*Environment and Development Economics* 8: 557–580 © 2003 Cambridge University Press
DOI:10.1017/S1355770X03000305 Printed in the United Kingdom

# Theory and Applications

## Development, trade, and the environment: how robust is the Environmental Kuznets Curve?

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ABSTRACT. This paper assesses the strength of the Environmental Kuznets Curve (EKC) which posits an inverted-U relationship between per capital income and pollution. Specifically, answers are sought to the following related questions: (1) How robust is the EKC relationship?; (2) To what extent can the EKC relationship be explained by changing trade patterns as opposed to growth-induced pollution abatement? With regard to question (1), the alleged weaknesses with the EKC are assessed and new EKCs are estimated using more appropriate econometric techniques. Turning to question (2), it is argued that the impact of trade liberalization on the environment will differ from country to country depending on whether or not they have a comparative advantage in pollution-intensive production. In turn, it is argued that this depends on a country's relative factor endowments and/or its relative environmental regulations. EKCs are therefore estimated in a manner that allows the impact of trade liberalization on pollution to depend on these country characteristics. The results indicate that the inverted-U relationship between per capita income and emissions is reasonably robust and little evidence is found to suggest that trade patterns are a significant determinant of the inverted-U shape.

### 1. Introduction

A large number of studies have claimed to find evidence of an inverted-U shaped relationship between pollution and per capita income, generally referred to as an Environmental Kuznets Curve (EKC) (see for example Shafik, 1994; Grossman and Krueger, 1995; Cole, Rayner, and Bates, 1997). This relationship is potentially of great significance since it implies that countries can 'grow out' of environmental problems.

However, several recent studies have criticized the EKC relationship and the methodology used to estimate it on a number of grounds (see for example Arrow *et al*., 1995; Ekins, 1997; Stern, 1998; Stern and Common, 2001). One such criticism is that the basic EKC methodology fails to account for the effects of trade. It is often claimed that the developed countries are increasingly specializing in industries with low pollution intensities, whilst the developing world is doing the opposite. The difference in the stringency of environmental regulations between the developed and the developing worlds is often implicated as a cause of such specialization. If true, then the

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developed countries are doing nothing more than exporting their pollution to the developing countries, rather than experiencing growth-induced pollution abatement. Other EKC criticisms relate to the econometric procedures adopted, the manner in which the estimated results are interpreted, and the extent to which the findings for a relatively small number of pollutants can be extrapolated to other environmental problems.

The aim of this paper is to assess the strength of the EKC critique. Specifically, answers are sought to the following related questions : (1) How robust is the EKC relationship? (2) To what extent can the EKC relationship be explained by changing trade patterns? With regard to question (1), the alleged weaknesses with the EKC are assessed and new EKCs are estimated using more appropriate econometric techniques. Turning to question (2), following Antweiler, Copeland, and Taylor (2001), it is then argued that previous studies, to have incorporated trade into the EKC relationship, have done so in an inappropriate manner by assuming the existence of a single relationship between trade liberalization and pollution. In contrast, it is here claimed that the trade–environment relationship is determined by a country's characteristics since it is these that determine whether or not a country will specialize in pollution-intensive production. As such, the trade–environment relationship will be country specific. New EKCs estimated in this paper therefore allow the impact of trade to interact with country characteristics. This provides a more robust indication of the extent to which trade patterns influence pollution emissions.

The remainder of the paper is organized as follows: section 2 summarizes the findings of previous EKC studies; section 3 outlines the criticisms that have been levelled at the EKC; section 4 examines the role of trade in the EKC relationship; section 5 estimates new EKCs in the light of these criticisms and reports the results; section 6 considers the implications of these results for the EKC and concludes the paper.

## 2. Previous findings

Typically, the basic EKC equation that has been estimated is of the following form, estimated in either logs or levels

$$E_{it} = (\alpha + \beta_i F_i) + \delta Y_{it} + \phi(Y_{it})^2 + \epsilon_{it} \quad (1)$$

where $E$ denotes the environmental indicator, either in per capita form or in the form of concentrations, $Y$ denotes per capita income, $F$ denotes country-specific effects, and $i$ and $t$ refer to country and year, respectively. Note that some studies include an income cubed term.

In equation (1), if $\delta > 1$ and $\phi < 1$ then the estimated curve has a maximum turning point per capita income level, calculated as $Y^* = (-\delta/2\phi)$. Table 1 summarizes the results of those EKC studies that have covered a range of environmental indicators.

Table 1 indicates a reasonable degree of compatibility across studies.[1]

[1] Each study tests several different functional forms, with each providing a different estimated turning point. Table 1 could therefore be accused of implying more compatibility between studies than actually exists. However, the functional forms that provide the above turning points are those that the authors of each study favour on econometric, or other, grounds.

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For local air pollutants, turning points are estimated at reasonably low levels of per capita income, indicating that emissions/concentrations are now falling in most developed economies. The turning points of Shafik (1994) and Grossman and Krueger (1995) are notably lower than those of the other two studies due to their use of data in the form of concentrations, rather than per capita emissions.[2] For carbon dioxide, turning points are typically estimated at very high, future, income levels or else a monotonically increasing relationship is estimated with per capita income.[3] Pollution concentrations in river water also tend to have relatively low estimated turning points, with the exception of nitrates from Cole *et al*. (1997). Municipal waste is estimated to increase monotonically with per capita income in the two studies to have examined it.

Many other studies have included additional variables in the EKC relationship, or considered different pollutants. Hilton and Levinson (1998), for instance, examine automotive lead emissions and find evidence of an inverted-U relationship with per capita income. Whilst the inverted-U relationship is quite robust, they do find that the estimated turning points are sensitive to functional form. Panayotou (1997) attempts to decompose the EKC relationship by including variables to capture the scale of economic activity (GDP per square kilometer), and the composition of GDP (share of industry in GDP). He finds both to be positive determinants of sulphur dioxide concentrations. Torras and Boyce (1998) argue that income inequality is a cause of pollution since it implies that the political influence of those who bear the costs of pollution is less than the influence of those who benefit from pollution. They therefore include Gini ratios and measures of literacy in the EKC functional form. The results generally support their hypothesis. Finally, several studies have attempted to include the role of trade in the EKC relationship. These are discussed in section 4.

There are, however, several studies that find very different results to those summarized above and in table 1. Dijkgraaf and Vollebergh (1998) estimate EKCs for carbon dioxide emissions using both an OECD panel and individual time-series regressions for each country. Interestingly, for the panel as a whole they find an inverted-U-shaped relationship between per capita income and emissions with a turning point level of income well within the sample income range. This is in stark contrast to the $CO_2$ results from other EKC studies (for example Cole, Rayner, and Bates, 1997; Holtz-Eakin and Selden, 1995). For their individual country time-series regressions, Dijkgraaf and Vollebergh find very varied results thereby questioning the existence of a meaningful global EKC for $CO_2$ emissions.

Harbaugh, Levinson, and Wilson (2002) also question whether there is a systematic relationship between per capita income and pollution. They estimate the relationship between per capita income and concentrations of

[2] Countries tend to find it easier to reduce urban air concentrations than aggregate emissions since something as simple as a taller chimney stack will reduce the former but not the latter. Turning points estimated using concentrations data have therefore tended to be at lower income levels than those estimated using per capita emissions.

[3] See also Holtz-Eakin and Selden (1995) and Tucker (1995).

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Table 1. *Estimated turning points from EKC studies (all in 1985 US dollars)*

| *Medium* | *Env. Indicator* | *Shafik*[1] | *S&S*[2] | *G&K*[3] | *Cole et al.*[4] |
|---|---|---|---|---|---|
| Air | Nitrogen oxides | | $12,041 | | $14,700 |
| | Sulphur dioxide | $3,670 | $8,916 | $4,053 | $6,900 |
| | Carbon monoxide | | $6,241 | | $9,900 |
| | SPM[5] | $3,280 | $9,811 | $6,151 | $7,300 |
| | Carbon dioxide[6] | ⇑ | | | $62,700 |
| Water (rivers) | Nitrates | | | $10,524 | £25,000 |
| | Faecal coliform | | | $7,955 | |
| | Lead | | | $1,887 | |
| | Mercury | | | $5,047 | |
| | Arsenic | | | $4,900 | |
| General | Municipal waste | ⇑ | | | ⇑ |

*Notes*:
[1] Shafik refers to Shafik (1994), the turning points are estimated using a logged quadratic functional form. Pollution data are in the form of concentrations.
[2] S&S refers to Selden and Song (1994). Estimates are from their fixed-effects quadratic levels functional form, without population density. Data are in the form of emissions per capita.
[3] G&K refers to Grossman and Krueger (1995). Their estimates result from a quadratic levels functional form. Suspended particulate matter data were split into smoke and heavy particles. This reported turning point is for smoke. Heavy particles were estimated to monotonically decrease with per capita income. All pollution data are in the form of concentrations.
[4] Cole *et al*. refers to Cole, Rayner, and Bates (1997). All pollution data are in the form of per capita emissions.
[5] SPM = suspended particulate matter.
[6] The ⇑ symbol indicates that the indicator was estimated to increase monotonically with per capita income.

sulphur dioxide, total suspended particulates and smoke and find their results to be highly sensitive to choice of functional form, to additional covariates, and to changes in the countries, cities, and years included in their sample. A plausible reason for this, as suggested by the authors, is the noisy nature of concentrations data which require the use of dummies to control for a number of site-specific determinants. Stern and Common (2001), however, consider $SO_2$ *emissions* and also question the traditional EKC methodology (and its results). This study is briefly discussed below.

## 3. Criticisms of the EKC

Criticisms of the EKC fall into two categories, firstly those aimed at the EKC methodology and secondly those concerned with the interpretation of EKC results. The following are criticisms of the EKC methodology:

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(i) The basic EKC is determined by changing trade patterns rather than growth-induced pollution abatement, and these trade patterns have typically been neglected by EKC studies. The North's declining share of manufacturing in GNP, in part resulting from its more stringent environmental regulations relative to the South, indicate that the North is simply exporting its pollution to the South. The EKC inverted U therefore merely represents a redistribution of pollution from North to South. Stern (1998) and Stern, Common, and Barbier (1996) both cite this as a criticism of the EKC relationship. This issue is discussed in detail in the next section.

(ii) The EKC assumes unidirectional causality from GNP to emissions and allows no mechanism through which environmental degradation can affect income levels. Least square estimation in the presence of such simultaneity will provide biased and inconsistent estimates. Although pollution emissions do not appear to be affecting per capita GNP in the developed economies, there are situations where causality does appear to move from environment to GNP, for example where land degradation in developing countries affects agricultural output.

(iii) Econometric issues. The most fundamental econometric criticisms are provided by Stern and Common (2001) and Perman and Stern (1999). These papers raise two key issues:
   (a) Studies that use only OECD data will typically estimate turning points at lower per capita income levels than those using data for the world as a whole. This arises because the developing countries are experiencing increasing emissions of even local air pollutants such as $SO_2$.
   (b) Per capita income and emissions are typically non-stationary variables and EKC regressions do not appear to co-integrate. It is also likely that there are omitted non-stationary variables. Standard EKC estimation in the presence of these features is likely to generate spurious results.

(iv) Other econometric criticisms have also been raised in the literature. Stern, Common, and Barbier (1996) are concerned that many EKC studies ignore the issue of heteroscedasticity which is likely to be present in cross-section data. Furthermore, most EKC studies estimate a quadratic relationship between pollution and income and therefore fail to allow for the possibility of emissions beginning to increase again at high income levels. Finally, Harbaugh, Levinson, and Wilson (2002) and Ekins (1997) argue that different datasets, functional forms (e.g. logs versus levels) and estimation techniques all provide different results, suggesting that the EKC relationship is fragile.

(v) Stern (1998) criticizes EKC regressions that allow levels of pollution to become zero or negative as being incompatible with the laws of thermodynamics, since all resource use inevitably produces waste.

In addition to these, a number of concerns have been raised regarding the interpretation of EKCs:

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(i) Arrow *et al*. (1995) argue that although EKCs have been estimated for some local air pollutants it is dangerous to assume that similar relationships will exist for all other environmental indicators.
(ii) EKCs do not indicate that economic growth automatically solves environmental problems. Emissions reductions have only been attained through investment and regulations, neither of which are automatic consequences of economic growth.
(iii) Mean versus median income. Although many EKCs estimate turning points around the current world mean per capita income level, this does not mean that, globally, emissions are about to decline. Global income distribution is skewed with far more people below the mean than above it. If median income levels are considered rather than mean, EKCs indicate that emissions will continue to increase for many years to come. Whilst this point addresses the interpretation of EKCs, it is clearly related to the econometric criticism raised in (iii) (a) above.

We address many of these criticisms in section 5, but first focus on the role of trade in the EKC.

## 4. The EKC and trade

The relationship between trade liberalization and the environment has received a great deal of attention in recent years, amongst both academics and policy makers (see for example Anderson and Blackhurst, 1992; Chichilnisky, 1994; Copeland and Taylor, 1994). A well known study by Grossman and Krueger (1991) separates the environmental impact of trade liberalization into scale, technique, and composition effects. *Ceteris paribus*, the scale effect refers to the increased pollution likely to result from the economic growth generated by increased market access. The technique effect refers to the changing technique of production which accompany increasing incomes, due to the increased demand for environmental regulations. However, it is the composition effect of trade that has been used to explain the inverted-U shape of the EKC. The composition effect refers to the compositional changes which occur as a result of liberalization, as countries increasingly specialize in those sectors in which they enjoy a comparative advantage. The resultant impact on the environment will therefore depend whether or not a country's comparative advantage is in pollution-intensive production.

Whilst a number of studies have suggested that the trade composition effect may, at least partly, determine the EKC relationship (Sachs, Panayotou, and Peterson, 2000; Grossman and Krueger, 1995; Stern, 1998; Stern, Common, and Barbier, 1996), perhaps the most notable evidence is provided by Suri and Chapman (1998). Within their EKC they include the ratio of manufactured imports to domestic manufacturing production, and the same ratio for exports, as determinants of energy use. They generally find that the import ratio has a negative relationship with energy use whilst the export ratio has a positive relationship. This suggests that the trade composition effect is a determinant of energy use and hence is a likely determinant of air pollution emissions. Lucas, Wheeler, and Hettige

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(1992) also claim that their findings are consistent with the notion that reduced pollution intensity of production in developed countries and the consequent increase in pollution intensity in developing countries is the result of locational displacement. It should be noted, however, that Hilton and Levinson's (1998) EKC for automotive lead emissions suggests that trade patterns are not determining EKCs for all pollutants (if any). Since automotive lead emissions stem from a consumption activity (that is driving) their decline is not due to the migration of this source to developing regions.

Other EKC studies have attempted to assess the role of trade by including a single measure of trade openness (for example, Shafik and Bandyopadhyay, 1992; Grossman and Krueger, 1991; Rock, 1996). These have tended to provide mixed results. However, this is not surprising as there is no reason to expect a unique relationship between trade liberalization and the environment. This is the key finding of Antweiler, Copeland, and Taylor (2001) who model the relationship between pollution, income, trade, and factor endowments. Since their methodology is of direct relevance to this paper, a brief summary of Antweiler *et al*.'s model is here provided. They assume a small open economy produces two goods, $X$ and $Y$, with two factors, capital ($K$) and labor ($L$). Industry $X$ is capital intensive and generates pollution, whilst industry $Y$ is labor intensive and clean. The presence of trade barriers means that domestic prices differ from world prices. If $p$ is the relative price of $X$ then

$$p = \beta p^{w} \tag{2}$$

where $\beta$ denotes trade frictions and $p^{w}$ is the common world relative price of $X$. It is important to note that $\beta > 1$ if a country imports $X$ and $\beta < 1$ if a country exports $X$.

Antweiler *et al*. decompose pollution ($z$) into scale, composition, and technique effects

$$\hat{z} = \hat{S} + \hat{\sigma} + \hat{e} \tag{3}$$

where $\hat{}$ denotes percentage change. $S$, the scale effect, represents the change in emissions that would occur, *ceteris paribus*, if the size of the economy changed. The variable $\sigma$ denotes the share of the pollution-intensive good $X$ in total output, otherwise known as the composition effect. Variable $e$ represents the pollution intensity of the dirty industry, known as the technique effect.

If equation (3) is decomposed further, it allows Antweiler *et al*. to identify the private sector's demand for pollution. Pollution demand is a positive function of scale, capital abundance, and the world price of dirty goods, and is a negative function of a pollution tax. Whilst the degree of trade frictions also affects pollution demand, as we shall see, the direction of this effect depends on whether a country is an importer or an exporter of pollution-intensive goods. Pollution supply is determined by the price of polluting, as given by a pollution tax. In turn, real income is a determinant of the pollution tax, since it is assumed that an increase in real per capita income will increase the demand for environmental quality. Combining pollution demand and supply yields the following reduced-form equation

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$$\hat{z} = \pi_1 \hat{S} + \pi_2 \hat{\kappa} - \pi_3 \hat{I} - \pi_4 \hat{T} + \pi_5 \hat{p}\, w + \pi_6 \hat{\beta} \tag{4}$$

where all $\pi_i$ are positive, $\kappa$ denotes the capital–labor ratio, $I$ represents real per capita income, $T$ represents 'country type' and all other variables are as already defined.[4] It is now possible to illustrate how the environmental impact of trade liberalization will differ across countries.

Since $\beta < 1$ for an exporter of the dirty good, trade liberalization will increase $\beta$ and hence $\hat{\beta} > 0$. For a country with a comparative advantage in pollution-intensive output, trade liberalization will therefore increase emissions. In contrast, $\beta > 1$ for an importer of dirty goods and hence trade liberalization will mean $\hat{\beta} < 0$. Thus, for a country with a comparative advantage in clean output, trade liberalization will reduce emissions.

According to Antweiler *et al.*'s model, therefore, trade liberalization does not have a unique relationship with emissions. The effect of liberalization on the environment will instead be country specific, depending on a country's comparative advantage. In their model, comparative advantage is driven by relative factor (capital and labor) abundance and relative incomes, with the latter reflecting the relative strength of environmental regulations.

Thus, from Antweiler *et al.*'s model it is possible to identify two potentially opposing forces driving comparative advantage. The first, which we may call the factor endowment effect, predicts that trade liberalization will result in trade patterns being driven by traditional factor endowment differentials, as predicted by the Heckscher–Ohlin–Samuelson (HOS) model of trade.[5] Since pollution-intensive goods are known to be relatively capital intensive,[6] the factor endowment effect will see trade liberalization causing pollution-intensive industries to relocate from the relatively labour abundant South to the relatively capital abundant North.

The second force driving comparative advantage is the pollution haven effect. This effect, which is also compatible with the HOS model of trade, will occur if comparative advantage is determined by environmental regulation differentials. Since the stringency of environmental regulations is known to be closely correlated with per capita income (Dasgupta *et al.*, 1995), the pollution haven effect assumes that developing countries possess a comparative advantage in pollution-intensive production. If so, then trade liberalization is likely to cause a relocation for such production from the North to the South. A number of theoretical papers allow comparative advantage to be driven by differences in the stringency of environmental regulations and therefore predict the widespread

[4] 'Country type' refers to the proportion of those who care about the environment, relative to the proportion who do not.

[5] Referring to this motive as the factor endowment motive does not preclude the environmental regulation (pollution haven) motive from also stemming from factor endowments. Since environmental regulations may be based on a country's 'environmental' endowment, the factor endowment motive should be interpreted as the motive resulting from the endowment of '*traditional*' factor endowments, that is capital and labour.

[6] See, for example, Antweiler, Copeland, and Taylor (2001), Cole and Elliott (2002), and Mani and Wheeler (1998).

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formation of pollution havens (see Pethig, 1976; Baumol and Oates, 1988; Copeland and Taylor, 1994; and Chichilnisky, 1994).

These competing hypotheses therefore claim that comparative advantage in pollution-intensive production is a function of relative factor abundance and relative incomes. Thus, a country's characteristics will determine how trade liberalization affects its pollution emissions and we would not expect to see a unique trade–environment relationship across all countries. In contrast to previous EKC studies, section 5 therefore estimates EKCs in a manner that controls for such country characteristics thereby assessing the extent to which trade-induced compositional changes are responsible for the inverted-U relationship. However, before estimating these EKCs we first consider the extent to which previous empirical studies find support for pollution haven and factor endowment effects.

Previous empirical tests of the pollution haven hypothesis provide mixed results. Janicke, Binder, and Monch (1997), van Beers and van den Bergh (1997), and Tobey (1990) find very little evidence to suggest that a country's net exports of dirty products are determined by the stringency of its environmental regulations. Similarly, Xu and Song (2000) find that trade in embodied environmental factor services does not appear to be influenced by environmental regulations. Jaffe *et al*. (1995) provide a review of the literature and conclude that there is little evidence to suggest that stringent environmental regulations have a significant effect on industrial competitiveness in developed countries. In contrast, Mani and Wheeler (1998) examine the import–export ratio for dirty industries and also find evidence consistent with the pollution haven hypothesis. Similarly, Lucas, Wheeler, and Hettige (1992) and Birdsall and Wheeler (1992) find some support for this hypothesis and claim that the growth in pollution intensity in developing countries was highest in periods when OECD environmental regulations were strengthened. The one paper to make the distinction between the pollution haven and factor endowment effects is Antweiler, Copeland, and Taylor (2001) who claim to find evidence that both differences in the stringency of environmental regulations *and* relative factor endowments drive comparative advantage and hence determine the composition effect. This raises the possibility that these two effects are tending to cancel each other out, perhaps explaining the mixed evidence found by other studies. Our econometric analysis will indicate if this is the case.

## 5. Estimating EKCs

### *5.1. Methodology*

In the light of the above discussion we start by estimating the following basic equation for emissions of three air pollutants (sulphur dioxide, nitrogen oxides, and carbon dioxide) and a water pollutant (biological oxygen demand, a measure of organic water pollution)

$$E_{it} = \gamma_i + \theta_t + \beta_1 Y_{it} + \beta_2 Y_{it}^2 + \beta_3 Y_{it}^3 + \epsilon_{it} \quad (5)$$

Where $E$ denotes per capita emissions, $\gamma$ denotes country-specific intercepts, $\theta$ denotes time-specific intercepts, and $Y$ represents per capita

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income. Subscripts $i$ and $t$ represent country and year, respectively. We then expand our model to test the trade considerations discussed in the previous section. Specifically, we estimate the following equation

$$E_{it} = \gamma_i + \theta_t + \beta_1 Y_{it} + \beta_2 Y_{it}^2 + \beta_3 Y_{it}^3 + \beta_4 KL + \beta_5 KL^2 + \beta_6 T_{it} + \beta_7 TRKL_{it} + \beta_8 T(RKL_{it})^2 + \beta_9 TRI_{it} + \beta_{10} T(RI_{it})^2 + \epsilon_{it} \quad (6)$$

Where $KL$ is the capital–labour ratio and $T$ represents trade intensity, or openness. $TRKL$ is an interaction of trade intensity with a country's relative capital–labour ratio, whilst $TRI$ is an interaction of trade intensity with a country's relative income.

Equation (6) is based on equation (4) from section 4 and hence stems from Antweiler, Copeland and Taylor's (2001) model. Per capita income represents the direct scale and technique effects of growth. Some studies have tried to separate these using GDP per km$^2$ to measure scale and per capita income to capture technique effects (for example Panayotou, 1997). However, this is only appropriate when estimating *concentrations* of pollution. In the present paper pollution data are in the form of national emissions per capita and hence there seems no obvious way to separate scale and technique effects. The direct composition effect of growth is represented by the capital–labour ratio ($KL$). The square of the capital–labour ratio is included to allow capital accumulation to have a diminishing effect at the margin.

It was argued in section 4 that trade liberalization is a determinant of pollution, with the direction of this effect depending on a country's comparative advantage. It was also argued that comparative advantage depends on factor endowment and the stringency of environmental regulations, with the latter determined by a country's income level. In order to incorporate these relationships into the econometric model, we include trade intensity (the ratio of imports + exports to GDP) as a measure of trade frictions. This measure of trade intensity then has to be interacted with a country's determinants of comparative advantage. More specifically, trade intensity is interacted with a country's *relative* capital–labour ratio to capture the factor endowment argument and with *relative* per capita income to test the environmental regulations, pollution-haven argument. Since comparative advantage is a relative concept, a country's capital–labour ratio and per capita income levels are here expressed relative to the world average.[7]

A quadratic term is included for both of these interacted variables. With regard to the interacted capital–labour ratio, the factor endowment effect suggests that an increase in trade intensity would be associated with rising pollution for a country with a high capital–labour ratio and with falling pollution for those with lower capital–labour ratios. Similarly, the

[7] See Appendix A for more information on all the data used in this paper. Note that we are not attempting to estimate the trade-induced scale and technique effects, a more onerous task than estimating the trade-induced composition effect. The composition effect is our prime concern since it has been used as an explanation of the inverted-U shape (between income and pollution) and hence as a criticism of the basic EKC methodology.

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pollution haven effect suggests that trade liberalization will increase pollution for countries with low per capita incomes (low regulations) and reduce pollution for those with high incomes (high regulations). Antweiler *et al*. claim that the trade-induced composition effect in country $_i$ ($C_i$) can be expressed as

$$C_i = \alpha_0 T_i + \alpha_1 T_i RKL_i + \alpha_2 T_i (RKL_i)^2 + \alpha_3 T_i RI_i + \alpha_4 T_i (RI_i)^2 \qquad (7)$$

Since the aim of this paper is to examine the robustness of the EKC as well as the role played by trade, other key determinants of pollution emissions suggested by the EKC literature also need to be considered. Aside from income, trade, and other independent variables that relate only to pollution *concentrations* (such as GDP per km$^2$), the most notable potential determinants of pollution are the political economy variables examined by Torras and Boyce (1998). They argue that the distribution of power within a society can influence the extent to which pollution emissions are abated. This occurs, they claim, since an inequitable distribution of power increases the influence on policy of those who benefit from pollution-generating activities, relative to the influence of those who bear the costs of pollution. In order to test this hypothesis they suggest using a measure of a country's income inequality (the GINI coefficient) and the literacy rate, as proxies for the distribution of power.[8] We therefore include these variables in our regressions. In doing so, we re-test Torras and Boyce's hypothesis using a different range of pollutants to those considered by them.[9]

Both the countries and years included in our samples vary by pollutant. For sulphur dioxide and nitrogen oxides we have five-yearly observations for 26 developed and developing countries, covering the period 1975–1990. For carbon dioxide and biological oxygen demand we have yearly observations for 32 developed and developing countries for the period 1975–1995. The Appendix contains further information on all data used to estimate equations (5) and (6).

Equations (5) and (6) are estimated in a manner that overcomes many of the methodological criticisms raised in section 3. First, the explanatory variables in equation (6) will indicate the role played by trade in the EKC relationship. Second, in response to the claim that the EKC may suffer from simultaneity bias due to causality moving from environmental degradation to income, a Hausman specification test is employed to test the null of exogeneity of current income.[10] Third, a cubic income term has been included in the equations in response to the claim that a simple quadratic equation does not allow for the possibility of pollution beginning to

[8] The Gini coefficient takes a value between 0 (perfect equality) and 1 (perfect inequality).

[9] Torras and Boyce consider *concentrations* of sulphur dioxide, particulate matter, and two measures of water pollution. Their hypothesis has not therefore been tested for nitrogen oxides, carbon dioxide, or biological oxygen demand (although their water pollution measures are likely to be related to the latter), or *emissions* of sulphur dioxide.

[10] Lagged income is used as the instrumental variable.

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increase again at high income levels. However, where the cubic term is not statistically significant (at 90 per cent confidence level) a quadratic equation is estimated. Fourth, the datasets contain a mixture of developed and developing countries and hence our estimations are not based on OECD data alone. Results are also estimated using only the OECD countries within the sample to compare with those from the full sample. Fifth, equations (5) and (6) are estimated using both fixed and random effects. Finally, where the time series is large enough (that is for carbon dioxide and biological oxygen demand) the data are tested for non-stationarity using both individual Augmented Dickey–Fuller tests and Im, Pesaran, and Shin (1997) panel unit root tests. Differencing the data then removes the non-stationarity that is found.

### *5.2. Results*

The results are presented by pollutant starting with sulphur dioxide in table 2. For all of the results in this section, significance at 99 per cent, 95 per cent and 90 per cent confidence levels is denoted by ***, ** and * respectively.

Table 2. *Estimation results for sulphur dioxide (random effects)*

| *Variable* | *Model 1* | *Model 2* | *Model 3* | *Model 4* |
|---|---|---|---|---|
| *Y* | 13.33*** | 12.19*** | 13.39*** | 21.22*** |
| $Y^2$ | −0.00076*** | −0.00072*** | −0.00074*** | −0.0095*** |
| *GINI* | | 114.7 | | |
| *LIT* | | 173.6 | | |
| *K/L* | | | 13.39 | −1.12** |
| $K/L^2$ | | | 8.21e-5 | 3.17e-6 |
| *Trade intensity* (*T*) | | | | −548.24*** |
| *T * relative K/L* | | | | −947.19*** |
| *T * relative* $(K/L)^2$ | | | | 164.47** |
| *T * relative Y* | | | | 229.78** |
| *T * relative* $Y^2$ | | | | −17.20 |
| Constant | 1107 | −12410 | −3735 | 12812 |
| $R^2$ (overall) | 0.43 | 0.43 | 0.39 | 0.40 |
| F-test on *Y*, $Y^2$ | 52.9*** | 46.8*** | 33.5*** | 32.6*** |
| F-test on trade terms | | | | 12.4*** |
| Hausman (FE v. RE) | 9.63*** | 8.83* | 0.06 | 5.72 |
| Hausman (simult.) | 2.04 | 1.60 | 1.91 | 2.25 |
| Turning point | $8,691 | $8,406 | $8,971 | $11,168 |
| Turning point: FE | $7,114 | $7,412 | $5,637 | $7,483 |
| Turning point: OECD | $8,181 | $5,431 | $9,250 | $10,521 |
| Observations | 104 | 104 | 104 | 104 |

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For reasons, of space only random effects results were reported. For model 1 (the basic EKC) and to a lesser extent for model 2, the Hausman specification test suggests that there is some correlation between the explanatory variables and the error terms. No such correlation is suggested by the test results for models 3 or 4.[11] Nevertheless, fixed effects results were very similar to those in table 2 and are available from the author upon request. Table 2 does report the estimated turning points from the fixed effects results to enable comparison with the random effects turning points. Note also that the Hausman simultaneity test accepts the null of exogeneity in all cases suggesting that simultaneity bias is not present.

Model 1 (from equation (5)) estimates a statistically significant inverted-U-shaped relationship between per capita emissions and per capita income. Model 2 then adds the political economy variables as suggested by Torras and Boyce (1998). Both of these are found to be statistically insignificant.[12] Since these variables were also insignificant when included in models 3 and 4, they have been omitted from the reported estimations.[13] Model 3 provides an extension to the basic EKC by including the capital–labour ratio as a measure of the composition effect, as suggested by Antweiler *et al*. (2001). A squared term is also included to allow the capital–labour ratio to have a diminishing effect at the margin. Perhaps surprisingly, both terms are insignificant despite the capital intensity of most pollution-intensive sectors (Cole and Elliott, 2002). Finally, model 4 (from equation (6)) provides the full trade specification. Before turning to the trade variables, it should be emphasized that a statistically significant inverted-U-shaped relationship is estimated between income and emissions in all four models. The cubic income term was insignificant in all four models (and all four pollutants) and has hence been omitted. The F-test on both income terms (which restricts the coefficients on the income terms to zero) is highly significant in all models. Table 2 reports the estimated turning points from these random effects estimations, from fixed effects estimations, and from estimations using only the OECD countries in our sample. There is a reasonable degree of consistency across all of these turning points, and there is little support for Stern and Common's (2001) claim that turning points from OECD studies are lower than those from 'world' studies.

Turning to the trade variables, we can firstly see that the actual trade intensity variable is negative for $SO_2$, whilst the trade interaction term provides evidence of both factor endowment and pollution haven effects

[11] Referring back to equations (5) and (6), the random effects specification treats $\gamma_i$ and $\theta_t$ as components of the random disturbance. In contrast, a fixed effects estimation treats these terms as regression parameters which are conditional on the country and time effects in the sample. Thus fixed effects results apply only to the observations in the sample. Finally, note that estimation in logs and levels provides very similar results. In order to conserve space only the levels results are reported here.

[12] In line with Torras and Boyce, model 2 was also estimated by allowing the Gini and literacy variables to interact with high- and low-income dummies. The variables were still insignificant, however.

[13] In fact, this was the case for all four pollutants and hence *GINI and LIT* are included only in model 2.

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(although the $T(RI)^2$ term is not statistically significant). A country with a low (high) capital–labour ratio will find pollution falling (rising) in response to trade liberalization. Furthermore, a low-income country (with a low level of environmental regulations) will find that an increase in trade liberalization will increase their pollution as their comparative advantage in dirty production deepens. In contrast, a high-income country will see pollution fall in response to trade liberalization. Finally the F-test on the trade terms (which restricts all of the trade coefficients to zero) is highly significant.

Table 3 provides the estimation results for nitrogen oxides. As with sulphur dioxide, the results for nitrogen oxides provide evidence of a robust relationship between per capita income and emissions. Again, individual income terms are highly significant as is the F-test for joint significance. Estimated turning points are also broadly similar across specifications and are slightly higher than those estimated for sulphur dioxide. This is consistent with the findings of other EKC studies (Selden and Song, 1994; Cole, Rayner, and Bates, 1997). It is notable that, again, the *GINI* and literacy (*LIT*) variables are statistically insignificant.

Table 3. *Estimation results for nitrogen oxides (random effects)*

| *Variable* | *Model 1* | *Model 2* | *Model 3* | *Model 4* |
|---|---|---|---|---|
| $Y$ | 4.65*** | 4.74*** | 3.95*** | 5.97*** |
| $Y^2$ | −0.00015*** | −0.00016*** | −0.00012** | −0.00015** |
| *GINI* | | −60.65 | | |
| *LIT* | | −27.58 | | |
| *K/L* | | | 17.39 | −0.014 |
| $K/L^2$ | | | −1.10e-4 | −8.84e-7 |
| *Trade intensity* ($T$) | | | | −94.93 |
| *T * relative K/L* | | | | 189.77* |
| *T * relative* $(K/L)^2$ | | | | −23.52 |
| *T * relative Y* | | | | −77.88** |
| *T * relative* $Y^2$ | | | | 6.12 |
| constant | 1695 | 5818 | 554 | 553 |
| $R^2$ (overall) | 0.56 | 0.56 | 0.59 | 0.69 |
| F-test on $Y$, $Y^2$ | 57.4*** | 30.9*** | 13.8*** | 17.09*** |
| F-test on trade terms | | | | 7.61 |
| Hausman (FE v. RE) | 9.77** | 29.81** | 10.09** | 18.4 |
| Hausman (simult.) | 2.85 | 2.16 | 3.54 | 2.54 |
| Turning point | $14,810 | $14,727 | $16,213 | $19,626 |
| Turning point: FE | $14,029 | $13,783 | $14,724 | $13,120 |
| Turning point: OECD | $13,659 | $14,450 | $15,774 | $18,403 |
| Observations | 104 | 104 | 104 | 104 |

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With regard to the trade variables, we can see that the trade intensity variable is negative but no longer significant, whilst the trade interaction terms now have opposite signs to those estimated for sulphur dioxide. This implies that our suggested sources of comparative advantage (capital–labour ratios and the stringency of environmental regulations) affect emissions of nitrogen oxides in a counter intuitive manner. Furthermore, the F-test on the trade terms is not statistically significant. The fact that we find trade to have a seemingly different impact on nitrogen oxides compared to sulphur dioxide may reflect the fact that a large proportion of the former stems form the transport sector, which is a non-traded good.[14]

Although Stern and Common (2001) suggest that their income and emissions data appear to be non-stationary, the extremely short time series in our sulphur dioxide and nitrogen oxides samples, with only four observations for each country, makes the notion of stationarity unlikely, and largely meaningless. Furthermore, it is obviously impossible to perform individual Augmented Dickey–Fuller (ADF) tests or panel unit root tests such as Im, Pesaran, and Shin (IPS) (1997) with only four time series observations. Issues of stationarity are discussed below, however, in the context of carbon dioxide and biological oxygen demand, for which a longer time series is available.

The results for carbon dioxide, again, indicate a statistically significant inverted-U-shaped relationship between income and emissions for models 1 and 2. Note that, in line with other studies, these turning points occur at higher per capita income levels than for the local air pollutants. Stern and Common (2001) question whether the higher turning points often estimated for global pollutants such as $CO_2$ were the result of larger samples containing a greater number of developing countries. However, the results in table 4 provide little support for this assertion since the turning points from the OECD sample are very similar to those from the full sample.

The *GINI* and *LIT* variables remain statistically insignificant.[15] For reasons of space, model 3 is not reported, although the *KL* variable was positive but statistically insignificant. Turning to model 4, the trade intensity variable is here estimated to be positive and significant, whilst the trade interaction terms are estimated to have the same signs as those estimated for nitrogen oxides. In terms of the factor endowment and pollution haven effects, these signs appear to be counter-intuitive. Nevertheless, an F-test on the trade variables is statistically significant.

If the data used in these estimations are non-stationary, however, then the reliability of the above results is open to question.[16] Individual Augmented Dickey–Fuller (ADF) tests and Im, Pesaran, and Shin (IPS) (1997) panel unit root tests are therefore undertaken, with results reported in appendix B. Across all variables (including biological oxygen demand),

[14] The OECD (1999) estimate that almost 54 per cent of nitrogen oxides emissions stem from transport, compared to less than 7 per cent of sulphur dioxide.

[15] There are fewer observations for model 2 than for the other models since GINI data were only available for 1975, 1980, 1985, and 1990 for each country.

[16] Statistical inference using classical methods and distributions will be invalid.

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Table 4. *Estimation results for carbon dioxide (random effects)*

| *Variable* | *Model 1* | *Model 2* | *Model 4* | *Model 4a (First diff.)* |
|---|---|---|---|---|
| *Y* | 12.77*** | 10.71*** | 20.75*** | 20.77*** |
| $Y^2$ | −0.00019*** | −0.00010*** | −0.00051** | −0.00026** |
| *GINI* | | −817.1 | | |
| *LIT* | | 1009.3 | | |
| *K/L* | | | −0.21 | 1.11 |
| $K/L^2$ | | | 1.03e-4*** | −2.18e-6 |
| *Trade intensity* (*T*) | | | 475.12*** | 296.68* |
| *T * relative K/L* | | | 672.00*** | 188.00 |
| *T * relative* $(K/L)^2$ | | | −182.24*** | −75.02 |
| *T * relative Y* | | | −811.13*** | −406.62* |
| *T * relative* $Y^2$ | | | 128.40*** | 54.40* |
| Constant | 57685 | 24583 | 11648 | −1187 |
| $R^2$ (overall) | 0.64 | 0.65 | 0.59 | 0.11 |
| F-test on *Y*, $Y^2$ | 172.0*** | 30.4*** | 58.0*** | 21.8*** |
| F-test on trade terms | | | 104.0*** | 20.1*** |
| Hausman (FE v. RE) | 9.47* | 3.05 | 11.10 | 10.17* |
| Hausman (simult.) | 0.11 | 1.90 | 9.62 | 7.11 |
| Turning point | $32,743 | $30,084 | $20,352 | $38,624 |
| Turning point: FE | $33,238 | $30,048 | $19,288 | $56,696 |
| Turning point: OECD | $33,157 | $24,048 | $18,162 | $39,157 |
| Observations | 672 | 128 | 672 | 640 |

the ADF tests are only able to reject the null of a unit root in a handful of cases. The results of the IPS panel unit root tests also suggest that the data are non-stationary. The same findings are made whether or not a time trend is included. Both ADF and IPS tests also indicate that first differenced data are stationary, suggesting that the data are all $I(1)$.[17]

In light of these test results, table 4 also reports model 4 estimated in first differences (model 4a). The signs of the estimated coefficients can be seen to be identical to those for model 4, with the only notable difference being the reduced significance of the trade variables. The F-tests on the income terms and the trade terms remain significant. Note that models 1, 2, and 3, when estimated in first differences, also provide estimated coefficients with the same signs and significance as those estimated in levels.

Finally, we can consider the results estimated for biological oxygen demand.

[17] Appendix B reports the IPS tests on first differenced data.

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Table 5. *Estimation results for biological oxygen (random effects)*

| *Variable* | *Model 1* | *Model 2* | *Model 4* | *Model 4a (First diff.)* |
|---|---|---|---|---|
| *Y* | −66.73*** | −86.44*** | 34.90 | −160.36*** |
| $Y^2$ | 0.0014*** | 0.0017*** | −0.00088 | 0.0019*** |
| *GINI* | | 24859.8 | | |
| *LIT* | | 6934.6 | | |
| *K/L* | | | −37.96 | −0.40 |
| $K/L^2$ | | | 0.00016 | 0.000027 |
| *Trade intensity* (*T*) | | | −17392.34*** | −8280.01*** |
| *T * relative K/L* | | | 21154.68*** | 5658.16 |
| *T * relative* $(K/L)^2$ | | | −5566.50 | −1638.37 |
| *T * relative Y* | | | −2136.81 | 901.86 |
| *T * relative* $Y^2$ | | | 351.82 | −6.29 |
| Constant | 6586639 | 5176404 | 7524509 | 18412 |
| $R^2$ (overall) | 0.15 | 0.18 | 0.15 | 0.051 |
| F-test on *Y*, $Y^2$ | 22.22*** | 6.98** | 1.23 | 16.34*** |
| F-test on trade terms | | | 80.90*** | 14.60** |
| Hausman (FE v. RE) | 1.11 | 1.67 | 5.01 | 40.63** |
| Hausman (simult.) | 3.19 | 2.00 | 5.35 | 4.32 |
| Turning point | $22,382 MIN | $24,982 MIN | $19,678 | $41,038 MIN |
| Turning point: FE | $21,332 MIN | $23,925 MIN | $19,752 | $41,705 MIN |
| Turning point: OECD | $19,165 MIN | $29,595 MIN | No turning pt. | $41,096 MIN |
| Observations | 672 | 128 | 672 | 640 |

In light of the unit root test results, model 4 is again estimated in first differences (becoming model 4a). Models 1, 2, and 4 are reported in levels for means of comparison. Model 3 is once more omitted for reasons of space. In contrast to the previous pollutants, we now find a U-shaped relationship estimated between income and emissions, at least for models 1 and 2. The estimated turning points are therefore minimum turning points. In model 4, an inverted-U-shaped relationship is estimated, although both of the income terms are statistically insignificant. The resultant turning point should therefore be treated with caution. Curiously, once estimated in first differences, a U-shaped relationship returns. Finally, note that in common with the other three pollutants, the null of exogeneity of income is accepted in all estimations, suggesting that simultaneity bias is not present.

Considering the trade variables, both models 4 and 4a estimate the trade intensity variable to have a negative, statistically significant, relationship with emissions. The actual trade interaction terms are generally insignificant, with inconsistent signs across both models. Despite this fact, models 4 and 4a both find the F-test on the trade terms to be statistically significant.

In sum, the estimated results for the four pollutants indicate a reasonable robust relationship between income and emissions. For the three air

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pollutants this relationship takes the form of an inverted-U shape. For biological oxygen demand it appears to form a U shape, suggesting that emissions have been falling at a declining rate with income, for the majority of the countries in the sample.[18] Estimated turning points do not appear to be particularly sensitive to the variety of different specifications, covariates or to whether our sample contains a wide mix of income levels or OECD countries alone.

The impact of trade appears to vary by pollutant, with only sulphur dioxide showing evidence of both factor endowment and pollution haven effects. The trade intensity variable is negative for sulphur dioxide, nitrogen oxides, and biological oxygen demand (although it is not significant for nitrogen oxides) whilst it is positive for carbon dioxide. The inclusion of the trade variables can be seen to add little, if anything, to the explanatory power of the estimated equations. Only for nitrogen oxides does the $R^2$ measure increase notably with the inclusion of the trade variables, although ironically the F-test on these variables is not significant for this pollutant. The effect of trade on pollution would generally seem to be small, certainly relative to the effect of income.

In order to quantify and compare the magnitude of the impact of trade and income on emissions, trade and income elasticities are presented in table 6.

As can be seen, positive income elasticities are estimated for all pollutants, with those estimated for the air pollutants being statistically significant. As would be expected given the previous results, the sign and significance of the trade elasticities varies by pollutant. The magnitude of the trade elasticities can be seen to be small, however, particularly relative to the income elasticities. In all but one case, the income elasticities are significantly larger than the trade elasticities.

## 6. Conclusions

The results of this paper appear to be largely supportive of the EKC. The estimated relationship between per capita income and per capita emissions is robust across the variety of functional forms utilized (fixed or random effects, levels or first differences). Furthermore, the inclusion of additional covariates (trade variables, political economy variables) does little to affect the income–emissions relationship. No evidence is found to support Torras and Boyce's (1998) assertion that the distribution of power (as captured by GINI coefficients and measures of literacy) determines pollution emissions. Our results also suggest that the use of a full (developed and developing country) sample or an OECD sub-sample does little to affect the income–emissions relationship. No support is therefore found for Stern and Common's (2001) claim that turning points from an OECD sample will tend to be lower than those from a larger sample that contains developing countries. However, whilst the samples used in this paper do contain a reasonably large number of developing countries, the sample used by

[18] This relationship is still consistent with the EKC since the high turning point indicates falling emissions across the sample and for emissions to fall they must once have risen.

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Table 6. *Trade and income elasticities*

| *Pollutant and Model* | | *Income* | *Trade* |
|---|---|---|---|
| Sulphur dioxide | Levels | 2.69*** | −0.53*** |
| Nitrogen oxides | Levels | 1.92*** | −0.30 |
| Carbon dioxide | Levels | 1.52*** | 0.21*** |
| | First differences | 4.03** | 0.27 |
| Biological oxygen | Levels | 0.063 | −0.18*** |
| Demand | First differences | 2.68 | −0.95 |

*Notes*: Estimated using models 4 (levels) and 4a (first differences), at the means of the independent variables.

Stern and Common does contain a greater number. This may explain the failure to replicate their results. With regard to simultaneity bias, for all estimations and all pollutants the Hausman specification test accepts the null of exogeneity of current income. No evidence of such bias is therefore found. Finally, although evidence of non-stationarity is found (at least for carbon dioxide and biological oxygen demand), the sign and significance of the variables changes only very little once this has been corrected.

This paper also finds the impact of trade patterns on pollution emissions to be small. Only for sulphur dioxide does the analysis suggest that trade patterns driven by environmental regulations and/or factor endowments are determining per capita emissions. With the exception of this pollutant, the full trade model appears to add little to the basic EKC estimation. More generally, the results suggest that the EKC relationship is not determined by the migration or displacement of pollution-intensive industry from the north to the south, as has been claimed by proponents of the pollution haven hypothesis.

So what are the determinants of pollution emissions? The income terms used in this paper appear to be capturing scale and technique effects, in particular. For local air pollutants, it would still appear that increasing incomes lead to changing techniques of production. Of course, this is not an automatic procedure. Growth does not reduce pollution. Rather, the evidence suggests that growth *can* facilitate the required legislation and investment to help reduce *per capita* emissions of *some* pollutants. This carefully worded statement illustrates the great care that is needed when interpreting EKC results. Whilst the basic EKC relationship may be more robust than some have claimed, the estimated turning points should only be interpreted as rough estimates. They simply provide evidence of the broad level of development at which countries in the sample found themselves when per capita emissions of a particular pollutant began to fall. EKCs do not indicate that countries can simply grow out of environmental problems, nor do they indicate that all aspects of environmental quality are compatible with economic growth. Furthermore, an estimated turning point at a relatively low level of per capita income does not mean that, globally, emissions will be falling. It is important to be clear that these points are not criticisms of the EKC but relate to the misinterpretation of EKC results. They are valid points nonetheless.

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## Appendix A: Data information

*Data sources*

| *Variable* | *Source* |
|---|---|
| $SO_2$ and $NO_x$ emissions | UNEP (1993) |
| $CO_2$ emissions | Marland *et al*. (2000) |
| BOD emissions | World Bank (1999) |
| Per capita income | Penn. World Tables (GDP per capita, PPP, 1985 US$) (Summers and Heston 1991) |
| Trade openness | World Bank (1999) |
| Capital–labour ratios | World Bank (1999) |
| Gini coefficients | Deininger and Squire (1996) |
| Literacy | World Bank (1999) |

Relative capital–labour ratios and relative income are capital–labour ratios and per capita income expressed relative to the world average (that is divided by the world average). World averages are calculated as the average of all countries for whom data are reported.

*Countries in the $SO_2$ and $NO_x$ samples*
Bangladesh, Canada, China, Denmark, Finland, France, Hong Kong, India, Indonesia, Ireland, Japan, South Korea, Malaysia, Nepal, Netherlands, Norway, Pakistan, Philippines, Portugal, Singapore, Sri Lanka, Sweden, Switzerland, Thailand, UK, USA.

*Countries in the $CO_2$ and BOD samples*
Argentina, Bangladesh, Brazil, Canada, Chile, China, Colombia, Demark, Finland, France, Ghana, Hong Kong, India, Indonesia, Ireland, Japan, Kenya, South Korea, Malaysia, Mexico, Netherlands, Norway, Pakistan, Philippines, Portugal, Singapore, South Africa, Sri Lanka, Sweden, Switzerland, UK, USA.

https://doi.org/10.1017/S1355770X0300305 Published online by Cambridge University Press

## Appendix B: Unit root tests

*Individual augmented Dickey–Fuller unit root test statistics*

| *Country* | $CO_2$ | *BOD* | *KL* | *Trad* | *Tradrel KL* | *Tradrel Y* |
|---|---|---|---|---|---|---|
| Argentina | −2.0 | −1.4 | 0.5 | −4.1* | −1.9 | −3.5* |
| Bangladesh | −0.3 | −2.6 | −0.3 | −1.9 | −1.4 | −0.1 |
| Brazil | −1.4 | 0.5 | −1.1 | −2.6 | −1.3 | −2.6 |
| Canada | −1.5 | −1.6 | 0.8 | 1.0 | 2.1 | 0.4 |
| Chile | −0.1 | −2.9 | 2.9 | −0.8 | 0.3 | 0.6 |
| China | 0.9 | −1.6 | 8.7* | 0.1 | 1.8 | 1.7 |
| Colombia | −0.8 | −0.9 | −1.7 | −0.9 | −2.0 | −0.03 |
| Denmark | −2.9 | −2.1 | −1.0 | −1.8 | −1.0 | −1.4 |
| Finland | −2.1 | −1.0 | −2.1 | −0.8 | −1.3 | −0.9 |
| France | −0.6 | −0.3 | −1.6 | −2.8 | −2.4 | −2.1 |
| Ghana | −3.4* | −0.7 | −1.9 | −0.2 | −3.3* | −0.4 |
| Hong Kong | −1.6 | 2.4 | 1.5 | 0.4 | 1.6 | 0.8 |
| India | 1.1 | −1.1 | 3.8* | 2.3 | 4.4* | 5.4* |
| Indonesia | −0.1 | −1.3 | 2.0 | −2.1 | 0.4 | 0.9 |
| Ireland | −1.0 | −0.6 | −3.6* | −0.9 | −2.9 | 2.5 |
| Japan | −0.5 | −1.3 | 0.9 | −1.0 | −1.6 | −2.0 |
| Kenya | −2.0 | −0.8 | 1.2 | −1.6 | −1.3 | −2.3 |
| Korea, Rep. | 3.8* | −2.4 | 6.7* | −1.7 | 1.5 | 1.3 |
| Malaysia | 2.7 | 0.9 | 1.0 | 1.2 | 3.2* | 3.3* |
| Mexico | −2.6 | −1.3 | −1.1 | 0.6 | −1.1 | 0.2 |
| Netherlands | −1.7 | −1.4 | −1.3 | −2.0 | −1.0 | −1.5 |
| Norway | −0.5 | −0.4 | 1.2 | −2.3 | 0.1 | 2.3 |
| Pakistan | −0.4 | −0.9 | 1.7 | −1.9 | −0.2 | −0.3 |
| Philippines | −0.9 | −1.8 | −1.4 | 2.0 | −1.6 | 0.5 |
| Portugal | 0.3 | −3.8* | 3.2* | −1.7 | −0.7 | −0.9 |
| Singapore | −0.5 | −0.8 | −0.8 | −2.2 | −2.2 | 0.1 |
| S. Africa | −1.7 | −1.3 | 2.0 | −1.3 | 0.1 | −1.1 |
| Sir Lanka | −1.7 | −2.6 | −2.1 | −1.1 | −1.5 | 0.3 |
| Sweden | −0.9 | −2.0 | −0.8 | −0.8 | −1.4 | −0.7 |
| Switzerland | −2.2 | −0.6 | 0.6 | −3.2* | −2.8 | −2.2 |
| UK | −1.1 | −0.9 | 2.1 | −1.7 | −1.0 | −0.6 |
| USA | −1.4 | 0.002 | −0.1 | −0.3 | −0.6 | −0.1 |
| | 2 rejects of unit root at 5% | 1 reject of unit root at 5% | 5 rejects of unit root at 5% | 2 rejects of unit root at 5% | 3 rejects of unit root at 5% | 3 rejects of unit root at 5% |

*Notes*: $H_0$: there is a unit root in the time series. Critical value at 95 per cent significance = 3.0.

Estimated without a time trend. ADF test with a time trend provided an almost identical number of rejections of the null hypothesis.

ADF tests for $Y^2$, $KL^2$, $trad(relKL)^2$ and $trad(rely)^2$ are not reported since they are almost identical to those for *Y*, *KL*, *tradrelKL* and *tradrelY*, respectively.

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*Im, Pesaran and Shin (1997) Panel Unit Root Test Statistics*

| | | |
|---|---|---|
| $CO_2$ | Time trend | −1.65 |
| | No time trend | −0.93 |
| *BOD* | Trend | −2.05 |
| | No time trend | −1.24 |
| *Y* | Trend | −1.82 |
| | No time trend | −0.40 |
| *KL* | Trend | −1.11 |
| | No time trend | −0.54 |
| *Trad* | Trend | −1.94 |
| | No time trend | −1.06 |
| *TradrelKL* | Trend | −2.32 |
| | No time trend | −1.12 |
| *TradrelY* | Trend | −2.02 |
| | No time trend | −0.65 |

*Notes*: $H_0$: Each series in the panel contains a unit root.
Critical values at 95 per cent significance: −2.37 with time trend, −1.73 without time trend.
For all variables, the null of non-stationarity cannot be rejected.

*Im, Pesaran and Shin (1997) Panel Unit Root Test Statistics on FIRST DIFFERENCED DATA*

| | | |
|---|---|---|
| $CO_2$ | Time trend | −3.2 |
| | No time trend | −3.1 |
| *BOD* | Trend | −3.1 |
| | No time trend | −3.1 |
| *Y* | Trend | −2.7 |
| | No time trend | −2.5 |
| *KL* | Trend | −2.4 |
| | No time trend | −1.8 |
| *Trad* | Trend | −3.1 |
| | No time trend | −2.9 |
| *TradrelKL* | Trend | −3.2 |
| | No time trend | −3.2 |
| *TradrelY* | Trend | −3.1 |
| | No time trend | −3.0 |

*Notes*: $H_0$: Each series in the panel contains a unit root.
Critical values at 95 per cent significance: −2.37 with time trend, −1.73 without time trend.
For all variables, the null of non-stationarity is now rejected.

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