impact on the population – such as access to urban sanitation and clean water – tend to improve steadily with growth. When environmental problems can be externalized (as in the case of municipal solid wastes) the curve does not even fall at high income levels. Finally, even when an EKC seems to apply – as in the case of traffic volume and energy use – the turning points are far beyond the observed income range.

More recently, a large, second wave of studies has instead concentrated on the robustness of the previous empirical practice and criticized, from various standpoints, the previous work and findings.[2] The most recurrent criticism is the omission of relevant explanatory variables in the basic relationship. Thus, besides income and time trend, we ought to include trade because of the so-called "pollution heaven" or "environmental dumping" hypothesis (Hettige, Lucas, and Wheeler, 1992; Kaufmann, Davidsdottir, Garnham, and Pauly, 1998; Suri and Chapman, 1998), energy prices to account for the intensity of use of raw materials (de Bruyn, van den Bergh, and Opschoor, 1998), and a host of other variables if we care about political economy considerations due to the public good nature of the

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[2] Although the critique applies to the whole literature, we will make reference here to studies concerned with a specific pollutant, carbon dioxide. We do so for space reasons and because our empirical application uses CO_2 as a case study.

environment (Torras and Boyce, 1998). In addition, allowance should be made for changes in either the sectoral structure of production or the consumption mix (Rothman, 1998; Hettige, Mani, and Wheeler, 2000) or for the distinction, when data permit, between polluting activity and pollution intensity which, when related to GDP, work in opposite directions (Hilton and Levinson, 1998). A few studies check the robustness of the approach to alternative or more comprehensive datasets (Harbaugh, Levinson, and Molloy Wilson, 2002; Galeotti and Lanza, 2005).

By and large investigations in this literature are conducted on a panel data set of individual countries around the world. As for the data, those for CO_2 emissions almost invariably have come from a single source, namely the Oak Ridge National Laboratory, while for most of the other pollutants the GEMS data set is employed.[3] The functional relationship takes typically either a linear or a log-linear functional form, with a number of studies considering both. Finally, due to the almost complete coverage of world countries, the estimation technique is typically the least square dummy variable method, allowing for both fixed country and time effects.

Particularly the last two aspect of the usual EKC econometric practice have been the subject of further scrutiny in recent contributions. A first criticism is that of "income determinism" of empirical EKCs which implicitly hold that the experience of a country is equal to that of all others (Unruh and Moomaw, 1998). Indeed, a few studies have questioned the practice of pooling various countries together and carried out EKC investigations on data from individual countries. Thus, for instance, Vincent (1997) examines the link between per capita income and a number of air and water pollutants in Malaysia; while de Bruyn, van den Bergh, and Opschoor (1998) investigate emissions of several air pollutants in four OECD countries (Netherlands, West Germany, UK and USA); Dijkgraaf and Vollebergh (1998) consider CO_2 emissions for individual OECD countries; Egli (2001) considers per capita emission data of eight pollutants in the case of Germany.[4]

Parametric econometric techniques have been the dominating tool for studying the relationship between environment and economic growth. They offer a number of well known

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[3] The data for real per capita GDP are typically drawn from the Penn World Table and are on a PPP basis.

[4] de Bruyn, van den Bergh, and Opschoor (1998) show how a bell shaped EKC may spuriously obtain as a result of the interplay between time effect and aggregation across countries. Roberts and Grimes (1997) estimate individual cross sections for several years.

advantages, although departures from the basic approaches often require the availability of more data on more variables or impose a price in terms of reduced number of degrees of freedom. One aspect that deserves consideration is the issue of the functional form. The norm has been given by second order or at most third order polynomial linear or log-linear functions. However, recently a few papers have adopted a nonparametric approach by carrying out kernel regressions (Taskin and Zaim, 2000; Azomahu and Van Phu, 2001; Millimet, List, and Stengos, 2003; Bertinelli and Strobl, 2004; Vollebergh, Dijkgraaf, Melenberg, 2005) or a flexible parametric approach (Schmalensee, Stoker, and Judson, 1998; Dijkgraaf and Vollebergh, 2001; Galeotti and Lanza, 2005; Galeotti, Lanza, and Pauli, 2005).

The most recent line of investigation criticizes the Environmental Kuznets Curve on more fundamental grounds. The attack to the very concept of EKC is brought by Stern in a series of papers (Stern, Common, and Barbier, 1996; Stern, 1998, 2004). Besides stressing the econometric consequences of omitted variables for the estimated EKC parameters, the author notes the lack of rigorous statistical testing in much of this literature. Although for some pollutants there seems to be an inverted-U EKC, he states that the relationship is likely to be a monotonically increasing one, shifting downward over time. Attention is in particular drawn on the stationarity properties of the series involved – per capita emissions or concentrations and per capita GDP – and, in case of presence of unit roots, on the cointegration property that must be present for the Environmental Kuznets Curve to be a well-defined concept. Only at that point can the researcher ask whether the long-run relationship exhibits an inverted-U pattern. It is worth repeating here the basic analytical EKC relationship:

$$y_{it} = \alpha_i + \gamma_t + \beta_1 x_{it} + \beta_2 x_{it}^2 + \beta_3 x_{it}^3 + u_{it} \tag{1}$$

where *y* = *ln Y* and *x* = *ln X* and where *Y* is the measure of per capita pollutant, *X* is per capita GDP and *i* and *t* index country (i=1,...,N) and time (t=1,...,T).[5] According to the theory of integrated time series if *y* and *x* in (1) are integrated of order one, i.e. I(1), then their linear combination must be integrated of order zero, i.e. I(0), for the relationship (1) to be statistically and hence economically meaningful. If not, the inference on the EKC produces

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[5] Of course (1) needs not be log-linear, but simply linear in variables.

misleading results. It follows that, even before assessing the shape or other features of the estimated EKC, the researcher should make sure that pollutant and income, if nonstationary, are cointegrated. It is therefore necessary to run tests of integration and cointegration to guarantee the existence of a well-defined EKC prior to any subsequent step. These tests need be extended to a panel environment, a recent development in the econometrics literature.

3. What Do "Traditional" Tests of Panel Integration and Cointegration Say in the Case of CO_2 Emissions

As said, the series appearing in the basic EKC regression like (1) may or may not be stationary. If, as in most economic instances, they are integrated of order one, or I(1), then we must difference them once to make them stationary, or I(0). More generally, a time series z_t is I(d) if we have to apply d times the difference operator, so that $\Delta^d z_t$ is I(0). Augmented Dickey-Fuller type of tests are typically conducted to test the order of integration of a time series. Inference with integrated variables is not valid unless they are cointegrated. Denoting with Z_t a vector of individual I(1) variables, then we say that its components are cointegrated if the linear combination $\hat{\beta}'Z_t$ is I(0) ($\hat{\beta}$ is the cointegrating vector of coefficients estimated with OLS). Augmented Dickey-Fuller type of tests are conducted on the residuals of the OLS regression $\hat{u}_t = \hat{\beta}'Z_t$ (subject to a normalization) to test whether they are I(0) or not.

A recent development in the econometrics literature extends the tests of integration and cointegration to panel environments. Three are the most popular tests for a unit root in single variables observed across individuals and through time: the Levin and Lin (1992, 1993) (LL) statistic, the test by Im, Pesaran, and Shin (2003) (IPS), and a Fisher type statistic (FTT) proposed, among others, by Maddala and Wu (1999). The LL test considers the following regression model:

$$z_{it} = \rho_i z_{i,t-1} + \sum_{j=1}^{p_i} \phi_{ij} \Delta z_{i,t-j} + w_{it}'\gamma + u_{it} \tag{2}$$

where w_{it} represents a vector of determinist components (e.g. individual effects, time effects, time trend), $\Delta z_{i,t-j}$, j=1,…, p_i, are the augmentation terms aimed at modelling serial correlation in the error terms and u_{it} is a classical, stationary error process. Under the null hypothesis of a unit root in each series z_{it}, $\rho_1 = \rho_2 = ... = \rho_N = \rho = 1$, whereas, under the alternative hypothesis of stationarity of all series z_{it}, $\rho_1 = \rho_2 = ... = \rho_N = \rho < 1$. If $\hat{\rho}$ is the OLS estimator of ρ in model (2), LL show that an appropriately standardized ADF statistic of the null hypothesis $\rho = 1$ has a standard Normal distribution as $T \to \infty$, followed by $N \to \infty$ sequentially. The main drawback of the LL test is that it forces the parameter to be the same across different individuals.

The IPS statistic can be viewed as a generalization of LL, since it allows the heterogeneity of the ρ_i coefficients. Model (2) is estimated with OLS separately for the *i*-th individual and the ADF test for the null hypothesis $\rho_i = 1$ computed. The IPS test is the average of the individual ADF tests and has a standard Normal distribution as $T \to \infty$ followed by $N \to \infty$ sequentially. Both LL and IPS tests suffer from size distortions when either N is small or N is large relative to T.[6]

Maddala and Wu (1999) propose the Fisher type test $FTT = -2\sum_{i=1}^{N} \ln p_i$, where p_i is the asymptotic p-value associated with the test of a unit root for the *i*-th individual. Since $-2\ln p_i$ has a χ^2 distribution with 2 degrees of freedom, FTT has a χ^2 distribution with $2N$ degrees of freedom as $T_i \to \infty$ for finite N. Both IPS and FTT tests relax the restriction imposed by the LL statistic such that $\rho_i = \rho$ for each individual. Moreover, FTT does not require a balanced panel and it can be applied to any type of unit root test. Conversely, the p-values in the formula for FTT have to be obtained via Monte Carlo simulation.

Once the null hypothesis of a unit root in each individual series is not rejected, it is crucial to verify whether the series are cointegrated or not. Actually, the presence of cointegration allows us to overcome the spurious regression problem and to conduct valid inference with I(1) variables. As expected given the importance of this topic, the literature on testing for cointegration in a panel context is large (see Breitung and Pesaran, 2005, for an updated survey). Pedroni (1999, 2004) in particular proposes seven cointegration tests which have become very popular among the practitioners. In the EKC context these statistics are based on the regression model (1), where the parameters β_i are indexed with respect to $i=1,...,N$ in order to allow for heterogeneity in the cointegrating vector. The null hypothesis for each of the seven tests is the absence of cointegration for each individual. Equivalently, under the null

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[6] See Baltagi (2001, p. 239).

hypothesis the residuals $\hat{u}_{it}$ from N separate regressions of the form (1) are I(1) for each individual, that is ϕ_i=1 in the *i*-th regression: $\hat{u}_{it} = \phi_i \hat{u}_{i,t-1} + \eta_{it}$.

These statistics can be divided in two classes, depending on how they deal with the cross-sectional dimension of the panel. The first class (panel statistics) is based on a pooled estimate of ϕ_i, whereas the second class (group-mean statistics) uses an average of the different ϕ_i estimated separately for each individual. It is clear that the alternative hypotheses for the two classes of tests cannot be identical. For the panel statistics the alternative hypothesis is homogeneous, i.e. $\phi_i=\phi<1$, while the group-mean statistics are against heterogeneous alternatives. As in the case of panel integration tests, the panel and group-mean statistics are normally distributed, after appropriate standardization.

On the basis of panel integration and cointegration tests, Stern (2004) and Perman and Stern (1999, 2003) present evidence for the case of sulfur where forcefully state that the Environmental Kuznets Curve does not exist. Looking at CO_2 emissions, similar negative conclusions are arrived at by Müller-Fürstenberger, Wagner, and Müller (2004) and Wagner and Müller-Fürstenberger (2004).

In this section we carry out the LL and IPS tests for panel integration, as well as the seven tests for panel cointegration proposed by Pedroni (1999). All statistics are computed using 4 different specifications of the test regression, depending on the presence or absence of a linear time trend and/or time dummies. Our empirical application considers annual data of carbon dioxide emissions (CO_2), expressed in Mt, for 24 OECD countries over the period 1960-2002. The other two crucial variables are gross domestic product (GDP), measured in billions of PPP 1995 US dollars, and population (POP), expressed in millions of units.[7]

Each test does not reject the null hypothesis of a unit root in the logarithmic transformation of per capita CO_2 for 3 of 4 different specifications of the deterministic components (see Table 3). The next step is to check whether the logarithmic transformation of per capita GDP and its second and third powers are I(1) variables. As before, the LL and IPS statistics find that the series ln(GDP/POP), $[\ln(GDP/POP)]^2$ and $[\ln(GDP/POP)]^3$ are I(1) for most of the test equations, as shown in Tables 4-6.

A relationship among I(1) variables is not statistically reliable unless the I(1) variables are cointegrated. This well-known econometric caveat implies that the ECK specification (1)

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[7] Country-specific descriptive statistics on per capita CO_2 and GDP are reported in Tables 1 and 2.

has no statistical and economic meaning unless a stationary linear relationship holds among the log of per capita CO2 and the log of per capita GDP and its second and third powers. We have empirically checked the existence of cointegration in our panel using the seven statistics introduced by Pedroni (1999) on the two classical quadratic and cubic formulations of EKC, which correspond to $\beta_3 = 0$ and $\beta_3 \neq 0$ in model (1). As in the case of panel integration, the cointegration tests are calculated for different specifications of the deterministic components in the cointegrating relationship. The empirical results for the quadratic EKC are reported in Table 7. From a simple inspection of the table, it is clear that the presence of cointegration, and thus the existence of a meaningful ECK, crucially depends on the particular test chosen and the specification of the deterministic components in the test regression (a total of 28 different combinations). Polar cases are represented by the group-mean ρ-statistic, according to which cointegration is never present in the data, and the group-mean *t*-statistic, which always concludes in favour of cointegration. Overall, the results are mixed, with 12 cases of 28 (43%) suggesting the existence of a quadratic EKC relationship. The same comments apply to the empirical findings about the presence of a cubic ECK, which are presented in Table 8. In this case the results are only slightly more favourable to panel cointegration (13 cases of 28, i.e. 46%).

We have further investigated the robustness of the notion of EKC by estimating the quadratic and cubic EKC for each country separately as well as in a pooled panel with the Fully Modified OLS (FMOLS) estimator described in Pedroni (2000). Tables 9 and 10 present the estimation results. The coefficients on ln(GDP/POP) and the square of ln(GDP/POP) in the quadratic EKC specifications are statistically significant for all countries, with the exception of Greece, Iceland, Luxemburg, New Zealand and UK. The inclusion of the time dummies does not alter the sign of the coefficients in the pooled panel model; on the contrary, it affects their magnitude, which reduces by one third in presence of temporal fixed effects. The picture offered by the estimation of the cubic EKC is different. Out of 24 countries, only 10 can exhibit statistically significant coefficients for the linear, quadratic and cubic terms. Moreover, the estimation of the pooled panel specification evidences the sensitivity of the cubic EKC to temporal fixed effects. When time dummies are included in the model, all slope coefficients change sign, reduce their size and lose statistical significance.

The combination of the results obtained by testing for panel cointegration with the findings of FMOLS estimation suggest that further empirical investigation is needed in order to draw any conclusion about the meaningfulness of the notion of EKC.

4. Tests of Panel Fractional Integration and Fractional Cointegration

In Section 3 it is noted that the aforementioned unit root tests are the standard ones (though in a panel context) where the order of integration of time series is allowed to take on only integer values. So, for instance, a linear combination between pollutant and income gives rise (does not give rise) to a valid EKC only if it is integrated of order zero (one). As a matter of fact, recent progress in econometrics has led to the formulation of the notion and tests of fractional integration and cointegration, according to which the order of integration of a series needs not be an integer. The consequence of this fact is that there is a continuum of possibilities for time series to cointegrate – and therefore for the existence of EKCs – thus overcoming the zero-one divide.

We have already defined an I(d) time series z_t as a series which needs to be differenciated d times in order to be stationary, or I(0). Formally, if z_t is I(d), then $\Delta^d z_t = (1-L)^d z_t$ is I(0), where L is the lag operator ($Lx_t = x_{t-1}$). If we allow d to be any real value, the polynomial in L can be expanded infinitely as:

$$(1-L)^d = 1 - dL - (1/2)d(1-d)L^2 - \ldots - (1/j!)d(1-d)(2-d)\ldots((j-1)-d)L^j - \ldots \qquad (3)$$

If $d=0$ in expression (3), z_t is stationary and possesses “short memory”, since its autocorrelations die away very rapidly. If $0<d<1/2$, z_t is still stationary, however its autocorrelations take more time to vanish. When $1/2 \leq d < 1$, z_t is no longer stationary, but it is still mean reverting, that is shocks to the series tend to disappear in the long-run. Finally, if $d \geq 1$, z_t is nonstationary and non-mean reverting (Gil-Alana, 2006). Thus, the knowledge of the fractional differencing parameter d is crucial to describe the degree of persistence in any time series, which typically increases with the value of d.

The econometric literature offers different methods to estimate and test the fractional differencing parameters d, which are generally complicated to implement even in a single equation context. A popular method is proposed by Geweke and Porter-Hudak (1983), who use a semiparametric procedure to obtain an estimate of d based on the slope of the spectrum around the zero frequency. Conversely, Sowell (1992) and Beran (1995) estimate the exact maximum likelihood function of an autoregressive (AR), fractionally integrated (FI) moving-average (MA) model for z_t using parametric recursive procedures. Robinson (1994) proposes a Lagrange Multiplier type of test of the null hypothesis $d=d_0$, where d_0 is any real value. His test depends on functions of the periodogram and of the spectral density function of the error process for z_t (see Gil-Alana, 2002, 2005 for an extension of the Robinson's test to deal with structural breaks and for a critical evaluation of its performance). A simpler approach to the estimation and testing of d notices that expression (3) allows us to describes z_t as an infinitely lengthy AR polynomial:

$$\left(1-L\right)^d z_t = z_t - \varphi_1 z_{t-1} - \varphi_2 z_{t-2} - .... = u_t \tag{4}$$

where u_t is a classical error process and the parameters φ_j, j=1,2,..., are subject to the restrictions: $\varphi_1=d$, $\varphi_2=(1/2)d(1-d)$, ..., $\varphi_j=(1/j!)d(1-d)(2-d)...((j-1)-d)$, ...[8] Moreover, although they are always numerically different from zero, the parameters φ_j become very small quite rapidly. This means that the fractionally differencing parameter d can be estimated from model (4) using nonlinear least squares and a relatively small value of j.

The notion of cointegration has been recently extended to fractional cointegration (Cheung and Lai, 1993; Baillie and Bollerslev, 1994; Jeganathan, 1999; Davidson, 2002; Caporale and Gil-Alana, 2004; Robinson and Iacone, 2005). Given a vector of variables Z_t, its components are said to be fractionally cointegrated of order (d, b), if: i) all components of Z_t are $I(d)$, and ii) there exists a cointegrating vector $\tilde{\beta}$ such that $\tilde{\beta}' Z_t$ is $I(d-b)$, $b>0$. In order to test for fractional cointegration, a two-step procedure can be used. First, the order of integration for each component of Z_t has to be estimated and its statistical significance tested. Second, if all components of Z_t have the same order of integration, say d, the residuals from the cointegrating regression can be estimated and their order of integration tested. If the null hypothesis that the order of integration of the residuals is equal to d cannot be rejected, then the series are not fractionally cointegrated. On the contrary, if this null hypothesis is rejected in favour of a degree of integration which is less than d, then the series are fractionally

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[8] See, among others, Franses (1998, p. 79).

cointegrated. The values of *d* and *b* can be estimated and tested by applying the same statistics for fractional integration to the cointegrating residuals. In this context, Krämer (1998) has shown that the popular ADF unit root test is consistent if the order of autoregression of the series does not tend to infinity too fast.

In this section we perform tests for panel fractional integration and cointegration, that is we allow the order of integration d_i of a generic variable z_{it} to take any real value, while in the traditional view d_i is typically limited to be equal to 0, 1 or (rarely) 2. Estimates of the fractional differencing parameter d_i have been obtained using a nonlinear Seemingly Unrelated Regressions (SUR) estimator on the following panel extension of model (4):

$$z_{it} = c_i + d_i z_{i,t-1} + (1/2)d_i(1-d_i)z_{i,t-2} + ... + (1/j!)d_i(1-d_i)(2-d_i)...((j-1)-d_i)z_{i,t-j} + ... + u_{it} \quad (5)$$

where the variable z_{it} is equal, in turn, to $\ln(CO_2/POP)_{it}$, $\ln(GDP/POP)_{it}$, $[\ln(GDP/POP)_{it}]^2$ and $[\ln(GDP/POP)_{it}]^3$. The value of *j* in (5), which controls the length of the AR approximation (3), is chosen to be equal to 8, and corresponds to the minimum number of lags for which the null hypothesis of no residual autocorrelation in the unrestricted version of model (5) is not rejected. Significance of the d_i parameters is carried out on the basis of robust asymptotic standard errors. Relative to the traditional panel integration and cointegration tests illustrated in Section 3, our procedure has the advantage of taking into explicit account panel heterogeneity, since the fractional differencing parameters d_i are allowed to vary across individuals.

Table 11 report the results of estimating and testing the significance of d_i for each country and the log transformed per capita CO_2, as well as per capita GDP and its powers. For the log of per capita GDP and its powers the minimum value of d_i is attained at 0.678 in correspondence of ln(GDP/POP) for Japan. This finding implies that the log of per capita GDP and its nonlinear transformations are in general nonstationary, although shocks to these series tend to die away in the long-run. The situation is different when we test the dependent variable in the classical EKC specification for fractional integration. In 6 countries of 24 (namely, Austria, Finland, Italy, Japan, The Netherlands and Switzerland) the values of d_i are below 0.5, denoting a stationary behaviour of $\ln(CO_2/POP)$. Since the order of panel fractional integration of the variables has to be comparable for fractional cointegration to be a meaningful concept, the 6 aformentioned countries are excluded from the subsequent cointegration analysis.

Panel fractional cointegration tests are conducted using model (5) where z_{it} is now the residuals from the quadratic and cubic EKC specifications. From the empirical findings reported in Table 12, both EKC specifications are statistically adequate for 7 countries out of 18 (Australia, Denmark, Ireland, New Zealand, Portugal, Turkey and UK), while Norway supports the cubic EKC relationship only.

The final stage of our empirical analysis is to estimate the parameters of the quadratic and cubic EKC with a panel fixed-effect estimator only for those countries which support the presence of panel fractional cointegration. The panel estimates of the quadratic EKC are illustrated in Table 13. For all countries the slope parameters are statistically significant, with the exception of New Zealand (α and β_1 not significant, β_2 significant at 10%). The table provides also the computation of the so-called "turning points", i.e. the level of income which corresponds to CO_2 decline as income further increases. Figures 1-7 facilitate the interpretation of the estimation results. Australia, Ireland and Turkey are still on the ascending part of their EKC (see Figures 1, 3 and 6, graph a), since their respective turning points are expected to occur for income values which are not included in our sample (see Figures 1, 3 and 6, graph b). Conversely, Denmark has already reached the turning point and is presently at the beginning of the downward sloping part of its EKC (Figure 2, graphs a and b), whereas UK seems to have started the process of reducing per capita CO_2 emissions since the early Eighties (Figure 7, graph a). The predictions about New Zealand and Portugal are not informative, since their EKC are not concave (Figures 4 and 5). Estimates of the cubic EKC specifications are reported in Table 14, while Figures 8-15 represent the in-sample as well as the out-of-sample evolution of the individual EKC. Of 8 countries which support the hypothesis of panel fractional cointegration, only 3 suffer from misspecification of the cubic EKC relationship. For Australia, the fixed-effect coefficient α and the slope coefficients β_1, β_2 and β_3 are not statistically significant at conventional levels. Denmark shows that the quadratic and the cubic terms are statistically not relevant, while the log of per capita GDP is significant only at 10%. In the case of Turkey, the only statistically significant coefficient is the individual country effect. Among the remaining countries, Ireland, New Zealand, Norway and Portugal are on the upward sloping part of their individual EKC (see Figures 10, 11, 12 and 13). With respect to the quadratic specification, per capita CO_2 emissions in Ireland are increasing at an increasing rate. As in the quadratic case, the cubic EKC for UK is suggesting that this country has started the reduction of per capita CO_2 emission quite early, although, in contrast with the predictions of the quadratic EKC, it is now experiencing decreasing rates of per capita CO_2 reductions.

To summarize, the concepts of panel fractional integration and cointegration that we have introduced in this paper extend the notion of EKC, in that they introduce more flexibility in determining the order of integration of (and the presence of cointegration among) the variables entering the classical specifications of EKC. The existence of a unit root in the log of per capita CO_2 and GDP series, in addition to the absence of a unit root in the linear combination among these variables, are pre-requisites in order for the notion of EKC to be statistically and economically meaningful. Nonetheless, our empirical analysis has pointed out that the EKC still remains a very fraglie concept.

5. Conclusions and Further Open Issues

In this paper we carry out tests of fractional integration and of fractional cointegration extended to a panel context. We use as an example the case of carbon dioxide for 24 OECD countries over the period 1960-2002.

Our main findings can be summarized as follows. First, traditional panel integration tests such as LL and IPS do not reject the null hypothesis of a unit root in the log of per capita CO_2, per capita GDP and its second and third powers. These findings are generally independent of the choice of a particular statistic and of a specific model for the deterministic components. Second, the existence of a meaningful ECK crucially depends on the particular panel cointegration test chosen and the specification of the deterministic components in the test regression. Overall, the results are mixed, with 12 cases of 28 (43%) suggesting the existence of a quadratic EKC relationship. The same comments apply to the empirical findings about the presence of a cubic ECK, which are only slightly more favourable to panel cointegration (13 cases of 28, i.e. 46%). Third, the estimation of the quadratic and cubic EKC for each country separately as well as in a pooled panel with the Fully Modified OLS (FMOLS) estimator reveals that the coefficients in the quadratic EKC specifications are statistically significant for all countries, with the exception of Greece, Iceland, Luxemburg, New Zealand and UK. The picture offered by the estimation of the cubic EKC is different. Out of 24 countries, only 10 can exhibit statistically significant coefficients for the linear, quadratic and cubic terms. Fourth, panel fractional integration estimation and testing show that for the log of per capita GDP and its powers the minimum value of the fractional integration parameter d_i is attained at 0.678 in correspondence of ln(GDP/POP) for Japan. This finding implies that the log of per capita GDP and its nonlinear transformations are in general nonstationary, although shocks to these series tend to die away in the long-run. The situation is different when we test the dependent variable in the classical EKC specification for fractional integration. In 6 countries of 24 the values of d_i are below 0.5, denoting a stationary behaviour of ln(CO_2/POP). Fifth, panel fractional cointegration tests suggest that both EKC specifications are statistically adequate for 7 countries out of 18, while Norway supports the cubic EKC relationship only. Sixth, the fixed-effect panel estimates of the quadratic EKC indicate that for all countries the slope parameters are statistically significant, with the exception of New Zealand. Of 8 countries which support the hypothesis of panel fractional cointegration, only 3 suffer from misspecification of the cubic EKC relationship.

To summarize, the combination of the results obtained by testing for panel cointegration with the findings of FMOLS estimation suggests that further empirical investigation is needed in order to draw any conclusion about the meaningfulness of the notion of EKC. Moreover, the concepts of panel fractional integration and cointegration that we have introduced in this paper extend the notion of EKC, in that they introduce more flexibility in determining the order of integration of (and the presence of cointegration among) the variables entering the classical specifications of EKC. The existence of a unit root in the log of per capita CO_2 and GDP series, in addition to the absence of a unit root in the linear combination among these variables, are pre-requisites in order for the notion of EKC to be statistically and economically meaningful. Nonetheless, our empirical analysis has pointed out that the EKC still remains a very fraglie concept.

Although this paper represents a contribution in the direction of checking the statistical robustness of the EKC, nevertheless we believe that further theoretical and empirical investigation is needed before any unquestionable conclusion can be drawn on the existence of EKC. In particular, at least three are the open issues. First, the robustness of traditional, as well as fractional, panel integration and cointegration tests merits additional attention. On the one hand, many popular panel integration tests rely on implausible assumptions on the behaviour of the error terms (e.g. independent and identically distributed) and on the data generating process (e.g. absence of structural breaks), while critical values for the majority of traditional cointegration tests are simulated and hence heavily dependent on the Monte Carlo experimental design. On the other hand, more precise methods for estimating and testing the fractional differencing parameter d_i than the one used in this paper should be extended to a panel framework (for instance, Davidson, 2002, proposes boostrapped standard errors in multivariate fractional cointegrating models). Second, many panel integration and cointegration testing procedures impose the unrealistic assumption of cross-sectional independence. Although the panel fractional integration and cointegration approaches adopted in this paper have the advantage of taking explicitly into account panel heterogeneity, further investigation should be welcome. Finally, the statistical properties of nonlinear transformations of integrated variables are generally unkown (see McAleer, McKenzie and Pesaran, 1994; Kobayashi and McAleer, 1999). That is, if GDP is I(1), it is easy to show that the logarithmic transformation of GDP cannot have a unit root, the same being true for powers of GDP and of log GDP. Moreover, if GDP and POP are both I(1), nothing can be said about the order of integration of per capita GDP. Given the typical structure of the EKC specification, the importance of additional research in this area is evident.

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Table 1. CO_2/POP - descriptive statistics

Country	Obs.	Mean	Median	Max.	Min.	Std. Dev.
Australia	43	13.473	14	17.003	8.822	2.355
Austria	43	6.965	7.207	8.591	4.492	1.084
Belgium	43	11.501	11.374	14.081	8.994	1.172
Canada	43	15.234	15.652	17.693	10.486	1.803
Denmark	43	10.540	10.615	13.382	6.712	1.440
Finland	43	9.498	10.598	12.817	3.347	2.678
France	43	6.959	6.606	9.200	5.571	1.113
Germany	43	11.240	11.750	14.303	7.204	2.131
Greece	43	4.607	4.615	8.012	0.872	2.246
Ireland	43	7.807	7.554	11.057	4.749	1.707
Italy	43	5.867	6.352	7.409	2.050	1.526
Japan	43	7.298	7.715	9.277	2.843	1.877
Luxembourg	43	32.669	28.472	47.600	16.698	10.102
The Netherlands	43	9.886	10.425	11.525	6.050	1.456
New Zealand	43	6.261	6.163	8.770	4.177	1.232
Norway	43	6.340	6.505	8.543	3.584	1.260
Poland	43	9.593	9.233	12.324	6.849	1.716
Portugal	43	2.864	2.517	6.089	0.703	1.649
Spain	43	4.577	4.853	7.468	1.721	1.586
Sweden	43	7.575	6.953	11.578	5.140	1.972
Switzerland	43	5.732	6.023	6.812	3.368	0.817
Turkey	43	1.789	1.746	3.046	0.592	0.722
UK	43	10.299	10.105	11.688	8.981	0.800
USA	43	19.534	19.614	22.289	15.556	1.660

Notes. CO_2/POP is the ratio between carbon dioxide emissions expressed in Mt (CO_2) and population measured in millions of units (POP); Obs = number of observations (annual data from 1960 to 2002); Mean = sample mean; Median = sample median; Min. = minimum value in the sample; Max. = maximum value in the sample; Std. Dev. = standard deviation.

Table 2. GDP/POP - descriptive statistics

Country	Obs.	Mean	Median	Max.	Min.	Std. Dev.
Australia	43	16.780	16.271	24.927	10.074	4.101
Austria	43	17.016	17.152	26.307	8.133	5.492
Belgium	43	16.531	16.896	24.620	8.183	4.895
Canada	43	18.295	15.526	26.843	10.373	4.535
Denmark	43	18.258	17.926	25.838	10.633	4.109
Finland	43	15.548	16.025	24.360	7.413	4.889
France	43	16.350	16.719	23.727	8.232	4.482
Germany	43	16.220	16.126	23.499	8.746	4.592
Greece	43	10.848	11.843	16.123	4.379	3.076
Ireland	43	12.434	10.785	29.885	5.297	6.472
Italy	43	15.579	15.925	23.065	7.197	4.812
Japan	43	15.437	15.334	23.872	4.492	6.209
Luxembourg	43	22.538	18.500	42.682	11.839	9.390
The Netherlands	43	17.172	16.887	25.365	9.549	4.522
New Zealand	43	15.073	15.187	19.450	11.097	2.028
Norway	43	16.847	16.437	28.132	7.721	6.361
Poland	43	6.643	6.665	9.739	3.981	1.463
Portugal	43	9.302	9.015	15.781	3.272	0.127
Spain	43	11.919	11.441	19.309	4.864	3.907
Sweden	43	17.760	17.544	25.394	10.204	4.061
Switzerland	43	22.772	22.989	27.591	15.324	3.483
Turkey	43	4.263	4.169	6.185	2.467	1.111
UK	43	15.516	14.591	23.607	9.724	3.977
USA	43	21.898	21.249	31.992	13.153	5.568

Notes. GDP/POP is the ratio between gross domestic product expressed in billions of PPP 1995 US dollars (GDP) and population measured in millions of units (POP); Obs = number of observations (annual data from 1960 to 2002); Mean = sample mean; Median = sample median; Min. = minimum value in the sample; Max. = maximum value in the sample; Std. Dev. = standard deviation.

Table 3. Panel integration - unit root tests for ln(CO_2/POP)

Test	Model I	Model II	Model III	Model IV
LL ρ-statistic	-0.80583	1.78298	0.59462	-3.2925**
LL t-ρ-statistic	-2.00842*	-1.02564	0.43421	-1.81852
LL ADF-statistic	-0.02421	-0.19342	2.17863*	-1.12808
IPS ADF-statistic	-1.74864	-0.32272	0.79214	-2.38968*

Notes. CO_2/POP is the ratio between carbon dioxide emissions expressed in Mt (CO_2) and population measured in millions of units (POP). LL refers to Levin and Lin (1992, 1993); IPS indicates Im, Pesaran and Shin (2003); all test statistics have a standard Normal distribution, after appropriate scaling; LL and IPS tests are calculated using the RATS procedure PANCOINT.SRC and RATS (2004); * (**) indicates a rejection of the null hypothesis of a unit root at the 5% (1%) statistical level; each test is computed using four different specifications: i) no trend, no time dummies (Model I); ii) trend, no time dummies (Model II); iii) no trend, time dummies (Model III); iv) trend, time dummies (Model IV).

Table 4. Panel integration - unit root tests for ln(GDP/POP)

Test	Model I	Model II	Model III	Model IV
LL ρ-statistic	2.00873*	2.12912*	0.26864	0.16235
LL t-ρ-statistic	0.96456	-0.54808	0.63892	-0.33855
LL ADF-statistic	4.8021**	-0.56807	0.36504	-0.82579
IPS ADF-statistic	6.5250**	-0.56213	-0.58605	-1.04530

Notes. GDP/POP is the ratio between gross domestic product expressed in billions of PPP US dollars (GDP) and population measured in millions of units (POP). LL refers to Levin and Lin (1992, 1993); IPS indicates Im, Pesaran and Shin (2003); all test statistics have a standard Normal distribution, after appropriate scaling; LL and IPS tests are calculated using the RATS procedure PANCOINT.SRC and RATS (2004); * (**) indicates a rejection of the null hypothesis of a unit root at the 5% (1%) statistical level; each test is computed using four different specifications: i) no trend, no time dummies (Model I); ii) trend, no time dummies (Model II); iii) no trend, time dummies (Model III); iv) trend, time dummies (Model IV).

Table 5. Panel integration - unit root tests for $[\ln(GDP/POP)]^2$

Test	Model I	Model II	Model III	Model IV
LL ρ-statistic	2.7836**	1.23275	1.41423	0.87156
LL t-ρ-statistic	2.71262**	-0.17835	2.42747*	0.20555
LL ADF-statistic	5.1280**	-1.11773	1.40783	-0.63369
IPS ADF-statistic	6.86365*	-1.70206	0.70408	-1.31288

Notes. See Table 4.

Table 6. Panel integration - unit root tests for $[\ln(GDP/POP)]^3$

Test	Model I	Model II	Model III	Model IV
LL ρ-statistic	3.51197**	-0.10296	2.15658*	1.47148
LL t-ρ statistic	4.32777**	0.07674	3.39633**	0.59033
LL ADF statistic	5.79863**	-1.30530	1.82047	-0.77377
IPS ADF statistic	7.73874**	-1.77127	0.85577	-1.63066

Notes. See Table 5.

Table 7. Panel cointegration - Quadratic EKC

Test	Model I	Model II	Model III	Model IV
Panel *v*-statistic	3.07897**	1.14465	0.13798	0.75297
Panel ρ-statistic	-2.50054*	-0.72121	-0.68051	-0.97762
Panel *t*-statistic	-2.92589**	-2.62990**	-1.70974	-3.11806**
Panel ADF-statistic	-1.52018	-1.00369	-0.56789	-2.96972**
Group ρ-statistic	-1.85558	-0.22477	-0.87717	-0.55732
Group *t*-statistic	-3.14850**	-2.66915**	-2.58476**	-3.50957**
Group ADF-statistic	-2.05220*	-1.53475	-1.13691	-3.13127**

Notes. The panel cointegration tests refer to Pedroni (1999); each statistic has an asymptotic standard Normal distribution, after appropriate standardization (see Pedroni, 1999, pp. 665-668); each test is calculated using the RATS procedure PANCOINT.SRC and RATS (2004); * (**) indicates a rejection of the null hypothesis of a unit root (no cointegration) at the 5% (1%) statistical level; each test is computed using four different specifications: i) no trend, no time dummies (Model I); ii) trend, no time dummies (Model II); iii) no trend, time dummies (Model III); iv) trend, time dummies (Model IV).

Table 8. Panel cointegration - Cubic EKC

Test	Model I	Model II	Model III	Model IV
Panel *v*-statistic	2.21195*	1.71434	0.62138	1.21331
Panel ρ-statistic	-1.78383	-0.96139	-0.39501	-1.89025
Panel *t*-statistic	-3.33697**	-3.93661**	-1.58988	-5.24341**
Panel ADF-statistic	-2.13247*	-1.92477	-0.75376	-3.89309**
Group ρ-statistic	-1.31916	-0.19691	-0.34388	-1.05499
Group *t*-statistic	-4.10958**	-4.18910**	-2.24964*	-5.58851**
Group ADF-statistic	-3.48292**	-3.32308**	-1.54318	-5.19425**

Notes. See Table 7.

Table 9. FMOLS estimates of quadratic EKC

Individual FMOLS estimates				
Country	$\hat{\beta}_1^*$	t-statistic	$\hat{\beta}_2^*$	t-statistic
Australia	9.57	3.77	-0.46	-3.98
Austria	10.76	4.29	-0.54	-4.15
Belgium	12.89	2.51	-0.67	-2.49
Canada	26.77	5.80	-1.36	-5.72
Denmark	35.63	5.16	-1.81	-5.12
Finland	32.62	6.28	-1.67	-6.10
France	33.09	5.98	-1.74	-6.01
Germany	42.48	9.56	-2.19	-9.48
Greece	-10.31	-1.88	0.68	2.23
Iceland	2.26	0.83	-0.11	-0.80
Ireland	5.00	4.23	-0.24	-3.82
Italy	24.75	7.81	-1.25	-7.54
Japan	9.79	5.49	-0.49	-5.15
Luxemburg	-0.82	-0.13	0.00	0.01
The Netherlands	18.59	5.84	-0.94	-5.68
New Zealand	-25.94	-1.74	1.43	1.84
Norwey	12.14	3.50	-0.61	-3.37
Poland	36.42	3.35	-2.07	-3.31
Portugal	-4.08	-3.75	0.31	5.06
Spain	8.56	3.13	-0.40	-2.71
Sweden	72.73	5.33	-3.78	-5.38
Switzerland	88.58	10.65	-4.41	-10.57
Turkey	15.96	8.28	-0.76	-7.40
UK	5.15	1.49	-0.28	-1.57
USA	19.76	3.66	-0.99	-3.64

Pooled panel FMOLS estimates without time dummies			
$\hat{\beta}_1^*$	t-statistic	$\hat{\beta}_2^*$	t-statistic
19.29	19.89	-0.98	-18.87

Pooled panel FMOLS estimates with time dummies			
$\hat{\beta}_1^*$	t-statistic	$\hat{\beta}_2^*$	t-statistic
6.64	17.30	-0.31	-17.19

Notes. The Fully Modified OLS (FMOLS) estimator is described in Pedroni (2000) and computed using Pedroni's RATS program PANGROUP.PRG as well as RATS (2004); parameter estimates refer to the quadratic EKC:

$$\ln\left(\frac{CO2}{POP}\right)_{it} = \alpha_i + \beta_{1i}\ln\left(\frac{GDP}{POP}\right)_{it} + \beta_{2i}\left[\ln\left(\frac{GDP}{POP}\right)_{it}\right]^2 + u_{it}\,.$$

Table 10. FMOLS estimates of cubic EKC

Individual FMOLS estimates

Country	$\hat{\beta}_1^*$	t-statistic	$\hat{\beta}_2^*$	t-statistic	$\hat{\beta}_3^*$	t-statistic
Australia	98.35	0.60	-9.58	-0.57	0.31	0.54
Austria	198.75	1.80	-20.10	1.75	0.68	1.71
Belgium	586.37	2.80	-60.53	-2.78	2.08	2.75
Canada	499.65	2.27	-50.21	-2.22	1.68	2.17
Denmark	643.75	1.52	-64.47	-1.49	2.15	1.45
Finland	703.78	4.04	-72.21	-3.94	2.47	3.86
France	194.15	0.63	-18.59	-0.58	0.59	0.52
Germany	-377.49	-1.44	41.57	1.52	-1.52	1.60
Greece	95.91	0.43	-11.12	-0.45	0.44	0.48
Iceland	141.56	1.32	-14.57	-1.31	0.50	1.30
Ireland	97.35	2.71	-10.13	-2.65	0.35	2.60
Italy	477.87	4.49	-48.97	-4.37	1.67	4.27
Japan	83.38	1.35	-8.42	-1.27	0.28	1.21
Luxemburg	-41.67	-0.15	4.17	0.15	-0.14	-0.15
The Netherlands	304.84	1.77	-30.64	-1.72	1.03	1.67
New Zealand	-618.48	-0.38	64.04	0.37	-2.28	-0.38
Norway	482.33	7.19	-49.53	-7.10	1.69	7.02
Poland	-1060.25	-1.92	123.73	1.96	-4.79	-1.99
Portugal	-95.95	-3.30	10.62	3.26	-0.39	-3.17
Spain	-54.74	-0.48	6.57	0.53	-0.26	-0.57
Sweden	1956.22	3.06	-198.42	-3.01	6.70	2.96
Switzerland	1189.33	1.27	-114.94	-1.22	3.68	1.17
Turkey	-40.30	-0.40	5.88	0.48	-0.27	-0.55
UK	377.72	1.83	-39.11	-1.82	1.35	1.81
USA	919.10	3.97	-91.70	-3.93	3.05	3.90

Pooled panel FMOLS estimates without time dummies

$\hat{\beta}_1^*$	t-statistic	$\hat{\beta}_2^*$	t-statistic	$\hat{\beta}_3^*$	t-statistic
270.33	7.00	-26.27	-6.78	0.85	6.59

Pooled panel FMOLS estimates with time dummies

$\hat{\beta}_1^*$	t-statistic	$\hat{\beta}_2^*$	t-statistic	$\hat{\beta}_3^*$	t-statistic
-51.43	-4.62	6.18	4.98	-0.24	-5.22

Notes. The Fully Modified OLS (FMOLS) estimator is described in Pedroni (2000) and computed using Pedroni's RATS program PANGROUP.PRG as well as RATS (2004); parameter estimates refer to the cubic EKC: $\ln\left(\frac{CO2}{POP}\right)_{it} = \alpha_i + \beta_{1i}\ln\left(\frac{GDP}{POP}\right)_{it} + \beta_{2i}\left[\ln\left(\frac{GDP}{POP}\right)_{it}\right]^2 + \beta_{3i}\left[\ln\left(\frac{GDP}{POP}\right)_{it}\right]^3 + u_{it}$.

Table 11. Fractional integration - summary of the empirical results

Country	$\ln\frac{CO_2}{POP}$	$\ln\frac{GDP}{POP}$	$\left(\ln\frac{GDP}{POP}\right)^2$	$\left(\ln\frac{GDP}{POP}\right)^3$
Australia	0.616	1.057	1.093	1.122
Austria	0.490	0.809	0.861	0.932
Belgium	0.886	0.823	0.873	0.936
Canada	1.116	1.275	1.196	1.197
Denmark	0.570	0.919	0.957	0.993
Finland	0.342	1.478	1.444	1.463
France	1.002	0.792	0.842	0.913
Germany	1.124	0.823	0.872	0.924
Greece	0.613	0.679	1.293	1.277
Ireland	0.703	1.381	1.488	1.591
Italy	0.369	0.779	0.838	0.902
Japan	0.356	0.678	0.767	0.843
Luxembourg	0.972	1.062	1.127	1.177
The Netherlands	0.339	1.606	1.545	1.503
New Zealand	0.698	0.978	1.017	1.045
Norway	0.541	0.932	1.019	1.142
Poland	1.194	1.339	1.313	1.296
Portugal	0.763	1.423	1.399	1.378
Spain	0.645	1.671	1.659	1.658
Sweden	0.899	1.375	1.329	1.318
Switzerland	0.141	1.319	1.271	1.264
Turkey	0.633	0.726	0.753	0.760
UK	0.698	1.055	1.099	1.147
USA	1.061	0.987	1.001	1.023

Notes. The figures presented in this table are the estimated fractional differencing parameters d_i . Estimates of d_i are obtained using nonlinear SUR on the restricted system of equations:

$$z_{it} = c_i + d_i z_{i,t-1} + (1/2)d_i(1-d_i)z_{i,t-2} + \ldots + (1/j!)d_i(1-d_i)(2-d_i)\ldots((j-1)-d_i)z_{i,t-j} + \ldots + u_{it},$$

where i=1,...,N, t=1,...,T and z_{it} = ln(CO$_2$/POP)$_{it}$, ln(GDP/POP)$_{it}$, [ln(GDP/POP)$_{it}$]^2, [ln(GDP/POP)$_{it}$]^3.

The panel size is T=43 (annual data from 1960 to 2002) and N=24 (number of OECD countries); j = 8 is the minimum number of lags for which the null hypothesis of no residual autocorrelation in the following unrestricted system of equations is not rejected: $z_{it} = \varphi_{1i} z_{i,t-1} + \varphi_{2i} z_{i,t-2} + \ldots + \varphi_{ji} z_{i,t-j} + \ldots + u_{it}$; all estimates are statistically significant at 1%; all computations have been carried out using RATS (2004).

Table 12. Fractional cointegration - summary of the empirical results

Country	Quadratic EKC	Cubic EKC
Australia	0.296	0.287
Belgium	0.692	0.626
Canada	0.835	0.739
Denmark	0.253	0.268
France	0.780	0.742
Germany	0.543	0.550
Greece	0.920	0.818
Ireland	0.479	0.482
Luxembourg	0.981	0.921
New Zealand	0.296	0.251
Norway	0.589	0.270
Poland	0.919	0.957
Portugal	0.223	-0.158
Spain	0.583	0.619
Sweden	0.877	0.713
Turkey	-0.121	-0.074
UK	0.490	0.413
USA	1.059	0.974

Notes. The figures presented in this table are the estimated fractional differencing parameters d_i. Estimates of di are obtained with nonlinear SUR on the following restricted system of equations: $\hat{u}_{it} = d_i\hat{u}_{i,t-1} + (1/2)d_i(1-d_i)\hat{u}_{i,t-2} + \ldots + (1/j!)d_i(1-d_i)(2-d_i)\ldots((j-1)-d_i)\hat{u}_{i,t-j} + \ldots + \varepsilon_{it}$, where i=1,...,N, t=1,...,T and $\hat{u}_{it}$ are the panel residuals from quadratic and cubic EKC; j = 8 is the minimum number of lags for which the null hypothesis of no residual autocorrelation in the following unrestricted system of equations is not rejected: $\hat{u}_{it} = \varphi_1\hat{u}_{i,t-1} + \varphi_2\hat{u}_{i,t-2} + \ldots + \varphi_j\hat{u}_{i,t-j} + \ldots + \varepsilon_{it}$; all estimates are statistically significant at 1%, with the exception of Portugal (significant at 5%) and Turkey (not significant) ; all computations have been carried out using RATS (2004).

Table 13. Panel estimates of quadratic EKC

Country	Parameter		standard error	t-statistic	p-value	Turning point	
						$\ln\frac{GDP}{POP}$	$\frac{GDP}{POP}$
Australia	α	-3.172	0.486	-6.530	0.000	3.520	33.790
	β_1	3.435	0.351	9.785	0.000		
	β_2	-0.488	0.063	-7.733	0.000		
Denmark	α	-12.020	1.439	-8.348	0.000	2.938	18.876
	β_1	9.845	1.019	9.654	0.000		
	β_2	-1.675	0.179	-9.321	0.000		
Ireland	α	-0.555	0.159	-3.480	0.000	3.494	32.914
	β_1	1.672	0.128	13.013	0.000		
	β_2	-0.239	0.025	-9.474	0.000		
New Zealand	α	2.874	2.602	1.104	0.269	-	-
	β_1	-2.186	1.935	-1.129	0.259		
	β_2	0.662	0.359	1.842	0.066		
Portugal	α	-1.133	0.163	-6.951	0.000	-	-
	β_1	0.347	0.165	2.098	0.036		
	β_2	0.263	0.041	6.486	0.000		
Turkey	α	-3.375	0.159	-21.196	0.000	2.471	11.835
	β_1	3,879	0.235	16.479	0.000		
	β_2	-0.785	0.085	-9.264	0.000		
UK	α	0.638	0.524	1.218	0.224	2.350	10.483
	β_1	1.492	0.387	3.856	0.000		
	β_2	-0.317	0.071	-4.470	0.000		

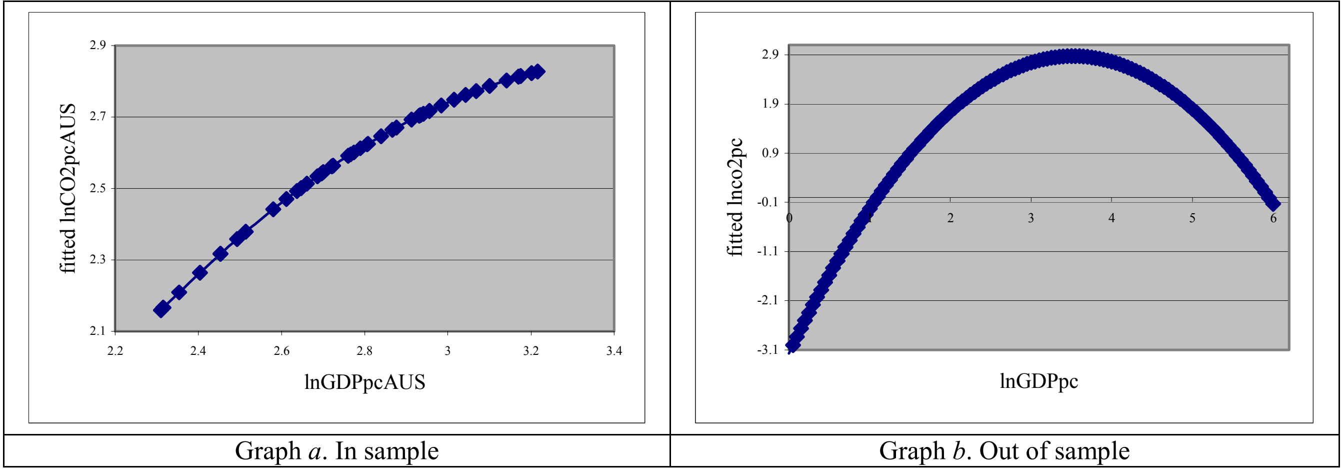
Notes. Parameter estimates are obtained with a panel fixed-effect estimator on the following system of quadratic EKC: $\ln\left(\frac{CO2}{POP}\right)_{it} = \alpha_i + \beta_{1i}\ln\left(\frac{GDP}{POP}\right)_{it} + \beta_{2i}\left[\ln\left(\frac{GDP}{POP}\right)_{it}\right]^2 + u_{it}$; estimates of the turning points are computed as $\ln\frac{GDP}{POP} = \frac{\beta_{1i}}{-2\beta_{2i}}$ and $\frac{GDP}{POP} = e^{\frac{\beta_{1i}}{-2\beta_{2i}}}$, respectively; all computations have been carried out using RATS (2004).

Table 14. Panel estimates of cubic EKC

Country	Parameter		standard error	t-stat.	p-value	Turning point	
						$\ln\frac{GDP}{POP}$	$\frac{GDP}{POP}$
Australia	α	4.311	5.339	0.807	0.419	min=1.346	min=3.842
	β_1	-4.803	5.841	-0.822	0.411		
	β_2	2.517	2.119	1.188	0.235	max=3.276	max=26.870
	β_3	-0.363	0.255	-1.424	0.155		
Denmark	α	-32.141	16.401	-1.959	0.050	max=2.904	max=18.247
	β_1	31.42	17.566	1.789	0.074		
	β_2	-9.343	6.245	-1.496	0.135	min=3.990	min=54.055
	β_3	0.903	0.737	1.226	0.221		
Ireland	α	-3.364	0.811	-4.147	0.000	-	-
	β_1	5.284	1.001	5.277	0.000		
	β_2	-1.743	0.404	-4.318	0.000		
	β_3	0.203	0.053	3.814	0.000		
New Zealand	α	98.717	42.213	2.338	0.019	min=2.402	min=11.045
	β_1	-109.529	47.241	-2.318	0.020		
	β_2	40.645	17.593	2.310	0.021	max=3.069	max=21.520
	β_3	-4.953	2.180	-2.272	0.023		
Norway	α	-20.168	3.029	-6.657	0.000	-	-
	β_1	22.479	3.404	6.604	0.000		
	β_2	-7.686	1.261	-6.093	0.000		
	β_3	0.883	0.154	5.726	0.000		
Portugal	α	1.154	0.752	1.534	0.125	min=0.984	min=2.675
	β_1	-3.351	1.191	-2.812	0.005		
	β_2	2.167	0.607	3.570	0.000	max=3.602	max=36.671
	β_3	-0.315	0.100	-3.146	0.001		
Turkey	α	-2.645	0.832	-3.178	0.001	max=2.151	max=8.593
	β_1	2.197	1.895	1.159	0.247		
	β_2	0.470	1.406	0.334	0.738		
	β_3	-0.304	0.340	-0.894	0.371		
UK	α	-14.758	4.914	-3.003	0.003	max=2.423	max=11.280
	β_1	18.912	5.466	3.460	0.001		
	β_2	-6.843	2.019	-3.389	0.001	min=3.216	min=24.928
	β_3	0.809	0.247	3.269	0.001		

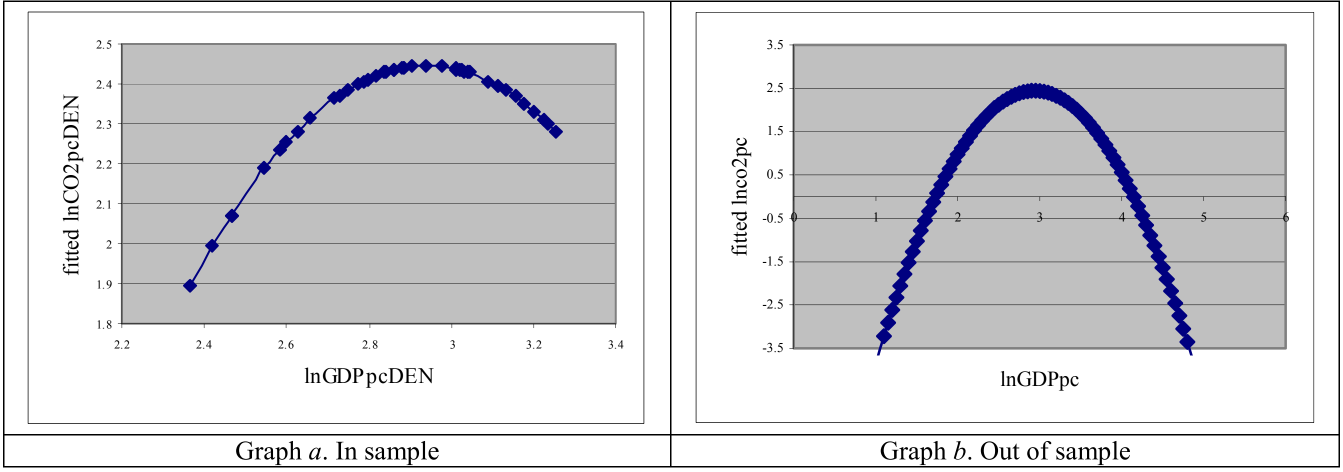
Notes. Parameter estimates are obtained with a panel fixed-effect estimator on the following system of cubic EKC: $\ln\left(\frac{CO2}{POP}\right)_{it} = \alpha_i + \beta_{1i}\ln\left(\frac{GDP}{POP}\right)_{it} + \beta_{2i}\left[\ln\left(\frac{GDP}{POP}\right)_{it}\right]^2 + \beta_{3i}\left[\ln\left(\frac{GDP}{POP}\right)_{it}\right]^3 + u_{it}$; estimates of the turning points are computed by equating to zero the value of the first derivative of the cubic EKC for each country. For countries where two values are present, min (max) indicates the relative minimum (maximum) of the EKC function; all computations have been carried out using RATS (2004).

Figure 1. Quadratic EKC - Australia



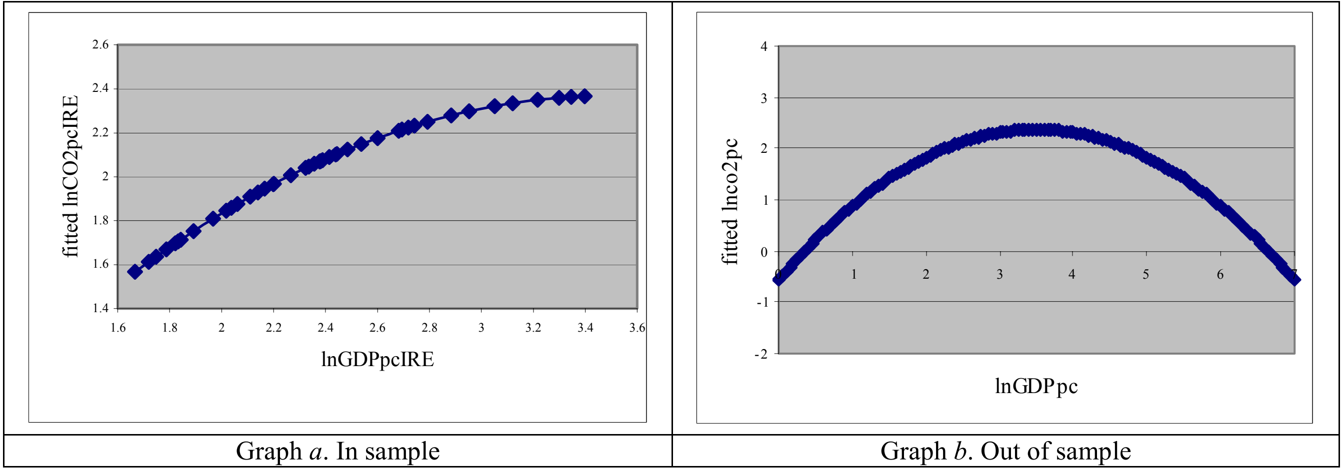
Graph *a*. In sample | Graph *b*. Out of sample

Figure 2. Quadratic EKC – Denmark



Graph *a*. In sample | Graph *b*. Out of sample

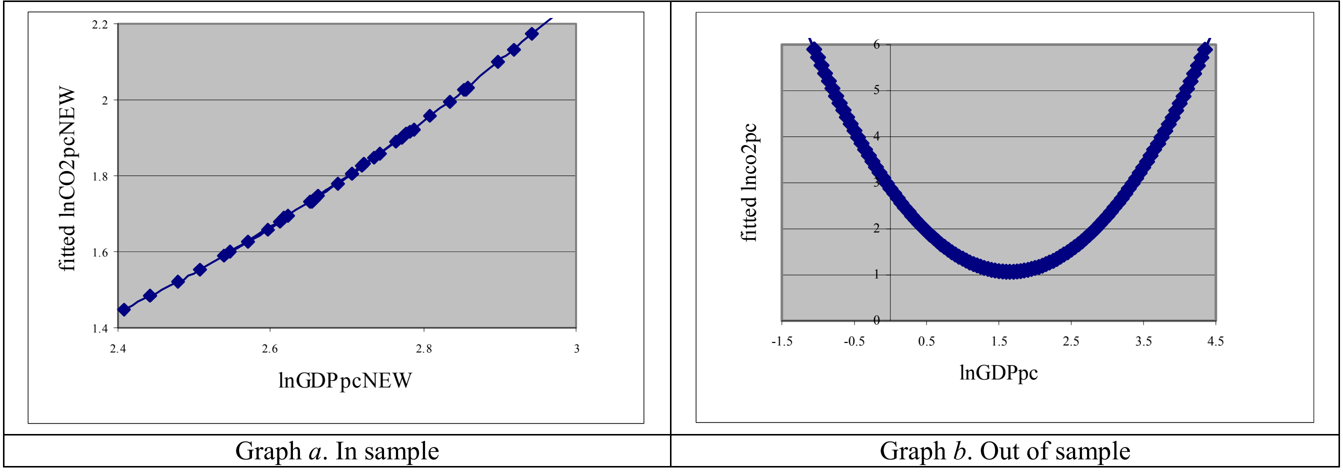
Figure 3. Quadratic EKC – Ireland



Graph *a*. In sample | Graph *b*. Out of sample

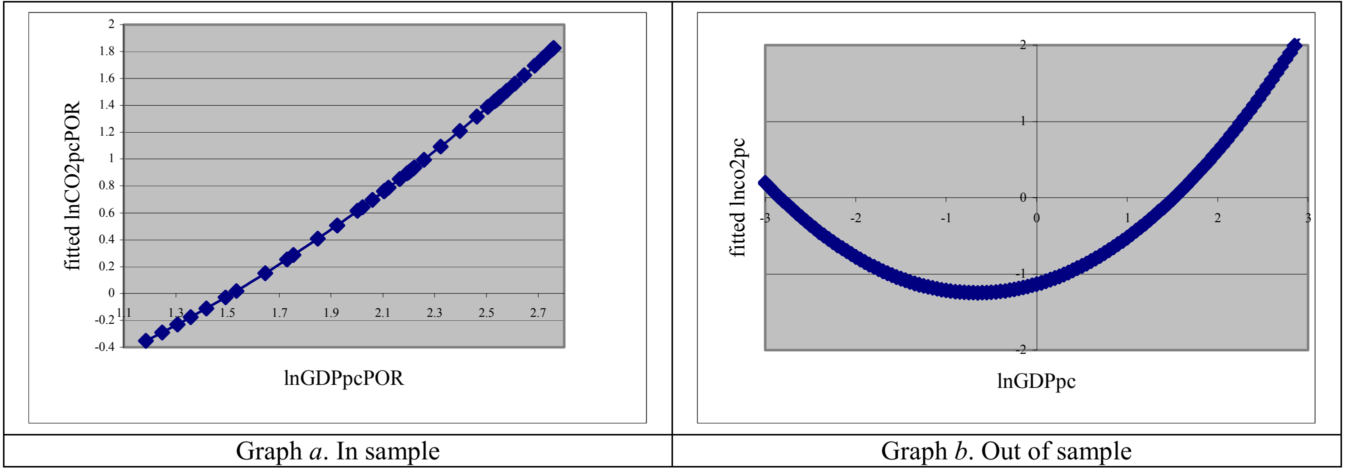
Notes to Figures 1-3. Fitted lnCO2pc is the estimated value of ln(CO2/POP) from a given EKC specification; lnGDPpc=ln(GDP/POP); "In sample" indicates that the values of lnGDPpc reported on the x-axis are observed; "Out of sample" indicates that the estimated EKC curve is plotted against values of lnGDPpc which are observed only partially.

Figure 4. Quadratic EKC – New Zealand



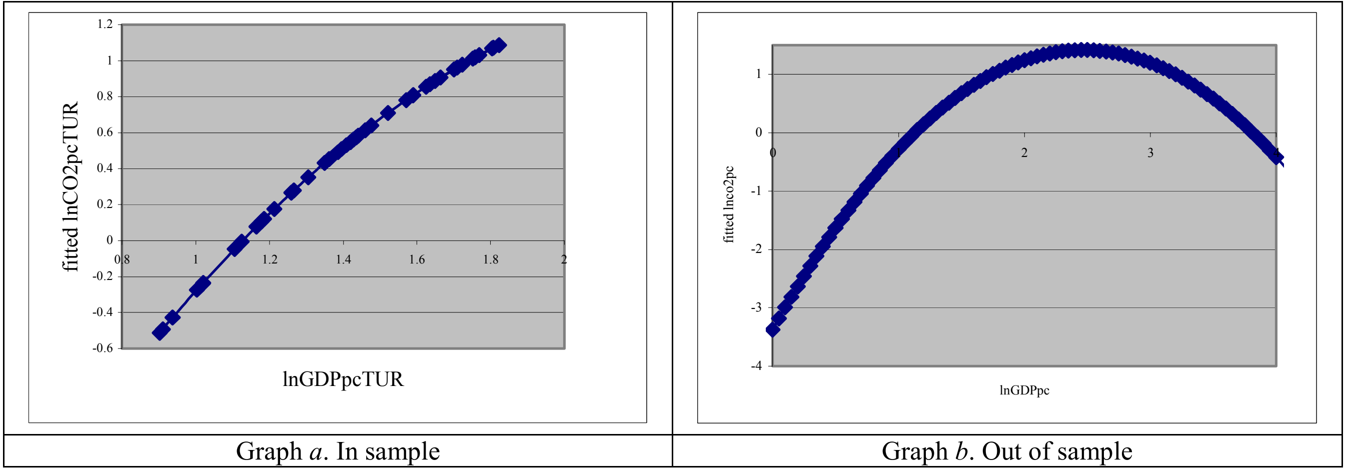
Graph *a*. In sample | Graph *b*. Out of sample

Figure 5. Quadratic EKC – Portugal



Graph *a*. In sample | Graph *b*. Out of sample

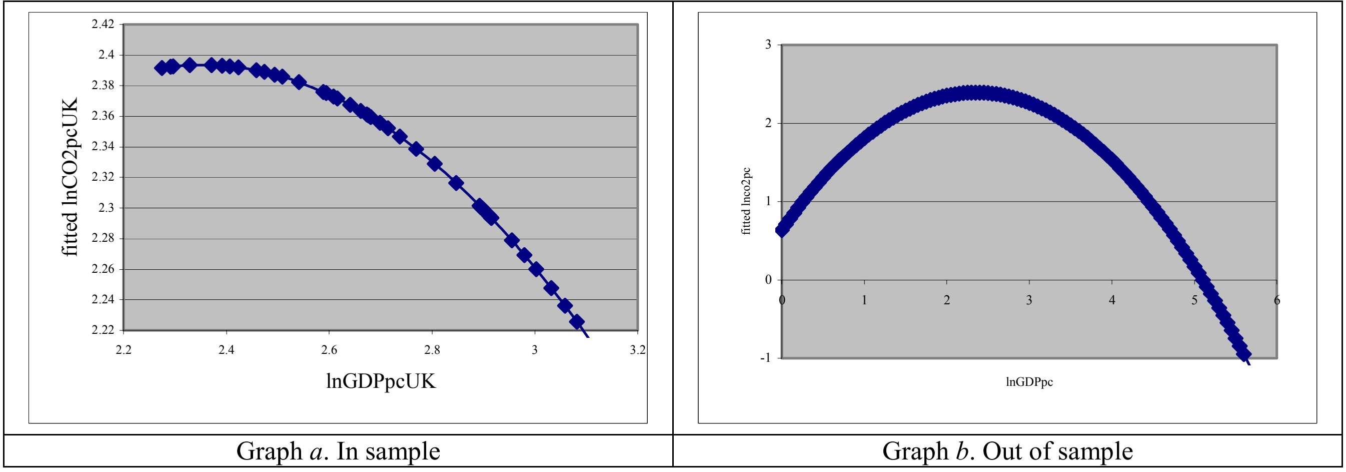
Figure 6. Quadratic EKC – Turkey



Graph *a*. In sample | Graph *b*. Out of sample

Notes to Figures 4-6. Fitted lnCO2pc is the estimated value of ln(CO2/POP) from a given EKC specification; lnGDPpc=ln(GDP/POP); "In sample" indicates that the values of lnGDPpc reported on the x-axis are observed; "Out of sample" indicates that the estimated EKC curve is plotted against values of lnGDPpc which are observed only partially.

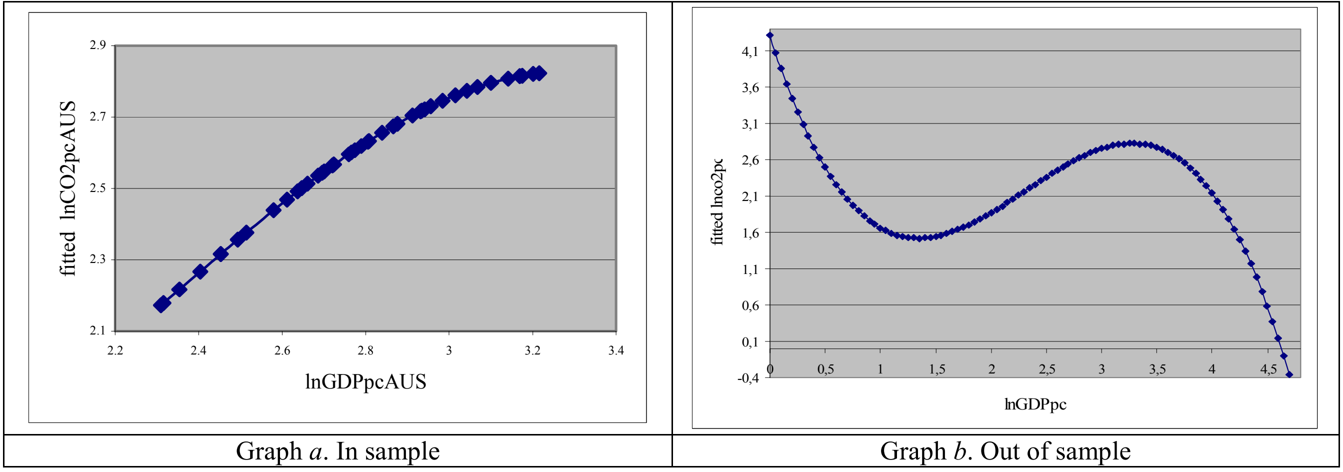
Figure 7. Quadratic EKC – United Kingdom



Graph *a*. In sample

Graph *b*. Out of sample

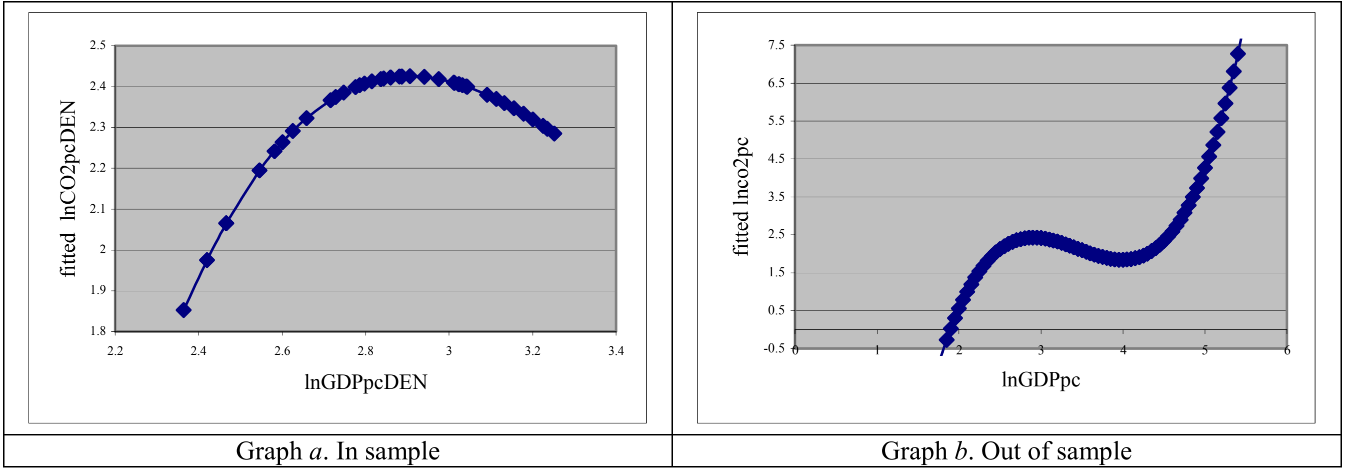
Figure 8. Cubic EKC – Australia



Graph *a*. In sample

Graph *b*. Out of sample

Figure 9. Cubic EKC – Denmark

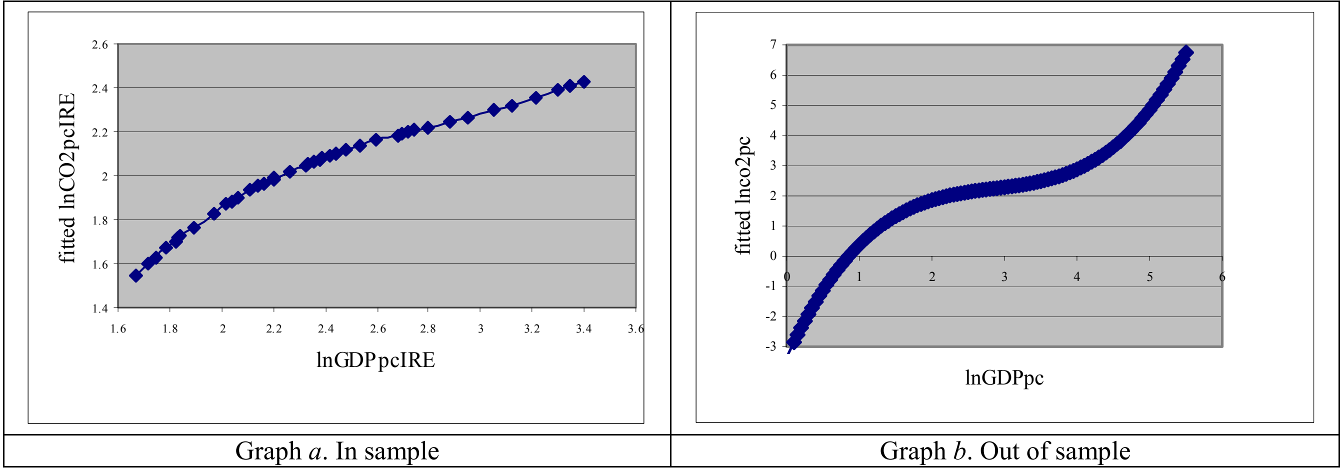


Graph *a*. In sample

Graph *b*. Out of sample

Notes to Figures 7-9. Fitted lnCO2pc is the estimated value of ln(CO2/POP) from a given EKC specification; lnGDPpc=ln(GDP/POP); "In sample" indicates that the values of lnGDPpc reported on the x-axis are observed; "Out of sample" indicates that the estimated EKC curve is plotted against values of lnGDPpc which are observed only partially.

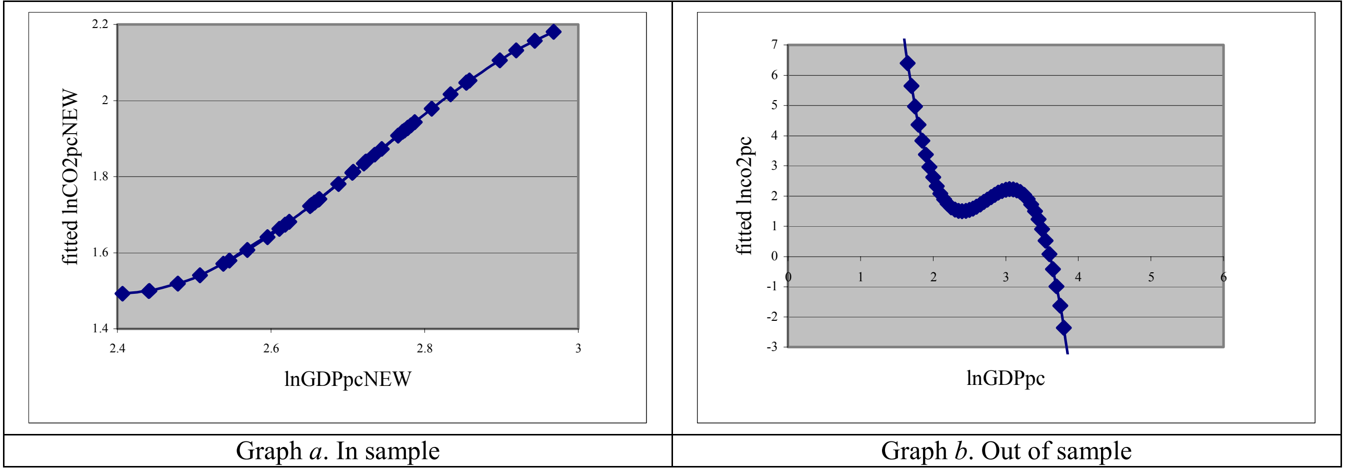
Figure 10. Cubic EKC – Ireland



Graph *a*. In sample

Graph *b*. Out of sample

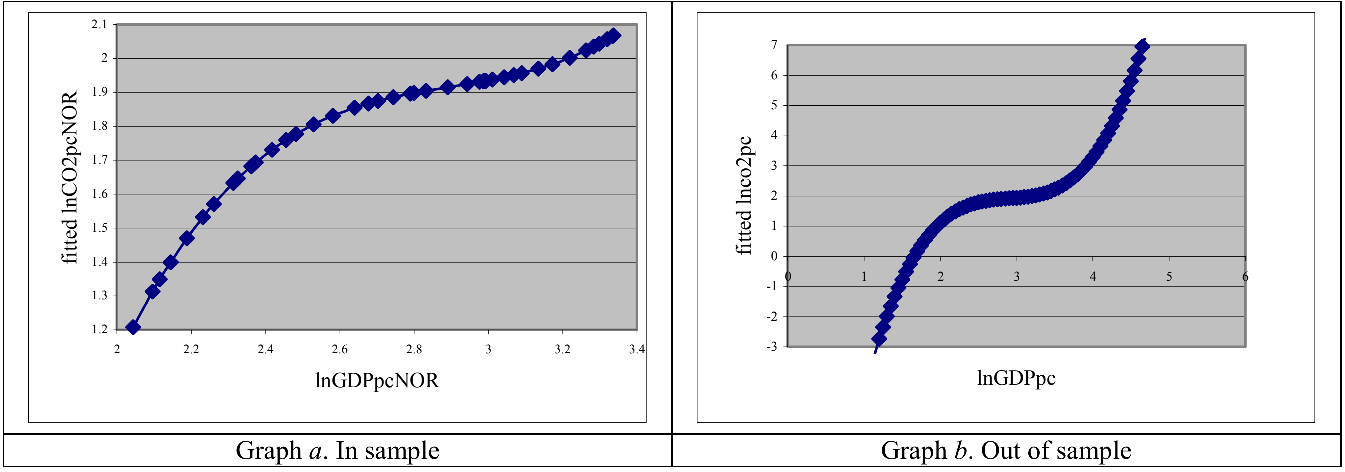
Figure 11. Cubic EKC – New Zealand



Graph *a*. In sample

Graph *b*. Out of sample

Figure 12. Cubic EKC – Norway

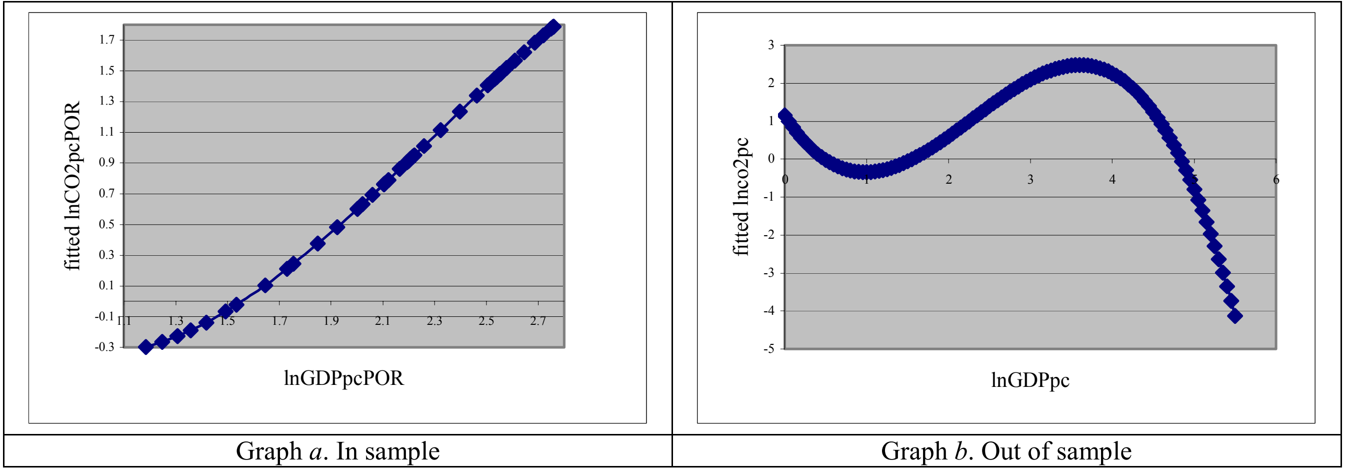


Graph *a*. In sample

Graph *b*. Out of sample

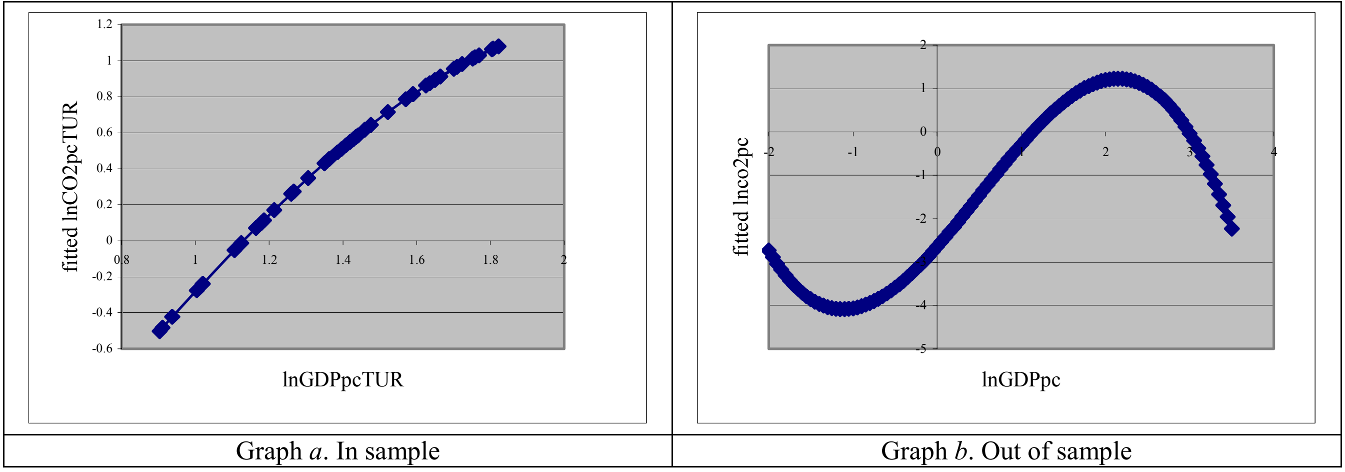
Notes to Figures 10-12. Fitted lnCO2pc is the estimated value of ln(CO2/POP) from a given EKC specification; lnGDPpc=ln(GDP/POP); "In sample" indicates that the values of lnGDPpc reported on the x-axis are observed; "Out of sample" indicates that the estimated EKC curve is plotted against values of lnGDPpc which are observed only partially.

Figure 13. Cubic EKC – Portugal



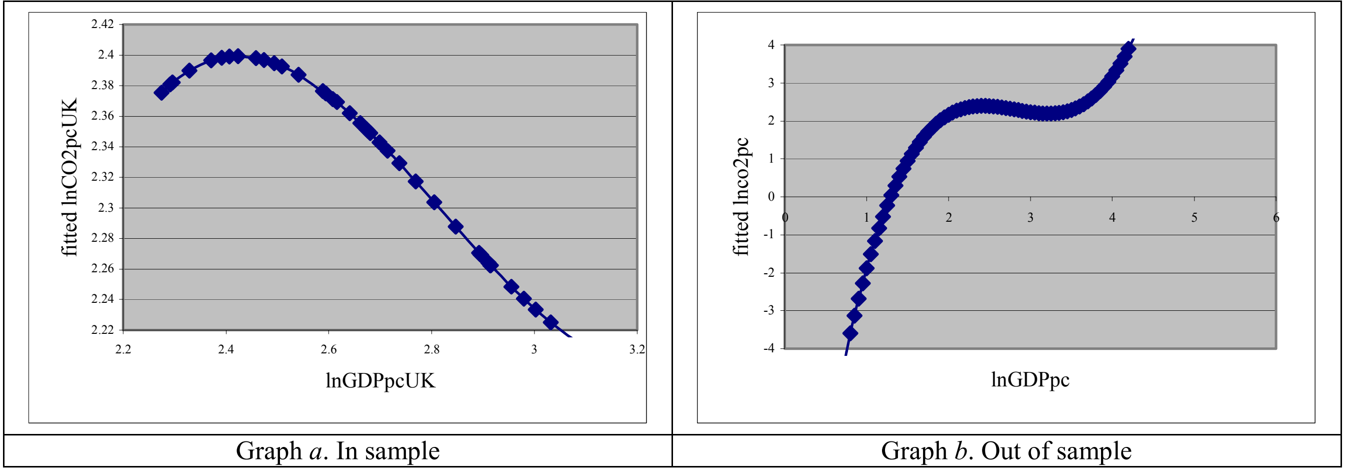
Graph *a*. In sample | Graph *b*. Out of sample

Figure 14. Cubic EKC – Turkey



Graph *a*. In sample | Graph *b*. Out of sample

Figure 15. Cubic EKC – United Kingdom



Graph *a*. In sample | Graph *b*. Out of sample

Notes to Figures 13-15. Fitted lnCO2pc is the estimated value of ln(CO2/POP) from a given EKC specification; lnGDPpc=ln(GDP/POP); "In sample" indicates that the values of lnGDPpc reported on the x-axis are observed; "Out of sample" indicates that the estimated EKC curve is plotted against values of lnGDPpc which are observed only partially.

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